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published in

Adapted Physical Activity Quarterly (APAQ)
2008

DOI (link to publisher)

[10.1123/apaq.25.1.17](https://doi.org/10.1123/apaq.25.1.17)

document version

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Deconinck, F. J., de Clercq, D., van Coster, R., Oostra, A., DeWitte, G., Savelsbergh, G. J. P., Cambier, D., & Lenoir, M. (2008). Sensory contributions to balance in boys with developmental coordination disorder. *Adapted Physical Activity Quarterly (APAQ)*, 25(1), 17-35. <https://doi.org/10.1123/apaq.25.1.17>

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Sensory Contributions to Balance in Boys With Developmental Coordination Disorder

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This study examined and compared the control of posture during bilateral stance in ten boys with Developmental Coordination Disorder (DCD) of 6-8 years old and ten matched typically developing boys in four sensory conditions (with or without vision, on a firm or compliant surface). In all conditions mean postural sway velocity was larger for the boys with DCD, in spite of a normal score on the balance items of the Movement Assessment Battery for Children. A Group X Condition interaction revealed a larger dependency on vision in the boys with DCD when standing on a firm surface. These results suggest that in this specific subgroup of boys with DCD with predominantly problems in fine motor and

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ball skills postural control problems may still be prevalent and may possibly be associated with difficulties to re-weight sensory information in response to environmental demands.

Developmental Coordination Disorder (DCD) is characterized by coordination problems in fine and gross motor skills in the absence of an overt neurological disease or mental retardation (American Psychiatric Association, APA, 1994). Children with DCD, often designated as “clumsy,” may show difficulties with the acquisition and performance of several motor skills such as writing, catching, throwing, jumping, etc. (Henderson & Henderson, 2002; Hoare, 1994). Due to these movement problems, children suffering from this disorder are at high risk for developing significant academic and/or psychosocial functioning impairments (Cantell, Smyth, & Ahonen, 1994; Losse et al., 1991). Moreover, recent evidence indicates that DCD may also be a precursor for other health related problems such as overweight and obesity (Cairney, Hay, Faught, & Hawes, 2005). Behavioral studies have revealed a number of motor control and perceptual deficiencies in this group of children, but the picture of the underlying mechanisms of DCD remains unclear and additional research is needed to explore the nature of the impairment in further detail.

Given the heterogeneity of the population, it is imprudent to generalize characteristics in children with DCD. However, poor postural and balance control appears to be a reasonably common feature of the disorder (Williams, Fisher, & Tritschler, 1983). From the attempts that have been made to categorize the population into homogeneous subtypes, it can be concluded that 73-87% of the children with DCD actually have balance problems (Hoare, 1994; Macnab, Miller, & Polatajko, 2001). Several studies have demonstrated difficulties to maintain quiet stance (Geuze, 2003; Przysucha & Taylor, 2004) as well as to maintain stability when support surface is suddenly displaced (Williams & Woollacott, 1997), or when actively moving a limb (Johnston, Burns, Brauer, & Richardson, 2002), or the whole body during walking (Deconinck et al., 2006).

Since adequate balance control requires a very accurate tuning and integration of three sensory inputs (visual, proprioceptive, and vestibular; Forssberg & Nashner, 1982; Peterka, 2002), these stability problems of children with DCD might be not so surprising. Indeed, visual-spatial processing, visual-kinesthetic integration, and kinesthetic perception are prerequisites for successful maintenance of stability, but they are all often reported to be impaired in children with DCD (see Wilson & McKenzie, 1998 for a review regarding information-processing deficits of children with DCD), are prerequisites for successful maintenance of stability. Inter and intra-sensory matching difficulties have been found in for example the target point and location task, where the location of a target that is seen, felt, or seen + felt by one finger has to be matched with a the contralateral finger using only proprioception (Mon-Williams, Wann, & Pascal, 1999). Little research has been carried out to investigate the link between postural control and sensory-(motor) integration in children with DCD, however.

A number of studies have examined the control of balance and posture in children with DCD by using detailed posturography, measuring the displacement

of the center of pressure (COP) and/or center of gravity (COG). This offers a less reductionist approach compared to the balance assessments in motor assessment batteries (Geuze, 2003; Przysucha & Taylor, 2004; Wann, Mon-Williams, & Rushton, 1998). It appeared that children with DCD typically displayed increased amounts of postural sway in either one-legged (Geuze, 2003) or two-legged quiet stance (Przysucha & Taylor, 2004; Wann et al., 1998), indicating a less efficient (and more immature) control strategy and thus a less sound control of the COP positioning and the related displacement of the COG (Kirshenbaum, Riach, & Starkes, 2001). EMG-measures demonstrated that the increase of postural sway was generally accompanied by an increased activity and co-activation of the leg muscles (Geuze, 2003; Williams et al., 1983). The role of vision has been touched only briefly in these studies, and limited attention has been paid to the interplay of sensory sources. Moreover, there seems to be inconsistency with regard to the contribution of vision. Wann et al. conclude that a sub-group of the children with DCD over-rely on vision for the control of posture, as evidenced by a disproportional increase of the sway when eyes were shut. Although not based on detailed posturography, the results of Forseth and Sigmundsson (2003) offer some support for these findings, in that the performance (maximal duration) of one-legged stance in children with hand-eye coordination problems was affected more severely when vision was absent than in control-children. Furthermore, it seems that this propensity to be more dependent on visual cues for the control of posture was also a characteristic of a group of adults with motor impairments (Cousins & Smyth, 2003). In contrast to this, Geuze (2003) and Przysucha and Taylor (2004) could not confirm this increased visual dependency in children with DCD for one- or two-legged quiet stance. These conflicting results, therefore, indicate a need for new studies that focus on postural control and its underlying sensory integration processes.

