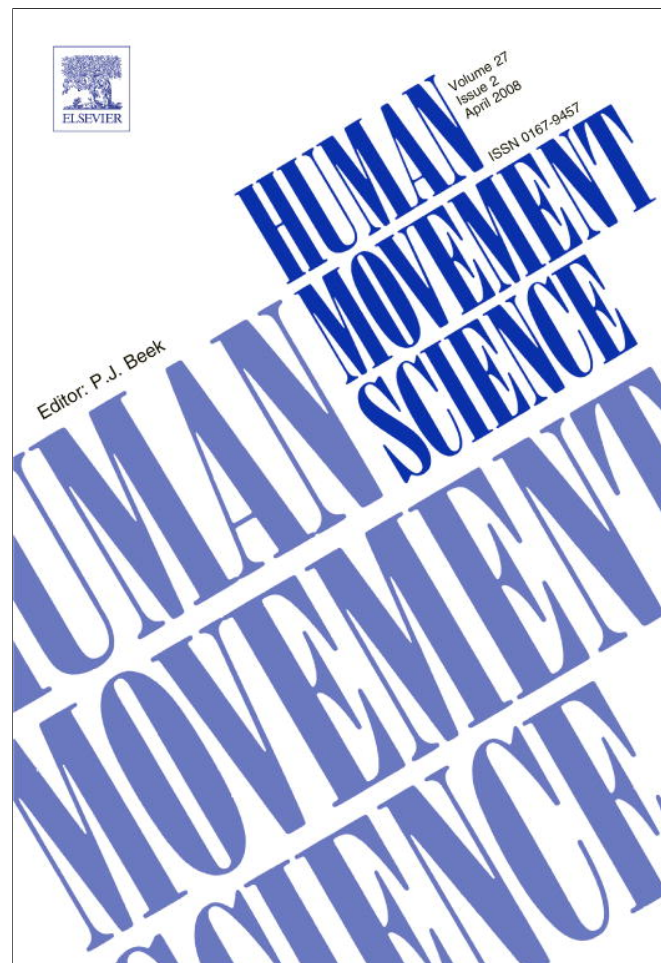


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A study of EEG coherence in DCD children during motor synchronization task

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Abstract

This paper investigates the hypothesis that the coordination difficulties of DCD children are associated with an increased coherence in the cortical motor regions, which persists with age. Forty-eight children participated in the study (24 DCD and 24 Controls). Their ages ranged from 8 to 13 years, divided into three groups (8–9, 10–11, and 12–13 years old). Children were required to perform finger flexion or extension either in synchrony or in syncopation with a rhythmic metronome, while a 32-channel EEG was recorded. Along with stability measures of motor performance, we analyzed the spectral EEG coherence between intrahemispheric (left frontal/left central; left central/left parietal) and interhemispheric (left central/right central) sites. Spectral coherence assesses functional coupling between distant areas of the brain. Two frequency bands related to sensorimotor activation were chosen: alpha (8–12 Hz) and beta (12–30 Hz). The synchrony task was chosen as a rest condition against which the two syncopation conditions at 0.5 Hz and 1.3 Hz were contrasted. For intrahemispheric comparison, 8–9-year-old DCD children showed that coherence between fronto-central regions increased for both rhythms and conditions, as compared to controls. No difference was found for interhemispheric comparisons. As frontal sites are related to motor planning, our results suggest that youngest DCD children were forced to maintain a high level of pre-programming to

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compensate for the difficulties caused by the perceptual-motor requirements of the task in light of their coordination disorder.

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1. Introduction

Beyond an overall clumsiness, slowness, and lack of coordination in most daily-life activities, children with developmental coordination disorder (DCD) are reported to exhibit a more variable motor performance in gross motor abilities, like running and jumping (Larkin & Hoare, 1992), as well as in finer motor abilities, like bimanual coordination (Albaret, Zanone, & de Castelnaud, 2000; Volman & Geuze, 1998) or synchronization with an external pacing signal (de Castelnaud, Albaret, Chaix, & Zanone, 2007). Moreover, such high variability in DCD appears to increase sharply under constraints imposed on movement, such as speed or frequency (de Castelnaud et al., 2007).

