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Developmental coordination disorder pertains to a deficit in perceptuo-motor synchronization independent of attentional capacities

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Abstract

We investigated from a dynamic pattern perspective to motor coordination whether the deficiency in motor coordination characterizing Developmental Coordination Disorder children pertains to a general disorder in synchronization leading to a lower stability of the performed coordination pattern, and the extent to which the trouble is linked to attentional capacities. Twenty-four DCD children without ADHD aged eight to thirteen and 60 control children were asked (1) to perform a Continuous Performance Test assessing sustained attention; (2) to flex one finger either in synchrony or in syncopation with a visual periodic signal whose frequency was increased stepwise, assessing synchronization abilities. For the attentional task, percentage of exact responses, number of errors and reaction time were recorded. For the synchronization task, we measured relative phase (i.e., the ratio between the stimulus and the response onset and the time separating two successive stimuli). DCD children were significantly more variable than controls in both conditions and the difficulty in synchronization was unrelated to attentional disorders (ANCOVA). These findings support the idea of a general synchronization disorder in DCD children underlying their poor motor coordination. Moreover, this synchronization disorder does not appear to be strictly dependent on the level of sustained attentional capacities.

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1. Introduction

Developmental Coordination Disorder (DCD) affects 5–6% of the school-aged children (DSM-IV, American Psychiatric Association, 1994). Children with DCD have normal intelligence but experience deep and persistent trouble in daily-life activities requiring motor coordination. Most patent signs are clumsiness (e.g., poor-quality writing, object dropping), a general slowness, and delays in psychomotor development. The detection of this disorder is critical, because the long-term prognosis for DCD children without therapeutic takeover is rather pessimistic (Cantell & Kooistra, 2002).

DCD is still a puzzling issue. Its definite etiology is unknown, and identification of the motor deficits specific to the disorder remains difficult. Although some deficiencies in perceptual processing (see Wilson & McKenzie, 1998, for a review) and motor control (Williams, Woollacott, & Ivry, 1992) have been ascertained, these do not fully capture the coordination (or lack thereof) between limb movements or between a moving limb and an external pacing signal. A fresh and promising approach to the issue is the dynamic pattern theory of coordination (Kelso, 1995), which posits that the motor and perceptual difficulties of DCD children may be conceived of as stemming from a deficit in synchronization.

Numerous studies at different observation levels support this hypothesis. Bearing on the model of Williams et al. (1992), Wing and Kristofferson (1973) showed that, in a task requiring motor synchronization with an auditory stimulus, DCD children exhibited a more variable performance than controls. Langaas, Mon-Williams, Wann, Pascal, and Thompson (1998) reported that in a visual tracking task, DCD children had more difficulties in smoothly synchronizing their eye movements with a moving object. Larkin and Hoare (1992) showed that the sequential chaining of the various articulations involved in a movement (e.g., jumping) was inappropriate in DCD children: the same articulations were used by control and DCD children, but the timing of their recruitment was different. From a dynamic pattern perspective, Volman and Geuze (1998), as well as Albaret, Zanone, and De Castelnau (2000), indicated that bimanual coordination was less stable in DCD children than in controls. Volman and Geuze (1998) also reported poorer synchronization in DCD children between finger movements and a visual signal in a tracking task. As stabilizing a coordination pattern, that is reducing its variability, and synchronization, that is, diminishing the time delay between the components, are two manifestations of a single mechanism, namely, phase attraction (see below for details), there is converging evidence for the notion of a deficit in synchronization, both at motor and perceptuo-motor levels.

Drawing on self-organization theories and dynamical systems devoted to understanding stability and change over time in complex systems, dynamic pattern theory provides an adequate theoretical and methodological framework to capture perceptuo-motor coordination (Kelso, 1995; Schöner & Kelso, 1988). In a seminal paper, Kelso (1984) showed that coordination between two homologous limbs (e.g., fingers) exhibits only two stable patterns: (a) in-phase, corresponding to the activation of agonist muscles in both fingers and leading to simultaneous flexion and extension movements, and (b) antiphase, in which a finger is flexing while the other is extending. In-phase coordination is characterized by a relative phase of 0° between the oscillating limbs and turns out to be the most stable and the easiest to achieve, whereas antiphase coordination corresponds to 180° of relative phase and is slightly more unstable and harder to perform. Interestingly, as movement frequency is increased, the less stable antiphase pattern eventually vanishes as soon as a critical oscillation frequency is attained, so that the observed coordination pattern switches from 180° to 0°. Bimanual coordination is thus endowed with spontaneous (non-linear) dynamics that governs stability and changes in motor behavior.