Mathematical modeling has been used to gain insight into the complex sensorimotor control system at the base of the maintenance of stability. It is thought that posture is controlled by a dual mode strategy where the role of a sensory-feedback control component and a feedforward estimating component are dynamically regulated dependent upon the inconstant and multivariate environment (Kiemel, Oie, & Jeka, 2002). The relative contribution of sensory information, originating from the visual, proprioceptive, and vestibular system, is also dynamically adjusted to changes in the environmental conditions (Jeka, Oie, & Kiemel, 2000; Peterka, 2002). An adequate, context-dependent, sensory re-weighting is thought to enable a correct estimation of the relative position of the COM with respect to the COP. This in turn is suggested to result in a proportionally corrective torque against the imbalance of the body, which is modeled as an inverted, inherently unstable pendulum (Peterka, 2002).

Young children (4-7 years and younger) employ a primarily ballistic postural control strategy, characterized by fast and large COG displacements and open-loop like COP corrections, but this progresses to a slower and more integrated feedback-feedforward strategy at approximately 8 years (Riach & Starkes, 1994). It is commonly assumed that this progression coincides with an improvement of the sensory re-weighting or integration capacity, characterized by a shift from a primarily visual dependent control at younger ages to a control involving visual,

proprioceptive, and vestibular information (Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1995). These sensory developments are accompanied by non-monotonic changes in the amount and velocity of sway between 5 to 8 years of age (Kirshenbaum et al. 2001; Riach & Starkes, 1994). Together, these changes result in a general decrease of the amplitude and variability of the COM behavior, which is suggested to reach adult-like levels between 7-10 years of age. In their recent study, however, Peterson, Christou, and Rosengren (2006) argue that adult-like use of sensory information for the control of posture is not demonstrated prior to the age of 12 years.

Overall, postural control is a skill that is often taken for granted, and the importance of adequate postural control is sometimes underestimated. It should be emphasized, however, that any kind of action is likely to result in an atypical movement if an optimal postural framework is lacking (Latash & Anson, 1996; Williams et al., 1983). Therefore, it is important to investigate postural control in children with DCD in further detail, especially with respect to the perceptual integration as a prerequisite for a sound balance control. The objective of the present study was to examine the postural control of children with DCD during quiet bilateral stance, in various sensory conditions, using a modified version of the Clinical Test of Sensory Interaction on Balance (mCTSIB; Shumway-Cook & Horak, 1986). The period between 5-8 years is of particular interest, because it has been described as a transition period where changes in strategy and performance of postural control accompanied by a crucial development of the sensory re-weighting capacity take place (Kirshenbaum et al., 2001; Shumway-Cook & Woollacott, 1995). With the mCTSIB it was tested whether 6- to 8-year-old children with DCD also displayed a decrease of the amount of postural sway reported for typically developing children around this period. Further, altering the sensory context enabled to look for differences in the influence and integration of inputs from sensory systems between children with and without DCD. Given the problems in processing of and mapping between visual and proprioceptive information of children with DCD, as demonstrated elsewhere (Mon-Williams et al., 1999; Schoemaker et al., 2001; Van Waelvelde et al., 2006), it seems reasonable to expect that children with this disorder would perform worse on the mCTSIB. This would not only be displayed in increased amounts of postural sway, but also in a decreased capability to re-weight multiple sensory inputs in response to the environment.

Current literature provides conflicting results with regard to gender effects in the developmental trajectory of balance (Foudriat et al., 1993; Peterson et al., 2006). It seems that environmental factors (for example the engagement in physical activities stimulating sensory integration for balance such as ballet) are responsible for these gender differences. DCD is commonly assumed to be overrepresented in boys (Gillberg, 2003); however, it is not fully clear whether this is due to an underlying genetic factor or is just the result of the sampling strategy and/or the nature of presentation of DCD in boys (Cairney, Hay, Faight, Mandigo, & Flouris, 2005). The selection procedure of the present study also resulted in predominantly boys, and although children of both groups were matched pairwise on gender and on the amount and nature of daily physical activity, it was decided to concentrate only on the boys to exclude a potential gender bias.

Method

Participants

Twenty children, all boys between 6 and 8 years old, were recruited for this study. The group consisted of ten boys with DCD (mean age = 7.7, $SD = 0.8$) and ten typically developing (TD) boys without DCD (mean age = 7.6, $SD = 0.9$). The boys with DCD were diagnosed with the disorder after a multidisciplinary examination including a neurological, psychological, and psychomotor assessment. All boys with DCD attended a physical therapist. They were neurologically healthy, had no signs of other developmental disorders such as ADHD or autism, and were free from serious intellectual impairments ($IQ > 80$). Their mean total impairment score on the Movement Assessment Battery for Children (M-ABC; Henderson & Sugden, 1992) was at the 8th percentile ($SD = 3.9$, range = 1-12), with 3 boys having a percentile at or below 5. A summary of the demographic data is shown in Table 1.