Variability is a critical feature and a key concept within the dynamical systems approach to coordination (Kelso, 1995; Schöner & Kelso, 1988), since it is an unambiguous behavioral sign of the stability of the produced coordination pattern and, hence, a reflection of the underlying coordinative activity of the central nervous system (CNS). Studies using dedicated paradigms requiring participants to coordinate their motor output either in-phase (synchronization) or anti-phase (syncopation) with respect to an external pacing stimulus (see Engström, Kelso, & Holroyd, 1996, and below for details) have indicated that as the stability of coordination increases, less cortical and subcortical networks are recruited (Jantzen, Steinberg, & Kelso, 2002; Mayville, Jantzen, Fuchs, Steinberg, & Kelso, 2002). The main goal of our study is to characterize brain activity in DCD children while they perform a sensorimotor task and to address the following issues: What are the electrophysiological underpinnings of their reportedly variable coordination patterns? How do they change when performance variability increases as a response to task constraints? Is there an atypical coordination between brain motor regions when DCD children are engaged in variable performance during a synchronization/syncopation task? The present paper tackles these issues by studying EEG signals in terms of coherence analysis, because this tool yields a reliable measure of the correlation between brain regions, that is, the synchronization of their oscillatory activities (Gerloff et al., 1998).

Typically, coherence analysis assesses the synchronization of oscillatory cortical activity between brain regions in terms of the coefficient of covariation between their activities, measured through a cross-correlation in a specific frequency band (Gerloff & Andres, 2002). This measure depends on the power and phase dynamics between two electrodes. If cortical oscillations are synchronized, high values of coherence arise, and vice versa. High values of coherence can be interpreted as an evidence of coactive neuronal populations, functional coupling of the regions involved in the tasks, and mutual information exchange (Andres et al., 1999; Andrew & Pfurtscheller, 1996).

Synchronization and coupling between cerebral areas, a phenomenon known as *sensorimotor binding* (Gerloff & Andres, 2002) and measured by EEG coherence, evolve with

age and motor learning (Andres et al., 1999; Bell & Fox, 1996). For example, Bell and Fox (1996) found that cortical organization, measured by EEG coherence, changes with crawling experience. These authors examined four groups of 8 month-old infants who varied in crawling experience. The groups included either pre-walking infants, novice crawlers with 1–4 weeks experience, infants with 5–8 weeks experience, and long-term crawlers with more than 9 weeks experience. Results showed that novice crawlers displayed a larger coherence than either pre-walking infants or experienced crawlers. These findings suggest that, right before and at the onset of locomotion, an overproduction of cortico-cortical connections occurs. Subsequently, when infants have acquired more crawling experience, EEG coherence decreases, because overabundant synapses have been pruned. In another study, Andres et al. (1999) investigated the coupling between motor areas during learning of a bimanual skill. The task consisted of combining two over-learned unimanual sequences into one single bimanual sequence. The acquisition of such a bimanual skill was tested before and after a 30-minute training period through a coherence analysis in the alpha and beta bands. The alpha frequency component is reputed to reflect somatosensory cortical functions, whereas the beta component is associated with motor cortical functions (Serrien & Brown, 2002). The authors noted an increase of the interhemispheric coherence at an early stage of bimanual learning, and a decrease of coherence after the bimanual training in both frequency bands. Both studies suggest that the acquisition of motor skills at various time scales (i.e., development and learning), which leads to a decrease in behavioral variability, induces a decrease in EEG coherence.

The present paper aimed to characterize the coherence of EEG signals of DCD children while they carry out a synchronization/syncopation task with an external signal, thought to give rise to a highly variable performance. A first hypothesis was that given their coordination difficulties and increased performance variability, DCD children should exhibit enhanced coherence in the cortical motor regions compared to control children. A second hypothesis was that since the coordination disorders do persist over age (Cousins & Smyth, 2003), such a high level of coherence should be maintained in DCD children whereas it should attenuate with increasing age or skill in the controls. A second goal of the study was to investigate the effect of adverse task constraints, such as an increase in movement frequency, on the cerebral synchronization, accompanying the resulting increase in performance variability. As DCD children are much more destabilized by a frequency increase, movement rate should affect the functional coupling between brain areas to a larger extent in DCD children than in controls.

2. Methods

2.1. Participants

Twenty-four children with DCD participated in the experiment and were matched with 24 control children picked from a larger sample population used in a previous study (de Castelnaud et al., 2007). Participants were divided in three age groups of the same size: 8–9 years, 10–11 years, and 12–13 years. DCD children were recruited from the pediatric neurology service at the Toulouse University Hospital after a neurological examination (DSM-IV-TR, criteria C). All DCD children had an IQ superior to 80 (criteria D), a score lower than the 5th percentile in a French version of Movement ABC (Henderson & Sug-

den, 1992; Soppelsa & Albaret, 2004), and all parents confirmed that the disorder significantly interfered with daily-life activities (criteria A and B).