These principles (stability, loss of stability) proved to be also valid for synchronization with an external stimulus (Engström, Kelso, & Holroyd, 1996; Kelso, Delcolle, & Schöner, 1990). Participants were instructed to synchronize index flexion either "on the beat" (each tapping should occur in strict simultaneity with an auditory periodic stimulus) or to syncopate "off the beat" (to produce a flexion exactly between two consecutive stimuli). Here again, the two observed synchronization and syncopation patterns corresponding to 0° and 180° of relative phase between the stimulus and the response exhibited the same dynamic properties as the in-phase and antiphase patterns of bimanual coordination, suggesting common or at least comparable underlying dynamics.

The association or comorbidity between DCD and attention deficit hyperactivity disorder (ADHD) is an unfortunate hindrance for diagnosis and a persistent source of difficulties for research and treatment: as noted by Kaplan, Wilson, Dewey, and Crawford (1998, p. 473), a "child with pure DCD or pure ADHD appears to be hard to find". The idea of a DCD/ADHD combination has been developed since the 1970s, particularly in Scandinavia with the concept of DAMP (*Deficit in Attention, Motor control and Perception*) (Gillberg, 2003). Currently, there is still debate as to whether incoordination, particularly regarding manual dexterity, is directly linked to attention deficits and to impulsiveness in ADHD children (DSM-IV, 1994), or whether it is independent of ADHD in children with a dual diagnostic (DCD and ADHD) (Piek & Dyck, 2004). Therefore, in order to define the exact nature of the trouble in DCD children, it is mandatory to eliminate children with a dual diagnostic (ADHD and DCD). Yet, previous studies on DCD did not always control a possible comorbidity with ADHD, so that putative deficits in timing may have been confounded with attentional ones.

The present study aims to compare perceptuo-motor coordination in DCD and control children in the light of a dynamic pattern approach, focusing on the stability properties of behavior. Our hypothesis is that the difficulties experienced by DCD children, with their various symptoms, result from a fundamentally lower stability of the underlying coordination dynamics, pertaining to a basic disorder in synchronization. Therefore, our goal is to demonstrate that the specific features of the DCD children found in bimanual coordination (Albaret et al., 2000; Volman & Geuze, 1998) are also manifest in a perceptuo-motor synchronization task. In order to explore the children's dynamics, we shall adopt Kelso's transition paradigm (1984) adapted for perceptuo-motor coordination (Engström et al., 1996) that induces a progressive destabilization of the produced pattern by increasing movement frequency, up to the expected change in the coordination pattern. Now, were the dynamics in DCD children intrinsically less stable, destabilization would have a more massive effect than in controls.

A second goal of the present study is to establish whether this deficient synchronization evolves with age. While there is a noticeable improvement for normal children in a synchronization tapping paradigm (Drewing, Aschersleben, & Li, 2006; Fraisse, Pichot, &

Clairouin-Oleron, 1949), little is known about the development of perceptuo-motor synchronization in DCD children.

Finally, we want to investigate the extent to which attentional capacities are linked to the DCD trouble. Previous studies involving normal adults showed a tight interplay between attentional cost and pattern stability (Zanone, Monno, Temprado, & Laurent, 2001; see Monno, Temprado, Zanone, & Laurent, 2002, for a review): Attentional demands modify the stability of coordination patterns, as well as destabilizing coordination between the moving limbs increases the incurred attentional cost. Here, we shall tackle the issue by taking the performance of DCD children in a sustained attention test as a covariable, so that their perceptuo-motor difficulties be assessed specifically and precisely.

2. Methods

2.1. Participants

Twenty-four children with DCD (6 girls, 18 boys) and 60 age-matched control children (30 girls, 30 boys) participated in the experiment. The children were divided in three age groups (8–9 years, 10–11 years, and 12–13 years) with 8 children with DCD and 20 control children in each of them. All children in the DCD group met the criteria of DSM-IV for DCD. DCD children were recruited from the pediatric neurology service at the Toulouse University Hospital after a neurological examination (criteria C). Language, motor, and cognitive performance was assessed. All DCD children had an IQ superior to 80 (criteria D), a score lower than percentile 5 in a French version of Movement ABC (Henderson & Sugden, 1992; Soppelsa & Albaret, 2004), following the recommendations by Geuze, Jongmans, Schoemaker, and Smits-Engelsman (2001), and all parents confirmed that the disorder significantly interfered with daily-life activities (criteria A and B). Based on the results of an attentional assessment through a d2 test (Brickenkamp, 1969) and a Stroop test (Albaret & Migliore, 1999), and according to the criteria of DSM-IV, all children with ADHD were excluded. Control children were selected from public schools and exhibited no trouble in motor activities and no delays in school according to the parents' and the teachers' reports.