The ten TD-children without DCD were recruited from a group of 300 children from two primary schools in the neighborhood of the department. They were matched pairwise to the boys with DCD for gender, age, height, and body weight. Since IQ was not available for the TD-boys, matching for intelligence was based on the math grade, which has been shown to correlate well with IQ in a Flemish population (Brusselmans-Dehairs et al., 2002). The mean total impairment score on the M-ABC of the TD-boys was at percentile 69 ($SD = 22.2$, range: 33-92). Furthermore, the children were also matched for the amount and nature of daily

Table 1 Mean (M), Standard Deviations (SD), and Paired t-Test Values Relative to Demographic Data and M-ABC Results of Boys With DCD and Typically Developing (TD) Boys

	Boys with DCD		TD-Boys		<i>t</i> (9)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>t</i> (9)	<i>p</i>
Age (years)	7.7	0.8	7.6	0.9	0.24	0.816
Body length (m)	1.29	0.07	1.32	0.04	0.89	0.397
Body weight (kg)	25.7	4.1	28.5	4.6	1.25	0.243
M-ABC percentile	8.4	4.6	69.1	22.2	7.69	< 0.001
M-ABC fine motor	6.8	3.4	0.8	1.2	4.65	0.001
M-ABC ball	4.8	2.0	1.1	1.4	4.77	0.001
M-ABC balance	0.7	0.5	0.3	0.6	1.50	0.168
M-ABC one-leg (s)	33.3	5.8	35.9	4.6	1.52	0.164
Physical activity (h/week)	4.7	2.1	5.4	3.2	0.58	0.577

Note. M-ABC fine motor, ball, and balance refer to the normalized scores for these subscales. M-ABC one-leg refers to raw score for this item, i.e., the sum of maximal one-legged stance on preferred and non-preferred leg.

physical activity, based on a questionnaire containing questions about the amount of hours of PE at school, the amount and nature of leisure time physical activity, and favorite sport(s) to be filled in by the child together with one of the parents. According to Verstraete (2006) a total physical activity index was calculated indicating the amount of time the children spend in physical activity or sports during a normal week. Based on this index, the TD-child was also matched to the child with DCD on its activity level with a maximum tolerance of one hour/week. Test-retest reliability of this index was good ($r = .86$). Convergent validity, tested by means of comparison with data obtained with an accelerometer, a small device worn on the body to register the amount of physical activity, was acceptable and in line with other studies ($r = .39-.50$; Verstraete, 2006). An additional matching was done for the nature of physical activity which is assumed to have an impact on proficiency in balance, by matching the favorite sport of the children.¹

It is commonly believed that balance is highly influenced by daily experience and practice (Shumway-Cook & Woollacott, 1995) and by following this matching procedure, it was attempted to control for these factors. By doing so a comparison group was formed with boys who did not necessarily have very proficient balance skills. Because the focus of the present study was on balance deficits rather than on a possible delay in balance skill due to experience or practice, this matching procedure was thought to be more appropriate. It should be noted, however, that the physical activity levels of both the boys with and without DCD, as depicted in Table 1, were congruent with other reported figures for physical activity for children in Flanders (Cardon et al., 2005; Verstraete, 2006). Thus, in spite of the well-documented activity deficit of children with DCD (Bouffard, Watkinson, Thompson, Causgrove Dunn, & Romanow, 1996; Cairney, Hay, Faught, Corna, & Flouris, 2006), the participants in the current did not seem to be abnormally inactive.

Coincidentally, the scores of the boys with DCD on the cluster of static and dynamic balance of the M-ABC (3 items: one legged stance, jumping, and walking on a line) were consistently above the 15th percentile. Maximal one legged stance time was not different from the TD-boys (see Table 1) and all boys achieved the maximum score for jumping (M-ABC Age band 4-6 years: over a cord; Age band 7-8 years: in squares) and for walking over a line item (Age band 4-6 years: with heels raised; Age band 7-8 years: heel-to-toe). It appeared that, by chance, a sub-group of boys with DCD with predominantly fine motor and ball handling problems but without clear cut balance problems was selected. Since this study focused on the sensory integration processing underlying postural control in boys with DCD, the absence of balance problems, as assessed with the M-ABC, did not have an influence on the original aim of the research. Written informed consent, in accordance with the standards of the Ethical Committee of the University Hospital, was obtained from all parents.

Materials and Procedure

The mCTSIB was assessed with the Basic Balance Master, a computerized posturography system (NeuroCom Inc., Clackamas, OR-USA). It consists of a dual force plate of 46 cm by 46 cm (two footplates connected to each other with a pin joint) connected to a computer equipped with the NeuroCom software. Four force transducers, one on every corner, measure the vertical forces exerted on the

plate with a sampling frequency of 100 Hz. The NeuroCom software calculates the position of the COP and derives the position of the COG from the height of the subject, assuming that the body acts as an inverted pendulum. The modified Clinical Test for Sensory Interaction on Balance (mCTSIB) is integrated in the NeuroCom software and is an analysis tool designed to assess the amount of postural sway in bilateral stance in various sensory conditions. In this modified version, the sway-referenced condition of the original CTSIB was replaced by a condition with compliant surface.