2.2. Procedure

Participants sat in a comfortable chair placed in a darkened room at a distance of 50 cm from a computer screen. EEG was recorded during the execution of the entire task.

2.2.1. Task

Following a paradigm developed by Engström et al. (1996), children tapped one finger with a visual periodic stimulus either in synchrony (each tap had to occur simultaneously with the visual stimulus) or in syncopation (halfway between stimuli). The stimulus frequency was progressively increased from 0.5 Hz to 1.3 Hz in small steps of 0.2 Hz every 20 cycles, in order to induce an increase in performance variability.

2.2.2. Electrophysiological recording and data analysis

During the synchronization/syncopation task, EEG was recorded from 32 scalp electrodes (Ag/AgCl) in an *Easycap*, appropriately sized for the children's heads, according to the international 10–10 system. An average reference montage was used, with Cz used as the reference during recording. Vertical and horizontal EOG were recorded with electrodes at the outer canthi and the superior orbital ridge. Trials contaminated with ocular activity greater than 50 μ V were rejected before averaging. Electrode impedances were maintained below 5 k Ω . The EEG was amplified with NuAmps (Neuroscan 4.2) with a band-pass of 0.1–100.0 Hz and digitized at a rate of 500 Hz. Only children who performed 40 epochs or more were included in the analyses.

EEG coherence analysis was computed on epochs of 512 ms. We kept the same number of epochs for all participants because assessment of the coherence can differ depending on the number of the epochs considered (Nunez, 1981). The minimal number of epochs for the analysis was 25 without artifacts (Gerloff et al., 1998). We removed the offset and detrended the signal over the entire epoch.

We carried out an intrahemispheric analysis of coherence of the EEG, F3–C3 (left frontal/left central) and C3–P3 (left central/left parietal), because these areas are implicated in sensorimotor activation (Classen, Gerloff, Honda, & Hallett, 1998; Knyazeva et al., 1997). Second, we carried out an interhemispheric analysis, F3–F4 (left frontal/right frontal) and C3–C4 (left central/right central), in order to examine the role of the corpus callosum (Andres et al., 1999; Serrien & Brown, 2002) (see Fig. 1). When DCD children perform unimanual movements, they often show synkinetic or mirror movements in the opposite hand. These movements are due to the inefficiency of the transfer of inhibitory signals through the corpus callosum (Andres et al., 1999). Coherence was calculated in two frequency bands related to sensorimotor activation, alpha (8–12 Hz) and beta (12–30 Hz), and was transformed using an inverse hyperbolic tangent.

2.3. Measures

As developed in a previous paper (de Castelnau et al., 2007), the behavioral measures of the pattern accuracy was the 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