Ethical approval was obtained from the CCPPRB (ethics commission) of the Toulouse Hospital, in accordance with the Helsinki convention. An informed consent was signed by the parents and an assent was given by the children.

2.2. Procedure

Two tasks were administered successively: an attentional and a perceptuo-motor task. The attentional task was a CPT (Continuous Performance Test) double version, which is extensively used in developmental studies (for a review, see Riccio, Reynolds, Lowe, & Moore, 2002) involving an assessment of sustained attention. The test presented a series of 360 letters on a computer screen in pseudo-random fashion. The duration of letter appearance was 200 ms with an interstimuli interval varying from 800 ms to 1100 ms. Participants had to depress the space bar as soon as a letter was identical to the previous one, which occurred in 20% of the cases.

The perceptuo-motor task was a synchronization-syncopation task adapted from the paradigm proposed by Engström et al. (1996, see above and Fig. 1 for details). The stimulus was a red square appearing periodically on a computer screen on the left side of a

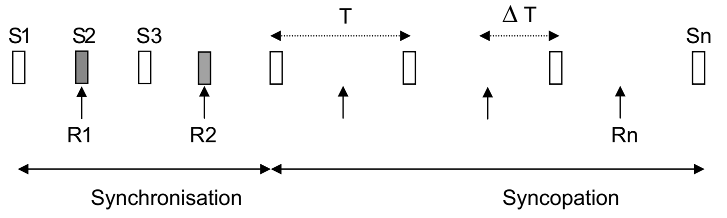

Fig. 1. Scheme of the perceptuo-motor (synchronization–syncopation) task for calculating relative phase. See text for details.

fixation cross. The required response was basically syncopation, that is, to depress the space bar between two successive stimuli. First, syncopation was facilitated by displaying a green square on the right side of the fixation cross mid-time between two red squares. The child was thus invited to synchronize with the green square, thereby providing an assessment of her/his capacity to synchronize. After 20 cycles, the green square vanished and the child had to keep on doing the same thing, that is, hitting the key exactly halfway in time between red square stimuli, thus providing an assessment of her/his capacity to syncopate. Finally, the frequency of the red square flashing was gradually increased every 20 cycles, from 0.5 Hz to 1.3 Hz, by steps of 0.2 Hz. Three of such trials lasting 3 min were carried out per participant.

2.3. Measures

For the attentional task, the percentage of correct responses served as a measure of attention, while the number of unsolicited responses (viz. errors) served as a measure of impulsivity. Reaction time was also recorded.

For the synchronization/syncopation task, we measured relative phase in degrees, that is, the ratio between the stimulus and the response onset (ΔT) and the time separating two successive stimuli (T), times 360° and standard deviation of the relative phase. Due to the adopted procedure, both synchronization and syncopation perfectly performed should result in a relative phase of 180° (see Fig. 1). Mean relative phase is a measure of the pattern accuracy and the associated standard deviation provides a measure of the pattern stability.

2.4. Data analysis

For the attentional task, a 3 (Age) × 2 (Group) analysis of variance (ANOVA) was carried out for the percentage of exact responses, the number of errors and the response time, respectively. For the synchronization task, a 3 (Age) × 2 (Group) × 3 (Trial) ANOVA with repeated measures on Trial was performed on mean relative phase (accuracy) and its standard deviation (variability). For the syncopation task, the ANOVA was performed according to a 3 (Age) × 2 (Group) × 5 (Plateau) × 3 (Trials) design with repeated measures on Trial and Plateau.

3. Results

We first present the results on the attention task, and then those on the perceptuo-motor (synchronization-syncopation) task.

3.1. Attentional task

Results are given in Table 1.

3.1.1. Percentage of exact responses

The average percentage of exact responses (74%) was significantly smaller for DCD participants than for the controls (86.2%), $F(1, 78) = 18.7$, $p < .0001$. The average number of exact responses significantly increased with age (78% for 8–9 years, 84% for 10–11 years and 86% for 12–13 years), $F(2, 78) = 4.8$, $p < .05$. There was no significant Group × Age interaction.

3.1.2. Number of errors

There was no significant difference in the number of errors between groups ($F < 1$), but it decreased significantly with age, $F(2, 78) = 5.86$, $p < .01$ (see Table 1). The Group × Age interaction was not significant.