The standard protocol for administering the mCTSIB was followed. The test includes four different conditions: (a) on a firm surface with eyes open (FEO), (b) on a firm surface with eyes closed (FEC), (c) on a compliant foam surface with eyes open (FOEO), and (d) on a compliant foam surface with eyes closed (FOEC). Three successive trials of 10 seconds (followed by a short rest period) were registered under each condition. A blindfold was used to assure that vision remained occluded in the eyes closed conditions and the compliant surface consisted of a foam cushion (46 cm × 46 cm × 15 cm) provided by NeuroCom Inc. All tests took place in the movement analysis laboratory at the university. After a demonstration and explanation of the balance test, the child stood on the plate. The feet were placed in the correct position as indicated on the plate to ensure a reliable calculation of the COG. Children were asked to adopt a relaxed, upright standing position and to stand as still as possible during the trial, while looking at the wall 2 m in front of them. The tester announced the initiation of the measurement, and at the end of the 10 s trial, a bell-sound was given by the computer. During the trial no talking was allowed. In between the trials the tester encouraged the child and made sure that he/she felt comfortable.

Analysis

The dependent variable of interest was the amount of sway of the COG, which is generally considered to be a general indicator of the integrity of the postural control system (Winter, 1995). The distance traveled by the COG was calculated based on the inverted pendulum model. Assuming that the body sways as an inverted pendulum, the difference between COP and COG is proportional to the horizontal acceleration of the COG (Winter, 1995). Double numerical integration of the COG horizontal acceleration gives the horizontal displacement. This displacement can be converted into the angle of sway of the inverted pendulum. While it should be acknowledged that body sway during standing on two legs is the result of a coordinated action between different body segments, the inverted pendulum has been shown to be a reliable method to model body sway in bilateral stance (Winter, 1995). Although qualitative observation during the test confirms that the children did not use a hip strategy, some inaccuracy due to invisible involvement of hip or other joints should be taken into account and caution is warranted when interpreting the absolute values. Still, the high intra-class correlation coefficients (ICC; Cronbach's $\alpha > .90$) of the three trials per condition of all boys are in favor of the reliability of the model, at least for the purpose of this comparative study.

The amount of sway was reported as the mean COG sway velocity (V) by the NeuroCom software. It is the total distance traveled by the COG during the trial (expressed in degrees) divided by the duration of the trial (10 s). The average COG

sway velocity of the three trials per condition was statistically analyzed with the SPSS software package (version 12.0) by means of a 2×4 (Group $\times$ Condition) ANOVA, with repeated measures on the second factor. Separate 2×2 ANOVA's and paired t -tests were used to investigate interaction effects. Given that ICCs for all boys were high the use of the average values per condition was justified (Portney & Watkins, 1993).

The contribution of the three sensory systems was investigated in more detail by means of the stabilization ratio (SR). By comparing the amount of sway in conditions with a sensory perturbation to the baseline condition (normal vision and fixed support) the SR offers a useful way to determine the relative contribution of the distorted sensory modality. This ratio is based on a logarithmic variance stabilizing transformation which accounts for the increase in variability of the V when the magnitude of V is larger. The Romberg-quotient, i.e., the ratio of the variable obtained in the eyes closed and the eyes open condition, traditionally used to measure the contribution of vision, does not account for the increase in variability and has been demonstrated to be less reliable than the recently suggested SR (Cornilleau-Pérès et al., 2005). In the present study, four SRs were calculated, that is two for the contribution of vision and two for proprioception. The first, $SR_{vf}(\log)$, was calculated as follows:

$$SR_{vf}(\log) = 1 - \frac{\log(V_{FEO} + 1)}{\log(V_{FEC} + 1)} \quad (1)$$

In the above formula (1) V_{FEO} is the mean COG sway velocity for the firm surface-eyes open condition and V_{FEC} is the mean COG sway velocity for the firm surface-eyes closed condition. Thus, $SR_{vf}(\log)$ provides a measure of the contribution of vision when standing on a firm surface. In other words, $SR_{vf}(\log)$ estimates to what extent the proprioceptive and the vestibular system can compensate for the loss of visual information. The second SR for vision, $SR_{vfo}(\log)$, was calculated with the following formula:

$$SR_{vfo}(\log) = 1 - \frac{\log(V_{FOEO} + 1)}{\log(V_{FOEC} + 1)} \quad (2)$$

with V_{FOEO} and V_{FOEC} being the mean COG sway velocity for the foam conditions with eyes open and eyes closed, respectively. $SR_{vfo}(\log)$ is a measure of the visual contribution when standing on a compliant, unstable surface, which compromises the input from the proprioceptive system (Allum, Zamani, Adkin, & Ernst, 2002). Thus, $SR_{vfo}(\log)$ gives an indication of the importance of vision to assist the vestibular system to control stability when sensory input originating from proprioception is less reliable.

The two measures of the contribution of proprioceptive input were calculated in a similar way:

$$SR_{peo}(\log) = 1 - \frac{\log(V_{FEO} + 1)}{\log(V_{FOEO} + 1)} \quad (3)$$

and

$$SR_{pec}(\log) = 1 - \frac{\log(V_{FEC} + 1)}{\log(V_{FOEC} + 1)} \quad (4)$$

Formula (3), $SR_{\text{peo}}(\log)$, refers to the contribution of proprioception to the control of posture in a situation where visual input is available. It gives an indication to what extent proprioceptive information is used to assist the visual and the vestibular system with the control of posture. Finally, $SR_{\text{pec}}(\log)$, measures the contribution of proprioception when visual information is absent.