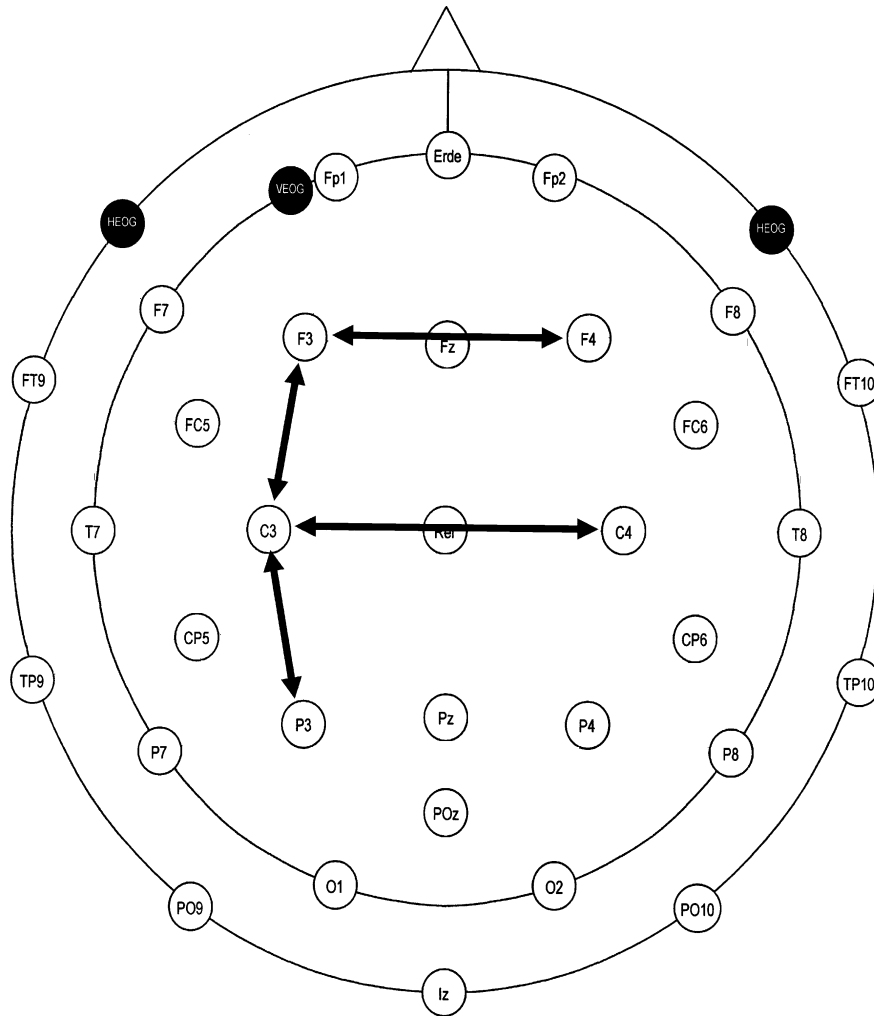


Fig. 1. Spatial localization of electrode pairs selected for coherence analysis on a schema of 32 electrodes assembly (international 10–10 system electrode placement) used in the study. F3–C3 = left frontal/left central; C3–P3 = left central/left parietal; F3–F4 = left frontal/right frontal; C3–C4 = left central/right central.

360°. The variability of performance was assessed by the standard deviation of the relative phase.

In order to separate task-related coherence from background coherence, the values of a resting state should be subtracted from those of the active state. This subtraction method reduces the contribution of the volume conduction of the signals between active electrodes (Serrien & Brown, 2002). In our case, the synchronization task was chosen as a rest condition, a procedure used in the MEG study of Jantzen, Fuchs, Mayville, Deecke, and Kelso (2001). Synchronization proves to be more stable and requires fewer attentional resources (Serrien & Brown, 2002) and less neuronal activation than syncopation (Mayville et al., 2002). Only the most extreme task constraints, namely, syncopation at 0.5 Hz and 1.3 Hz, were contrasted with the rest condition.

2.4. Data analysis

Coherence analysis was carried out for only two typical frequencies, low (0.5 Hz) and high (1.3 Hz), referred to hereafter as a frequency effect. Separate 3 (Age) \times 2 (Group) \times 2

(Frequency) ANOVAs with repeated measures on frequency were performed on the alpha- and beta bands for the different links (C3–C4, F3–C3, C3–P3, and F3–F4).

3. Results

3.1. Behavioral results

We only summarize the basic findings regarding performance that are closely related to the issue tackled here, as a complete report of the data may be found in de Castelnau et al. (2007). Although all DCD children were able to perform the syncopation/synchronization task without switching from the former to the latter, they did show significantly more performance variability than controls in both the synchronization and syncopation tasks. Moreover, performance variability in DCD children increased substantially with the imposed increment in response frequency, as compared to controls. Finally, DCD children did not improve with practice. All these differences persisted over the age range studied.

3.2. EEG coherence results

3.2.1. Results for the alpha band frequency

For the C3–C4, C3–P3 and F3–F4 links, no significant main effect or interaction were found. For the F3–C3 link, no significant main effect was detected, but a significant Group \times Age interaction was found, $F(2,42) = 4.9$, $p < .05$: Coherence values were positive for the 8-year-old DCD children with a mean of .1, whereas it was negative for controls, with a mean of -0.06 (see Fig. 2, alpha band, F3–C3 link). Coherence values were significantly larger for the high than for the low frequency, $F(1,42) = 7.1$, $p < .05$. Moreover, such an effect was larger for the youngest children (8 and 10 years-old), as suggested by a significant Frequency \times Age interaction, $F(2,42) = 4.3$, $p < .05$ (see Fig. 2, alpha band, F3–C3 link).