3.1.3. Reaction time (RT)

There was no significant difference between groups ($F < 1$), but RT decreased significantly with age, $F(2, 78) = 16.4$, $p < .0001$. There was no significant Group × Age interaction.

In sum, results of the attentional task indicated that DCD children were less attentive than the controls, but did not differ in terms of impulsivity and RT. All performances improved significantly with age.

3.2. Perceptuo-motor task

3.2.1. Relative phase for synchronization

For the synchronization, results indicated a significant decrease in mean relative phase over trials, $F(2,156) = 6.99$, $p < .001$. A significant Trial × Group interaction, $F(2, 78) = 4.4$, $p < .05$, reflected that, for controls, relative phase decreased slightly between trials 1 and 2 to stabilize around 180° (viz. a perfect synchronization) by trial 3, whereas DCD children, who were markedly lagging on trial 1, got closer to 180° on trial 2 before veering off on trial 3. Note that this interaction was essentially due to the erratic behavior

Table 1
Assessment of attention, impulsivity and reaction time for controls and DCD children

	8–9 year-old children		10–11 year-old children		12–13 year-old children	
	Control	DCD	Control	DCD	Control	DCD
Exact responses (%)						
Mean	82.2	67.8	85.3	81.0	91.0	73.4
Standard Deviation	10.4	20.0	9.9	10.8	9.0	14.2
Errors (number)						
M	7.3	9.9	3.9	5.6	3.3	2.3
SD	9.2	8.7	3.0	5.0	3.1	1.8
Reaction time (ms)						
M	650	646	631	658	557	558
SD	57	71	65	44	66	41

of a single 10-year participant on trial 3: removing the resulting outlying mean data would only withdraw the Trial × Group interaction, without affecting the significance of the other effects. A significant Group × Age interaction, $F(2, 78) = 4.9$, $p < .05$, indicated that the youngest control children (8- and 10-year-olds) were slightly lagging the stimulus and the oldest (12-year-olds) were leading, whereas the youngest and oldest DCD participants (8- and 12-year-olds) were slightly late, contrary to the 10-year-olds who were also leading (see plateau labelled 'Sync' in Fig. 2, Panels a, b, and c).

3.2.2. Standard deviation of the relative phase for synchronization

Regarding SD in the synchronization, the ANOVA yielded a significant effect of group, $F(1,78) = 23$, $p < .0001$, which revealed that DCD children were more variable than controls. A significant effect of trial, $F(2, 156) = 3.5$, $p < .05$, showed that standard deviation of relative phase was smallest on trial 1 and increased in trials 2 and 3, but especially so for DCD children, as reflected by a significant Trial × Group interaction, $F(2, 154) = 3$, $p < .05$. Variability of relative phase decreased with age, $F(2, 78) = 9.3$, $p < .001$, and more so for the DCD participants, as suggested by a significant Age × Group interaction, $F(2, 78) = 3.1$, $p < .05$ (see 'Sync' plateau in Fig. 3, Panels a, b, and c).