Group and condition effects were investigated with a 2×2 (Group $\times$ Condition) ANOVA for the contributions of vision and proprioception separately. Post-hoc *t*-tests were used to decompose the interaction effects. An alpha level of .05 was used for all statistical tests and partial η^2 was calculated to measure effect sizes.

Results

Postural Sway

Table 2 shows the mean sway velocities for both groups for all conditions. A significant main effect for Group indicated that the boys with DCD swayed significantly more than the TD-boys across the four conditions, $F(1, 18) = 17.743, p = .001, \eta^2 = .496$. The largest between-group difference was found in the FEC-condition, where the difference amounted to 0.51 °/s or 104% of the absolute value of the TD-boys. The differences in the FEO, FOEO, and FOEC were respectively 0.23 °/s (60.5%), 0.51 °/s (70.8%), and 0.49 °/s (24.1%). Further, a significant Condition-effect was found, $F(3, 16) = 71.279, p < .001, \eta^2 = .930$. Pairwise comparisons indicated that mean sway velocity increased across conditions, with $FEO < FEC < FOEO < FOEC$ ($p < .001$ for all comparisons, except for $FEC-FOEO$ where $p = .005$).

Interestingly, a significant Group $\times$ Condition interaction revealed that both groups responded differently to the sensory perturbations, $F(3, 16) = 4.137, p = .024, \eta^2 = .437$. Further analysis showed that this interaction was due to a differential response to the removal of vision when standing on a firm support, $F(1, 18) = 11.605, p = .003, \eta^2 = .392$. The data indicate that the mean sway velocity of boys with DCD increased when blindfolded, $t(9) = 6.082, p < .001$, while this variable remained virtually the same in the TD-boys, $t(9) = 1.941, p = .084$. This Group $\times$ Vision interaction was not significant when standing on a foam, $F(1, 18) = 0.005, p = .947, \eta^2 = .000$. When proprioception was disturbed, the removal of

Table 2 Means (M) and Standard Deviations (SD) of the Mean COG Sway Velocity (V) of Boys With DCD and Typically Developing (TD) Boys in Each Condition

	Boys with DCD		TD-Boys	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
VFEO (°/s)	0.61	0.25	0.38	0.15
VFEC (°/s)	1.02	0.35	0.49	0.19
VFOEO (°/s)	1.23	0.30	0.72	0.20
VFOEC (°/s)	2.52	0.73	2.03	0.52

Note. FEO: Firm surface, eyes open; FEC: firm surface, eyes closed; FOEO: foam, eyes open; FOEC: foam, eyes closed.

vision resulted in a significant increase of COG sway that was similar for both groups, $t(9) = 5.060$, $p = .001$ for the boys with DCD and $t(9) = 8.768$, $p < .001$ for the TD-boys.

In line with this effect for vision, the manipulation of proprioception also caused a differential response for both groups when visual information was present. A significant Group $\times$ Proprioception interaction, $F(1, 18) = 4.200$, $p = .05$, $\eta^2 = .189$, indicated a larger increase of mean sway velocity in the boys with DCD, $t(9) = 5.248$, $p = .001$, than in the TD-boys, $t(9) = 4.954$, $p = .001$. Again, the Group $\times$ Proprioception interaction was not significant when another sensory modality (vision) was manipulated, $F(1, 18) = 0.019$, $p = .892$, $\eta^2 = .001$. When visual information was absent, the effect of the foam resulted in a significant increase of COG sway that was similar for both groups, $t(9) = 5.981$, $p < .001$ for the boys with DCD and $t(9) = 10.533$, $p < .001$ for the TD-boys.

Stabilization Ratio

The calculation of the SRs gives a more detailed insight into the relative contributions of the sensory systems in the different conditions. All four ratios are depicted in Figure 1. Here, a $SR_{vf}(\log)$ of 0.32 indicates that the logarithm of the mean sway velocity is reduced by 32% when visual cues are available.

For the contribution of vision, a Group (DCD vs. TD) $\times$ Condition (firm surface vs. compliant surface) ANOVA revealed a significant interaction effect, $F(1, 18) = 7.395$, $p = .014$, $\eta^2 = .291$, indicating a different adaptation of the visual contribution between both groups when switching between a condition with firm support surface and a condition with a compliant surface. Post-hoc paired t -tests showed a significant increase of the relative contribution of vision in TD-boys when proprioceptive cues were less reliable, $t(9) = 5.899$, $p < .001$. In boys with DCD, on the other hand, the relative contribution of vision on a firm and on a compliant surface was virtually the same, $t(9) = 0.315$, $p = .760$. Further, an independent t -test revealed inter-group differences for both $SR_{vf}(\log)$ and $SR_{vfo}(\log)$, with a significantly higher ratio for boys with DCD in the first, $t(9) = 3.135$, $p = .006$, but a lower ratio in the latter, $t(9) = 2.763$, $p = .013$. In other words, according to the SR, the relative contribution of the visual input in boys with DCD is higher than in TD-boys when standing on a firm force-plate, but lower when standing on a foam.