3.2.2. Results for the beta band frequency

For the C3–C4, C3–P3 and F3–F4 links, neither main effects nor interactions were significant. For the F3–C3 link, whereas no significant main effects were shown for group or age, a significant Group \times Age interaction was found suggesting that the difference between DCD and controls in 8-year-old is no longer present at later ages, $F(2,42) = 4.9$, $p < .05$ (see Fig. 2, beta band, F3–C3 link). A significant frequency effect indicated that coherence was larger for the high than for the low frequency, $F(1,42) = 7.4$, $p < 0.01$, but a significant Frequency \times Age interaction suggested that this increase in the communications between frontal and central regions was larger for the youngest children (8 years-old), $F(2,42) = 4.4$, $p < .05$ (see Fig. 2, beta band, F3–C3 link).

4. Discussion

A first purpose of the study was to investigate how intra- and inter-hemispheric coherence was installed and modified in DCD children as compared to controls. Our results indicate that there are differences in the 8-year-old children, albeit only for intra-hemispheric coherence. A second aim was to show that the neurophysiological correlates of the variability observed at the behavioral level persist over age. Results did not support

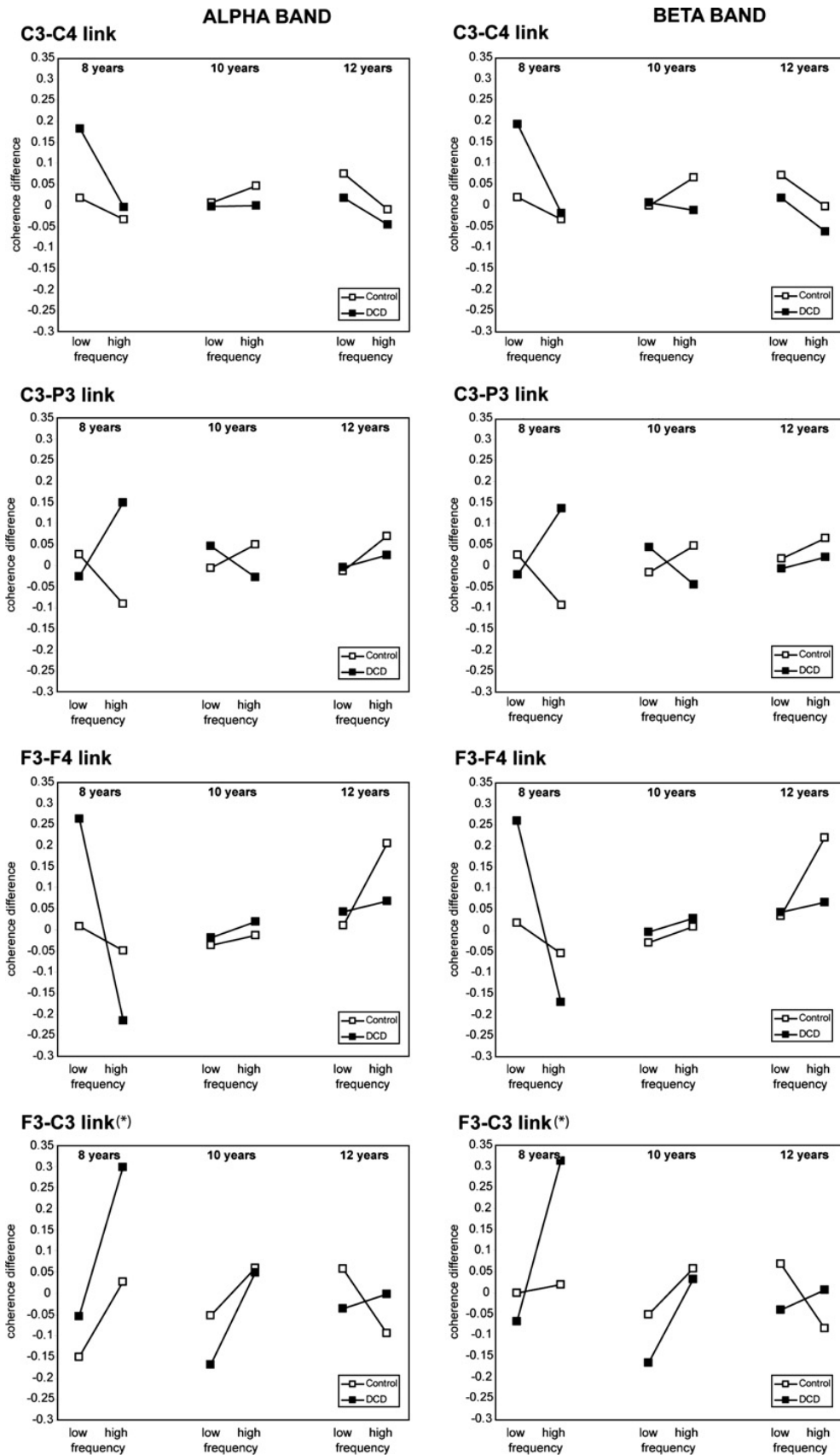


Fig. 2. Coherence changes in alpha and beta band for C3–C4, C3–P3, F3–F4 and F3–C3 electrode pairs expressed in difference from rest condition (synchronisation) and low and high frequency condition for DCD and control children. (*) indicates links with significant interactions.

this assumption. A third goal of the study was to determine how an increase in task constraints (i.e., movement frequency) affects coherence in DCD children. Our results showed that coherence in the fronto-central left link indeed rises, although this effect is not specific to DCD children. These findings raise several issues regarding DCD, learning, and development.

Regarding intrahemispheric comparisons, the effect manifested in the two (alpha and beta) frequency bands appears to characterize the DCD pathology: a significant coupling exists between brain areas in DCD children but not in controls, taking the form of an increased fronto-central coherence in 8 years-old DCD children. Interestingly, there is no relation between these electrophysiological data and behavior: 8-year-old DCD children are not different from controls with regard to the produced relative phase and its variability. We suggest three possible explanations for this finding pertaining either to some characteristics of the disorder itself, to a maturational delay, or to a compensation mechanism.

In a first line of thought, several studies regarding the acquisition of motor skills have shown that experience induces a destruction of useless synapses, leading to reduced coherence. Children who are unskilled in the performance of a motor skill exhibit higher EEG coherence than expert children (Bell & Fox, 1996). Assuming that development and learning are just the same process of acquisition unfolding along two different time scales, one may hypothesize that destruction of the extra synaptic links is dramatically slowed down in