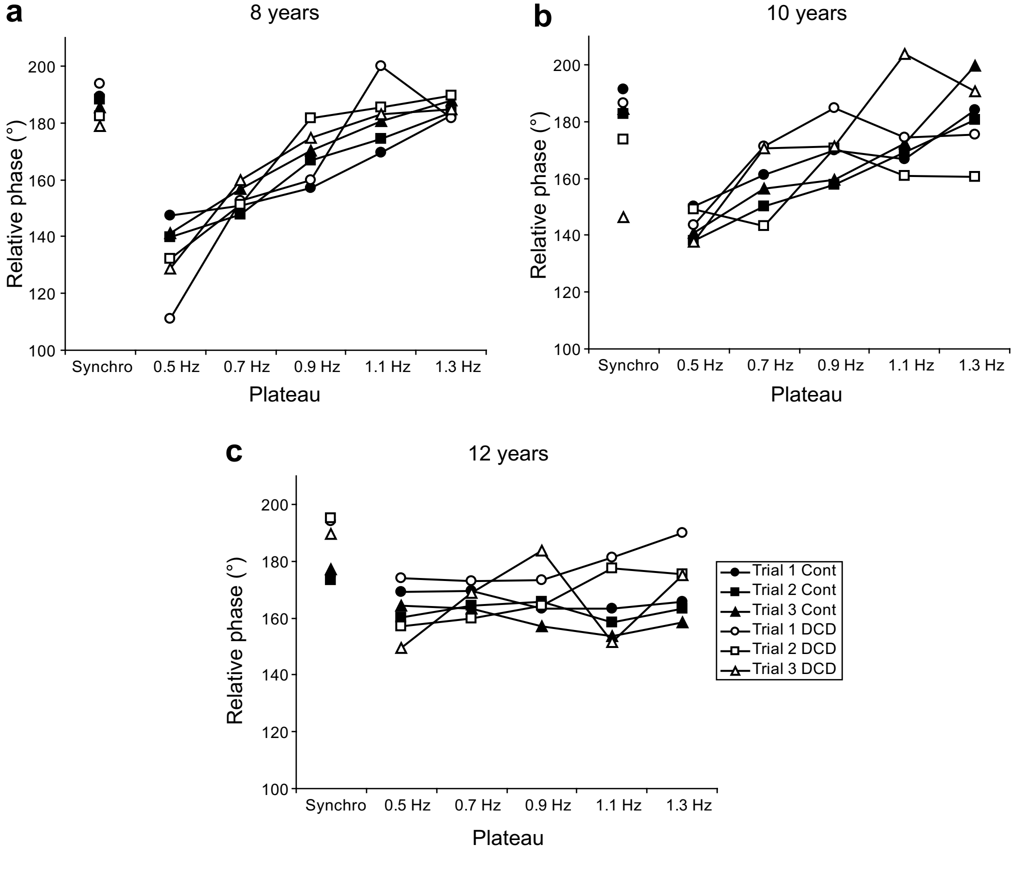

Fig. 2. Evolution of relative phase during synchronization and syncopation phases across trials for DCD and control groups of 8-, 10- and 12-year-old children (panels a, b, and c, respectively).

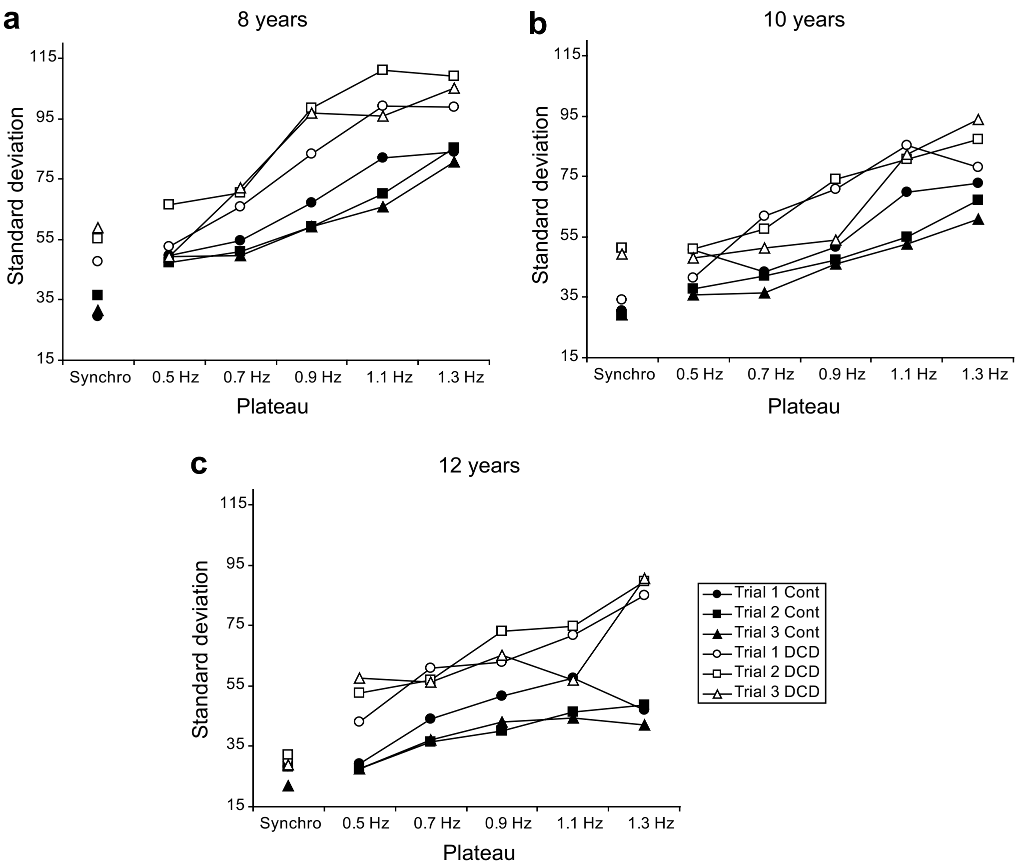

Fig. 3. Evolution of standard deviation during synchronization and syncopation phases across trials for DCD and control groups of 8-, 10- and 12-year-old children (panels a, b, and c, respectively).