For the relative contribution of proprioception a similar Group (DCD vs. TD) by Condition (eyes open vs. eyes closed) interaction effect was found, $F(1, 18) = 5.118$, $p = .036$, $\eta^2 = .221$. This effect indicated again a different adaptation of the contribution of proprioception between both groups when sensory conditions changed from presence to absence of visual information. Post-hoc paired t -tests showed a significant increase for TD-boys, $t(9) = 3.430$, $p = .008$, whereas no significant increase was found for boys with DCD, $t(9) = 0.497$, $p = .631$. Additional independent t -tests revealed a significant group difference for SR_{pec} , $t(9) = 3.235$, $p = .005$, but not for SR_{peo} , $t(9) = 0.134$, $p = .895$. The TD-boys relied more on proprioceptive cues than the boys with DCD did, but only when visual information was absent.

Figure 1 — Stabilization ratios for the contribution of vision (left panel: $SR_{vfo}[\log]$ and $SR_{vfo}[\log]$ for contribution of vision on a firm or foam surface respectively) and proprioception (right panel: $SR_{pec}[\log]$ and $SR_{pec}[\log]$ for contribution of proprioception when eyes are open or blindfolded respectively); boys with DCD are indicated with ○, typically developing (TD) boys with ▲.

Discussion

Postural control of this specific sub-group of boys with DCD, measured by means of the mCTSIB, differed significantly from postural control in TD-boys. Although the M-ABC did not reveal clear balance problems, the boys with DCD had larger amounts of postural sway, resulting in larger mean sway velocities and indicating less postural stability across the four sensory conditions. This was particularly the case in the condition without sensory perturbation, or when only one sensory system was degraded. When both vision and proprioception were disrupted, the relative difference between boys with and without DCD was substantially smaller. It seems that the increased postural sway of boys with DCD is at least partially associated with a decreased sensorimotor proficiency. This might be concluded from the finding that the boys with DCD tend to depend on visual information to a greater extent than TD-boys do. Further support for this poor sensorimotor skill is provided by the stabilization ratios, showing a decreased capacity to re-weight sensory inputs in response to the changing environmental constraints in the boys with DCD.

Before turning to the main findings regarding postural stability and sensory integration in these two groups of boys, two related issues that emerged from these data need to be addressed. First, it should be noted that the procurement of participants with DCD coincidentally resulted in a specific sub-group of boys with DCD. According to the M-ABC, the motor problems of this sub-group were confined to the areas of fine motor manipulative tasks and ball skills. The scores for static and dynamic balance, assessed by the items standing on one leg, jumping over a cord (Age band 4-6 years of the M-ABC) or in squares (Age band 7-8 years), and walking on a line heels raised (Age band 4-6 years) or heel-to-toe (Age band 7-8 years), were not deviant and similar to the scores for the TD-boys. While the finding of a specific sub-group of children with DCD is not uncommon (Hoare, 1994; Macnab et al., 2001), it does put the results of the present study into a different light in that the conclusions cannot be generalized to the entire population of children with DCD.

A second issue relates to the paradoxical discrepancy between the results of the boys with DCD on the M-ABC balance items and the mCTSIB on the Balance Master. Despite the absence of balance problems according to the M-ABC, this sub-group of boys with DCD displayed mean sway velocities that were indicative of less stability while standing on both feet across the four conditions; however, these findings are not mutually exclusive. Both tests measure two different aspects of balance and there is a difference between the levels of description. The M-ABC assesses balance in a more functional way recording the outcome on three balance skills, of which the one-legged stance is linked most closely to the mCTSIB. The mCTSIB takes a more fundamental approach and examines the underlying control process of the position of the COG relative to the COP in two-legged stance during 10s of bilateral stance, measuring the amount of sway and thus the corrective strategies used to prevent falling. In this way, the M-ABC—a product-score—gives an indication of the participant's capabilities to maintain stability without considering the amount of sway or the strategy employed, while this process is exactly the subject of investigation of the mCTSIB. *Balance*, assessed by the M-ABC, and *postural control*, measured by means of the mCTSIB, are not fully interchangeable,

but both depend on the same the perceptuo-motor processes (Shumway-Cook & Woollacott, 1995; Winter, 1995). Therefore, the results on the mCTSIB, a valid tool to gain insight in the fundamental control of posture, can also be meaningful with respect to the functional maintenance of balance.

Although the disparity in level of description may explain the difference between the M-ABC and the mCTSIB results, this finding calls for caution with regard to the validity the M-ABC score on balance. In this respect, the results of the present study add evidence to previous accounts demonstrating that the discriminative power of the balance items of the M-ABC is rather low (Miyahara et al., 1998; Van Waelvelde, De Weerd, De Cock, & Smits-Engelsman, 2004). Post-hoc analysis showed that neither the sub-score for balance nor the score for unilateral stance (maximal time) did correlate significantly with the mean COG sway velocity in one of the mCTSIB-conditions (correlation coefficients between the time of one legged stance, sum of preferred and non-preferred leg, and postural sway were $-.274$, $-.384$, $-.396$, $-.130$ for FEO, FEC, FOEO, and FOEC, respectively). It should be noted, however, that this can be partly due to a ceiling effect, because the goal in the one-legged stance task (M-ABC) is to maintain a stable position for 20 s and when this has been achieved, the trial is stopped. The maximal score for this item was achieved by five TD-boys and three boys of the DCD-group. It is acknowledged that the M-ABC is designed as an identification tool for children with general motor coordination problems and that comparison based on single item scores or sub-scores should be done with caution (Smits-Engelsman, 1998). Nevertheless, the present incongruence implies that previous reports with respect to sub-groups within the population of DCD, particularly those regarding the absence of balance problems, may need to be qualified. Subtle postural control problems may remain invisible for functional motor assessment batteries such as the M-ABC. Further implications of this issue are discussed below.