DCD children. An alternate if not exclusive view was developed by Hadders-Halgra (2000) who assigns the difficulties observed in DCD to an inappropriate selection of neuronal groups, which depends on the interaction between the actor and the environment. Accordingly, neuronal links may persist in DCD children because of a dysfunction in the selection of neuronal groups. The disorder would then be attributed to an atypical cerebral development, with additional synaptic links, contingent on poor interaction between the actor and his or her environment. At any rate, both mechanisms (weak pruning or faulty selection) would lead to an enhanced coherence in DCD children.

A second tentative explanation is that the observed strong linkage between the fronto-central areas reflects a maturational delay. Our findings suggest that this link wanes with age. Several studies on children with dyslexia or developmental retardation report an increase in coherence in some frequency bands and an attenuation of this effect with the advance in age. Marosi et al. (1995) noted that poor performance in reading and writing is associated with a greater EEG coherence in the delta, theta, and beta frequency bands, and with a reduced coherence in alpha frequency band. Such an increase in coherence in children suffering from intellectual delay or developmental dyslexia is thought to reflect reduced cortical differentiation and specialization. Moreover, cerebral activity becomes more focal or less diffuse during normal development (Durstun & Casey, 2006). It is then plausible that reduced or delayed cortical differentiation and specialization occur in DCD children.

A last assumption regarding the increased connectivity between these two areas pertains to some kind of compensatory mechanism. In light of Piek et al. (2004) who suggest that frontal executive functions are preserved in DCD children, frontal areas may serve palliative purposes. Let us recall that the frontal association cortex includes various areas, such as the prefrontal, the premotor, and the primary motor cortex. Prefrontal cortex is involved in movement planning, the premotor cortex is responsible for the organization of the motor sequences and the motor cortex carries out the specific movements. Thus, information appears to flow from the prefrontal to the motor cortex. As frontal sites

are related to motor planning, our results suggest that younger DCD children may be forced to maintain a high level of pre-programming to compensate for difficulties in the perceptual-motor and executive aspects of movement related to their coordination disorder. These difficulties in motor execution are perhaps due to an anomaly at the level of the motor areas (C3). Indeed, recent work of Scabar, Devescovi, Blason, Bravar, and Carrozzi (2006) showed in a population of eight DCD children (average age = 7.6 years) suffering from serious motor impairments (score lower than 5th percentile on the M-ABC) that 70% exhibited anomalies in sleep EEG on the central-temporal areas. Even if one does not know exactly the impact of these anomalies on motor behavior, this finding suggests that 8-year-old DCD children show some dysfunction at the level of the central areas.