3.2.3. Relative phase in the condition syncopation

Concerning syncopation, the ANOVA revealed a significant effect of plateau, $F(4, 312) = 28.8$, $p < .0001$, relative phase gradually going from 146.3° at 0.5 Hz to 179.3° at 1.3 Hz. A significant Plateau × Age interaction, $F(8, 312) = 5.5$, $p < .0001$, indicated that 12-year-olds were more stable, irrespective of the increase of frequency. A significant Plateau × Group interaction, $F(4, 312) = 2.7$, $p < .05$, revealed that control and DCD children did not reach the same mean relative phase at each frequency plateau, without any discernable trend. A significant Trial × Age interaction was found as well, $F(4, 156) = 2.9$, $p < .05$. No significant effect was found for the other factors (see plateaus '0.5 Hz' to '1.3 Hz' in Fig. 2, Panels a, b, and c).

3.2.4. Standard deviation of the relative phase in the condition syncopation

The results revealed a significantly larger variability for DCD participants than for controls, $F(1, 78) = 48.6$, $p < .0001$. Variability decreased rather abruptly with age, going from 74.3° at 8 years to 54° at 12, $F(2, 78) = 16.3$, $p < .0001$. Variability also decreased significantly with trial, $F(2, 156) = 3.6$, $p < .05$. However, DCD children tended to become more variable with trial repetition, whereas controls decreased in variability, as suggested by a significant Trial × Group interaction, $F(2, 156) = 8.4$, $p < .0001$. A progressive increase in variability with plateau was significant, $F(4, 312) = 82.1$, $p < .0001$, but DCD children degraded more with increasing frequency than controls, as indicated by a significant Plateau × Group interaction, $F(4, 312) = 4.1$, $p < .01$. Such an increase in variability with frequency differed over ages, with a significant Plateau × Age interaction, $F(8, 312) = 2.6$, $p < .01$ (see plateaus '0.5 Hz' to '1.3 Hz' in Fig. 3, Panels a, b, and c). A significant Plateau × Age × Group interaction, $F(8, 312) = 2.2$, $p < .05$, indicated a very intricate evolution, in particular that at age 12, the differences between DCDs and controls was much more pronounced for the 1.3 Hz plateau (see Fig. 3).

3.2.5. Comparison of the relative phase between the condition synchronization and the 1st plateau of the condition syncopation

The withdrawal of the stimulus occurring between the synchronization and syncopation phases induced a significant decrease in accuracy from 182.9° to 146.3°, $F(1,78) = 105.3$, $p < .0001$. This difference was larger for the 8-year-olds than for 12-year-olds, as suggested by a significant Plateau × Age interaction, $F(2, 78) = 6.6$, $p < .01$ (see plateaus 'Sync' and '0.5 Hz' in Fig. 2, Panels a, b, and c).

3.2.6. Comparison of the standard deviation of the relative phase between the condition syn- chronization and the 1st plateau of the condition syncopation

Mean variability increased significantly between synchronization and syncopation, $F(1, 78) = 22.1$, $p < .0001$. A significant Group × Age × Plateau interaction, $F(2, 78) = 7.2$, $p < .001$, indicated that this increase in variability tended to reduce with age in the control group, whereas for DCD children variability decreased in the synchronization task over age but remained the same in the syncopation task (see plateaus 'Sync' and '0.5 Hz' in Fig. 3, Panels a, b, and c).

3.3. Evaluating the influence of attentional performance: Analysis of covariance

An analysis of covariance (ANCOVA) with attention as covariate was performed to cancel out a possible effect of attention on the dependent variables. When attention was used as covariate, the group and age differences and their interaction still persisted, confirming the above findings. For relative phase in the synchronization task the Age × Group interaction was still significant, $F(2, 73) = 4.4$, $p < .05$, while no other effect was found significant. For standard deviation in the synchronization task there was still a significant effect of age, $F(2, 73) = 6.6$, $p < .005$, a significant effect of group, $F(1, 73) = 9.2$, $p < .005$, and a significant Age × Group interaction, $F(2, 73) = 3.2$, $p < .05$. In the syncopation task, no significant effect was found regarding relative phase for age, group and Age × Group interaction, while for standard deviation, there were still significant effects for age, $F(2, 73) = 11.6$, $p < .0001$, and group, $F(1, 73) = 22.3$, $p < .0001$.

4. Discussion

Following a central tenet of the dynamical systems perspective on coordination positing that behavioral stability stems from the self-organized synchronization of the subcomponents (for a review, see Kelso, 1995), the present study investigated the hypothesis that the lack of motor coordination observed in DCD children pertains to a deficient perceptuo-motor synchronization. The purpose of this study was to complete previous studies of bimanual coordination (Albaret et al., 2000) with results on perceptuo-motor synchronization and to clarify the putative relationship between attentional and DCD disorders.