Turning to the scope of the study again, the larger postural sway values of the boys with DCD are in line with the findings of Przysucha and Taylor (2004) and Wann et al. (1998). Geuze (2003), on the other hand, found larger excursions of the COP in children with DCD during unilateral stance, but not during bilateral stance. It should be noted, however, that maximal sway amplitude, the parameter used to describe postural sway by Geuze, is different from the mean COG sway velocity. Maximal sway amplitude can be interpreted as a measure of the degree of destabilization at the most unstable moment of the trial, while mean sway velocity is rather a reflection of the sway dynamics during the entire duration of the registration. Both measures seem to reveal different aspects of the postural control system and given the complexity and stochastic nature of the signal (the migration of the COP and/or COM), it is not impossible that they give rise to a different result (Duarte & Zatsiorsky, 1999). This calls for some caution when interpreting postural sway based on a limited amount of measures, but unfortunately, the Basic Balance Master equipment did not allow us to go beyond this level of analysis.

Comparison of the mCTSIB results with reference values shows that the postural sway behavior of the TD-boys in the present study comes up to the expectations. Reference values for children with the same age are not available, but the mean COG sway values of the TD-boys are clearly below those of the 5-year-old children (0.96 ± 0.47 , 1.06 ± 0.44 , 1.67 ± 0.55 , and 2.3 ± 0.79 for FEO, FEC, FOEO, and FOEC, respectively; Cambier, Cools, Danneels, & Witvrouw, 2001).

For FEO, FEC, and FOEO, the TD-boys are moving toward the lower values of the 9- to 10-year-old boys in Geldhof and colleagues (2006), while still showing a distinct higher amount of sway in the FOEC condition (0.35 ± 0.10 , 0.49 ± 0.14 , 0.75 ± 0.16 , and 1.591 ± 0.37 for FEO, FEC, FOEO, and FOEC). This suggests that the performance of the comparison group is in line with the developmental trend displayed around the age of 5-8 years. As a consequence, it may be assumed that the matching procedure, which also involved measures of physical activity and sport, did not skew the postural control behavior of the children of the comparison group and yielded a group of TD-boys with balance skill that is representative for boys of the same age.

When the sensory condition became more challenging, postural sway increased in both boys with DCD and TD-boys. This indicates a decrease in postural stability with loss or distortion of redundant sensory inputs and is in agreement with previous studies looking at the influence of alterations of the sensory condition on balance in children and adults (Foudriat et al., 1993; Shumway-Cook & Woollacott, 1985; Simoneau, Ulbrecht, Derr, & Cavanagh, 1995). While postural sway in the boys with DCD is higher than in the TD-boys for all four conditions, it is worth noting that also the latter group shows a substantial increase of sway in the most difficult condition, when vision is removed and proprioception is disturbed. This is in line with what Simoneau et al. called *system redundancy*, meaning that the effect when pairs of sensory systems are impaired or distorted is larger than the additive effect of altering each system separately; however, it also suggests that the typically developing 6- to 8-years-old boys in this study did not demonstrate a fully developed integration of sensory information yet. According to recent studies, it is not before the age of 12 that children show this adult-like use of sensory information (Peterson et al., 2006).

Interestingly, the boys with DCD appear to show a bias to use visual information more than other sensory input. This visual predominance is in line with observations in younger children, showing for example that the manipulation of the visual flow by moving the walls of the room may cause toddlers to stagger or fall (Lee & Aronson, 1974). By the age of 3 to 4 this visual dependence has been demonstrated to give way to a more proprioceptive-somatosensory control in a typically developing population (Foster, Sveistrup, & Woollacott, 1996; Foudriat et al., 1993). The reference data for the 5-year-old children (see above) are consistent with this trend, showing virtually no increase of postural sway when blindfolded. The finding that a proprioceptive distortion did induce more instability than the removal of vision in the TD-boys of the present study also corresponds with this developmental progression. Thus, in contrast to the TD-boys, the behavior of the sub-group of boys with DCD seems to indicate a preference for a more ballistic mode of control, showing faster sway motion and relying more on visual cues equivalent to younger children (Kirshenbaum et al., 2001; Riach & Starkes, 1994). Still, this similarity with the behavior of younger children does not necessarily imply a developmental delay, but can also be the result of a strategy that falls back on visual online control.

In addition to this, the boys with DCD did not seem to modify the weight of vision in response to altered sensory conditions. This difficulty or incapacity to re-weight sensory inputs is well illustrated by the absence of a shift of the visual contribution when standing on an unstable surface. Contrary to the comparison

group, the boys with DCD did not compensate for the less reliable information provided by proprioception in the foam-condition. A similar conclusion may be drawn with respect to the relative contribution of proprioception across conditions where TD-boys again displayed a more pronounced adjustment of the weight of proprioceptive input when vision was not available. It is worth noting, however, that the removal of vision induced a tendency to a larger contribution of proprioception in the boys with DCD too, although not significantly. Skillful sensory re-weighting requires the detection of sensory incongruence or inaccurate information and an adequate compensation of the sensory contributions, by elevation of reliable and reducing less reliable, inputs in response. Like the younger children in a study of Barela, Jeka, and Clark (2003), the boys with DCD of the present study appeared to rely on a default process of integration with a rather fixed contribution of the different sources of information, characterized by a relatively high input of the visual system in comparison with TD-boys. This default integration appeared to result in larger mean sway velocities, and it seemed less able to cope with changing sensory conditions requiring re-weighting of sensory inputs; however, it is clear that this hypothesis needs further investigation.