Regarding interhemispheric comparisons, no difference was found between the two groups, DCD vs. controls. Perhaps, the type of task was too easy and did not require the use of inhibitory processes of crossed associated movements, a role devoted to the corpus callosum (Serrien & Brown, 2002). In that respect, a bimanual task would have been perhaps more adapted. Indeed, Knyazeva, Kurganskaya, Kurgansky, Njiokiktjien, and Vildavsky (1994) showed that in normal 7-year-old children, interhemispheric EEG alpha coherence was significantly increased for bimanual rhythmic tasks as compared to unimanual movements.

A second goal of our study was to show that the neurophysiological correlates of the variability observed at the behavioral level in DCDs persist over age. Our results show that this was not the case. It is well known that large changes in the localization of EEG measures occur in children (Taylor & Baldeweg, 2002). It is quite possible that links other than those studied here may have exhibited increased coherence for a given age. Yet, there is no *a priori* argument for an involvement of other cerebral areas than the fronto-central cortex that was investigated here.

A third aim of our study was to establish a correlation between an increase in task constraints (i.e., frequency of movement) and coherence in DCD children. This effect was shown for all children, with an increased coherence in the fronto-central left link. This was not specific to the DCD group, but was significant for the two frequency bands (alpha and beta). Regarding development, there was a significant effect of frequency (1.3 Hz vs. 0.5 Hz) on the coupling between frontal and central areas in younger children. At high frequency (1.3 Hz), coherence between these two areas was enhanced in young participants (8 and 10 years), whereas it remained weaker at a lower frequency of execution (0.5 Hz). This effect tended to disappear with age, notably in 12-year-old children.

In the literature, authors generally note a strong involvement of frontal cortex in the acquisition of a coordinated motor pattern, like the syncopation task studied here. Moreover, the frontal cortex plays a key part in cerebral development. Most periods of growth spurt in EEG coherence are associated with connections with the frontal lobe. In addition, the activation of the prefrontal lobe generally decreases with development (Durstun & Casey, 2006). Similarly, the age of 8–9 years corresponds to a key period at which a major transition in coherence values occurs during the performance of motor tasks (Thatcher, 1994; Thatcher, Walker, & Giudice, 1987). The importance of this age is also reflected in behavioral measures. A study by Hauert, Badan, Pellizzer, and Sevino (1999) on a visuo-manual pointing task showed an abrupt change at about 7–8 years of age. Lastly, taking together behavioral and electrophysiological data, one can note that for young children of 8–9 years, the increase in the coupling between frontal and central areas that occurs with higher movement frequency is correlated with an increase in the observed

instability (see de Castelnaud et al., 2007). The frontal areas may thus be used to compensate for the increase in the task difficulty induced by the speed constraint. Work by Mayville et al. (2002) and Jantzen et al. (2002) also suggest a larger activation of cortical areas with increases in spatiotemporal constraints. An fMRI study by Mayville et al. (2002) showed that the acquisition of an unstable pattern (viz. syncopation) requires additional and auxiliary motor areas, compared with acquisition of a stable pattern (synchronization); an activation of contralateral sensorimotor and caudal supplementary motor cortices as well as the cerebellum is needed for both patterns. For the syncopation task, however, another parallel cerebral network is recruited: basal ganglia, dorsolateral premotor, rostral supplementary motor, prefrontal, and temporal association cortices. The authors concluded that the syncopation task requires more attentional resources.

In sum, EEG coherence reflects the time-course of learning with a large initial coherence, which decreases with the establishment of a more efficient motor solution (Andres et al., 1999). As DCD children have indeed a “motor learning disability” (Ahonen, Kooistra, Viholainen, & Cantell, 2004; Missiuna, 1994; Wilson, Maruff, & Lum, 2003), future work is needed to assess the changes in coherence between F3 and C3 in the pre- and post-learning periods, which should accompany the behavioral modifications induced by learning. As well, in order to further grasp the neural underpinnings of increased coherence in 8-year-old DCD children, EEG signals should be scrutinized with complementary techniques. In particular, an analysis of event-related potentials (ERPs) could clarify the nature of the synchronization process between the various brain areas; ERPs represent the time-course of the neural activity captured by each electrode in terms of different time components, reflecting the different phases in the underlying information processing.

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