A first yet trivial result is that both the DCD and control groups were more stable in synchronization than in syncopation, in our case when the green stimulus was present versus absent. This finding corroborates numerous studies on rhythmic synchronization with an auditory stimulus (Kelso et al., 1990; Oullier, Lagarde, Jantzen, & Kelso, 2006). A closer look into the process indicates that for periodic continuous motion, temporal variability decreases especially at points in the movement cycle coinciding with the stimulus, a phenomenon coined anchoring (e.g., Beek, 1989; Byblow, Carson, & Goodman, 1994). Such anchoring underscores the role of synchronization in the maintenance of a stable coordination, so that a syncopation task would elicit a less stable pattern than synchronization, hence their qualification as antiphase and in-phase, respectively.

A more central contribution of our study is the confirmation that DCD children are more variable than controls, in both the synchronization and syncopation tasks. Performance variability in DCD is well documented in the literature, whether in gross motor skills, like running and jumping (Larkin & Hoare, 1992), or in laboratory tasks (Henderson, Rose, & Henderson, 1992; Piek & Skinner, 1999; Williams et al., 1992). Moreover, this instability is more salient for the syncopation than for the synchronization task. This result is in line with findings by Volman and Geuze (1998) on a bimanual task showing that DCD children tended to be less stable for antiphase than for in-phase coordination. Such a difference suggests that the basic deficiency in stability of DCDs is enhanced by the inherent instability of the antiphase pattern relative to in-phase. Recent work on bimanual coordination (e.g., Calvin, Milliex, Coyle, & Temprado, 2004) or handwriting (Sallagoïty, Athènes, Zanone, & Albaret, 2004) has amply demonstrated an additive effect of destabilizing constraints of different origins on the stability of the performed coordination patterns. Note that enhanced instability may not be specific to DCD (Swinnen & Carson, 2002): Patients with a neurological disorder (lesion in the cerebellum, AMS, Parkinson disease, Gilles de la Tourette syndrome) manifest greater difficulties in executing an antiphase pattern. Moreover, Mayville, Jantzen, Fuchs, Steinberg, and Kelso (2002) hypothesized that syncopation requires more preparatory and attentional involvement and showed, using fMRI, that syncopation activates more areas than synchronization, notably an additional activation of the cerebellum and other subcortical networks like the basal ganglia, as well as the dorsolateral premotor, rostral supplementary motor, prefrontal, and temporal association cortices. Thus, as suggested by Williams et al. (1992), a cerebellar dysfunction, identified by soft signs such as a central timing deficit, could explain a disorder in syncopation.

Another result is that coordination dynamics does destabilize with adverse constraints, here, an increase in frequency. Although an increase in variability with frequency plateaus was found in both groups, DCD participants were clearly more sensitive to such destabilization, as reflected by the fact that variability rose markedly or remained at a high level over a single trial (viz. with increasing frequency). It is likely that destabilization with increasing levels of constraints has a massive deleterious effect on DCDs, because their coordination dynamics is intrinsically less stable to start with. Interestingly, such instability persisted across trials. Irrespective of the condition (synchronization versus syncopation), DCD children did not improve performance with the repetition of the task. This suggests that they may have some difficulties in learning motor rhythmic patterns. Recent work on motor learning (Ahonen, Kooistra, Viholainen, & Cantell, 2004) suggested that children with DCD or developmental dyspraxia are affected by a common 'motor learning disability'. The motor problems shown by these children may reflect a difficulty in learning and producing a novel motor skill and in generalizing a newly-acquired pattern to other situations.

A related issue is how this deficient synchronization evolves with age. Irrespective of the group and the condition, there is an age-related difference in the variability of performance. This finding is in agreement with a study by Drewing et al. (2006) on the life-span development of sensorimotor synchronization indicating a steep improvement in the ability to synchronize and to achieve stable performance during childhood. Nevertheless, our study suggests that whereas such a decrease in variability with age occurred in the synchronization task, it was not the case for syncopation in DCD children, contrary to controls: syncopation, that is, producing an antiphase perceptuo-motor pattern with an external pacing signal, remains an unsurpassed challenge for DCD children. A tentative explanation relies, again, on the concept of stability: if age may help stabilizing synchronization, corresponding to the more stable, 'easier' in-phase pattern, it fails to do so for the less stable, more 'difficult' antiphase pattern.