This bias to use visual information for postural control in children with DCD also was one of the findings in a similar study by Wann et al. (1998), but other studies (Geuze, 2003; Przysucha & Taylor, 2004) do not corroborate the present results. While this inconsistency with regard to the role of vision is remarkable, it remains speculative to put forward explanations. One possibility, however, lies in the use of different measures to quantify the contribution of single sensory inputs (stabilization ratio versus Romberg quotient). Cornilleau-Pérès et al. (2005) found that a logarithmic correction of the sway measures used to calculate sensory involvement resulted in a more consistent and reliable measure. In addition, it might well be that different characteristics of the participants with DCD account for the discrepancy. In both of the previous studies, the group of interest had DCD with specific balance difficulties (assessed with the M-ABC balance subtest). Clearly these children had more severe balance problems than the sub-group of boys in the present study, and it is very likely that this severity is also reflected in the control of the COP and COM during normal stance. It has been put forward that the behavior of children with impairments should be understood within the framework of a plastic neurological system in dynamic interaction with its environment (Hadders-Algra, 2000; Latash & Anson, 1996). From this perspective, although very speculative, it might be suggested that the visual predominance of the specific sub-group of boys with DCD but only mild balance problems can be interpreted as an adaptive strategy to circumvent deficits at the level of sensory integration.

While this exploratory study has provided some insight into the control of posture in a group of boys with DCD, some inconsistencies with previous findings highlight the need for extension of the present results. Mean COG sway velocity was able to discriminate between the postural control of both groups, but a more detailed analysis is necessary to cover the complex and stochastic nature of the sway motion and the contribution of different sensory sources. Furthermore, the inferences made here are limited to boys with problems with predominantly fine motor and ball handling skills. Given the heterogeneity of the population of DCD, caution should be paid when making generalizations. More research is required to investigate the relationship between gender, balance, or postural control and

sensory integration in different clinical subtypes of children with DCD. Moreover, the above stated suggestions do not mean to put forward sensory re-weighting deficits as the only underlying mechanisms for poor postural control in children with DCD. As suggested by Oie, Kiemel, and Jeka (2002) or Peterka (2002), the influence of changes in body dynamics, for example, as a result of increased muscle stiffness or co-activation as observed in patients with vestibular loss, may not be neglected. Evidence for the possible involvement of increased ankle stiffness for the control of COP migration in children with DCD has already been put forward by Geuze (2003). Future research is warranted to unravel the relation between impaired muscle control and sensory integration deficits with regard to postural control in children with DCD. This also highlights the need for studies that focus on the underlying factors or mechanisms of these possible deficits. In this respect, the internal model hypothesis, linking motor control, and sensory re-weighting to an internal representation within the cerebellum (Wolpert, Miall, & Kawato, 1998), has been put forward as a potential direction (Barela et al., 1995).

Difficulties with the control of posture are very likely to have an impact on the acquisition and performance of virtually all motor skills. For example, they may lead to less efficient catching techniques as was demonstrated by Savelsbergh, Bennett, Angelakopoulos, and Davids (2005). Moreover, Johnston and colleagues (2002) have shown that altered postural control was one of the causal factors for poor arm movement in children with DCD. From this perspective, atypical postural control can offer an explanation for atypical behavior. Moreover, it may well be that problems with the control of posture, through the influence on the success rate of a performance or the effort needed to acquire a certain level of proficiency, can ultimately lead to withdrawal of further physical activity (Bouffard et al., 1996; Cairney et al., 2006). Because of this effect on the performance or success and the associated risk of inactivity, it is important that even subtle differences and/or deficits in the control of posture are identified. A clinical test for posturography, such as the Basic Balance Master, in conjunction with usual motor assessment tests and batteries, such as the M-ABC, might help to ensure an accurate diagnosis of the problem. This in turn can facilitate the development of an effective therapeutic plan tailored to the specific needs of child and will stimulate the understanding of its motor problems.

The results of this study show that in a specific sub-group of boys with DCD with predominantly fine motor, manipulative, and ball handling problems, increased postural sway, and possibly associated difficulties with sensory integration may be a contributing factor to their motor deficits. Further research is needed to test the relationship of these deficits with other motor domains, to examine their underlying mechanisms, and to investigate whether or not these features can be generalized to more children with DCD.

Note

1. For example, a boy with DCD who reported that basketball was his favorite sport and played basketball regularly was matched with a boy that played basketball as well. If no boy with the same favorite sport was available, the matching was done according to four sport and movement categories: (a) invasion games (basketball, soccer, hockey etc.), (b) individual sports without

involvement of interceptive skills (swimming, gymnastics, athletics, dance etc.), (c) individual sports mainly involving interceptive skills (tennis, table tennis, etc.), and (d) martial arts (judo, karate etc.)

Acknowledgments

This research project was supported by a grant from Ghent University (BOF 01112902). We would like to thank all the children, their parents, COS Ghent, the physical therapists, and the graduate students for their contribution to this study.

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