Another look into the lesser synchronization of DCD children suggests a change, or at least some indecision, between a reactive versus anticipative response to the stimulus. The study by Engström et al. (1996) showed that when normal adults synchronize with an external stimulus, a transition occurs from a reaction to an anticipation mode as the stimulus frequency increases from 0.5 Hz to 0.8 Hz, an interval within which both modes coexist. As DCD children's dynamics is basically destabilized, this interval is likely to span within lower frequency boundaries, the very ones at which our experiment started. Thus, both reaction and anticipation modes would be adopted even by the oldest DCDs, contrary to controls, who, like adults, would favor an anticipatory mode.

A second contribution of our study is in clearly demonstrating an implication of attentional processes in coordination disorders, which are suggested by the frequent co-morbidity between DCD and ADHD (Kadesjö & Gillberg, 1998; Piek et al., 2004). In our study, results in the attentional task showed that children with DCD but without ADHD had a lower percentage of correct responses than control children, indicating that the DCD children had lower attentional capacity. Children with DCD made an equal number of errors compared to the control children, which indicates that they did not suffer from problems in inhibition. The covariance analysis suggested that, despite the fact that DCD children were less attentive than controls, their coordination difficulties, tallied to their attentional capacities, remained comparable, implying that coordination disorders are not (strictly) dependent on the level of attentional disorder. According to Pitcher, Piek, and Barrett (2002), who examined ADHD boys with and without comorbidity of DCD and showed that poorer performances in a finger tapping task is more strongly linked to DCD symptomatology than to ADHD status, we found a relative independence of attentional capacities and coordination difficulties.

A last contribution of the present study is that its results establish more clearly what the stability exhibited by DCD children is, compared to a previous study by Volman and Geuze (1998). These authors reported that although there was a difference in accuracy of the produced relative phase with respect to the required one, both the in-phase and antiphase patterns were of comparable variability. Our interpretation draws on the observation that, actually, the tasks were fundamentally different. The antiphase pattern in the Volman and Geuze study consisted of ''pointing in time with the stimulus but at another place, that is, where the stimulus was half-a-cycle ago'', as opposed to in-phase, that is, ''pointing in time with the stimulus where the stimulus is currently''. The Volman and Geuze antiphase pattern is then a misnomer, in that it involves synchronization (i.e., a temporal in-phase pattern) with a spatial incongruence (a spatial antiphase pattern). It comes then as no surprise that relative phase, assessing temporal synchronization, is reported to be similar for both patterns since, in fact, they differ only in spatial terms. Recent studies by Milliex and colleagues (Calvin et al., 2004; Milliex, Calvin, & Temprado, 2005) unraveled the subtle coalition that is brought about between temporal and spatial constraints in stabilizing coordination patterns.

What do these findings contribute to our understanding of DCD? Variability is interpreted as a sign of neurological non-optimality (Geuze & Kalverboer, 1993) and differences in movement variability have been linked to motor disability. But what is the process responsible for these changes in variability? On the one hand, some studies attribute the synchronization process of repetitive actions, in particular the control of timing, to a central clock. In this view, Williams et al. (1992) associated DCD with a cerebellar dysfunction. On the other hand, some authors like Piek and Skinner (1999) support the hypothesis that the deficit has a mechanical (peripheral) origin, since DCD children demonstrate difficulties in muscle co-contraction, which may induce some movement variability. From a dynamic pattern approach, timing is not specified or controlled explicitly by the CNS, but is an emergent property of the (nonlinear) coupling between the multiple subsystems involved in perceptuo-motor behavior. A promising suggestion is that the difference in variability between DCD and control children stems from an impaired coupling, in particular between perceptual and motor components.

As converging conclusions were drawn from studies on bimanual coordination in DCD children (Albaret et al., 2000; Volman & Geuze, 1998), a tentative tenet is that DCD motor behavior is governed by dynamics that differs from that of controls in that it is essentially less stable. Such instability may relate to a general deficit in synchronization processes which persists over age and is largely independent of attentional abilities. Ongoing research on the EEG signals associated with our perceptuo-motor task should help to reveal the neural underpinnings of such low stability in DCD children.

Additional work is needed to test this conclusion. Given the high variability of DCD children and the presence of subgroups in DCD population (Visser, 2003), a fine-grained study differentiating participants as a function of the intensity of their coordination deficit may further probe the relationship between (in)stability and DCD. The importance of synchronization processes subsuming normal and impaired coordination should also be tested in tasks in which the context is more akin to that of daily-life activities, such as coincidence anticipation abilities involved in intercepting a flying ball.

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