Developmental changes in lateralized inhibition of symmetric movements in children with and without Developmental Coordination Disorder

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ABSTRACT

The present study investigates developmental changes in selective inhibition of symmetric movements with a lateralized switching task from bimanual to unimanual tapping in typically developing (TD) children and with Developmental Coordination Disorder (DCD) from 7 to 10 years old. Twelve right-handed TD children and twelve gender-matched children with DCD and probable DCD produce a motor switching task in which they have (1) to synchronize with the beat of an auditory metronome to produce bimanual symmetrical tapping and (2) to selectively inhibit their left finger’s tapping while continuing their right finger’s tapping and conversely. We assess (1) the development of the capacity to inhibit the stopping finger (number of supplementary taps after the stopping instruction) and (2) the development of the capacity to maintain the continuing finger (changes in the mean tempo and its variability for the continuing finger’s tapping) and (3) the evolution of performance through trials. Results indicate that (1) TD children present an age-related increase in the capacity to inhibit and to maintain the left finger’s tapping, (2) DCD exhibits persistent difficulties to inhibit the left finger’s tapping, and (3) both groups improve their capacity to inhibit the left finger’s movements through trials. In conclusion, the lateralized switching task provides a simple and fine tool to reveal differences in selective inhibition of symmetric movements in TD children and children with DCD. More theoretically, the specific improvement in selective inhibition of the left finger suggests a progressive development of inter-hemispheric communication during typical development that is absent or delayed in children with DCD.

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1. Introduction

Many activities in daily-life require decoupling movements of the right and left hands in order to produce successful unimanual and bimanual movements (lacing the shoes, using a knife and a fork, tapping on a keyboard or a phone, writing, etc.). The problem is that human beings exhibit a spontaneous tendency to produce symmetric movements of both hands. Symmetric tendency comes from mirror movements (Armatas, Summers, & Bradshaw, 1996), also called motor overflows (Addamo, Farrow, Hoy, Bradshaw, & Georgiou-Karistianis, 2007; Hoy, Fitzgerald, Bradshaw, Armatas, & Georgiou-Karistianis, 2004), associated movements (Largo et al., 2001), reproductive associated movements (de Ajuriaguerra, 1969), contralateral
motor irradiations (Cernacek, 1961) or imitative synkinesia (“syncinésies d’imitation”, de Ajuriaguerra & Stambak, 1955). Mirror movements refer to non-intentional movements that accompany intentional unilateral movements of homologous muscles of the opposite side (Abercombie, Lindon, & Tyson, 1964). Despite the neural mechanisms underlying the generation of mirror movements are still in debate (see Addamo et al., 2007; Hoy et al., 2004; for reviews of theories), it is well accepted that mirror movements result from a lack of inhibition of contralateral movements. Many studies show that the suppression of mirror movements requires neural inter-hemispheric inhibitory transfer, in part from the controlateral to the ipsilateral hemisphere (Arányi & Rössler, 2002; Cardoso de Oliveira, Gribova, Donchin, Bergman, & Vaadia, 2001; Cernacek, 1961; Fling & Seidler, 2012; Liuazzi, Hönniss, Zimerman, Gerloff, & Hummel, 2011; Rao et al., 1993; Sadato et al., 1996).

Behavioral and neuroimaging studies reveal that normal right-handed adults present more mirror movements in the dominant right side compared to the non-dominant left side during contralateral unimanual movements (Armatas, Summers, & Bradshaw, 1994; Armatas et al., 1996; Cernacek, 1961; Liederman & Foley, 1987; Todor & Lazarus, 1986; Wolff, Gunnoe, & Cohen, 1983). This suggests a greater capacity to inhibit movements of the left hand compared to movements of the right hand. The present study aims at testing behavioral age-related improvement in the capacity to inhibit selectively the left and right hands in right-handed children. During the typical course of neurological development, the cortical activation theory (Todor & Lazarus, 1986) postulates that the inhibition of mirror movements depends on the refinement of cortical activations associated with the manipulative function of the moving effector. As right-handed children grow up, the right effector is increasingly utilized and the left cortical activations are refined. Hence, the left motor cortex becomes more prone to send inhibitory outputs to the right motor cortex, leading to less mirror movements of the left hand. This theory is supported by neuroimaging studies in adults suggesting a greater capacity of the left hemisphere to inhibit right motor regions (Beltramello et al., 1998; Kim et al., 1993; Kobayashi, Hutchinson, Théoret, Schlaug, & Pascual-Leone, 2004; Netz, Ziemann, & Hömberg, 1995). As right-handed typically-developed (TD) children grow up, we can expect a greater improvement in the capacity to inhibit the left hand than the right hand, due to a progressive increase in motor experience of the right hand.

We also test the development of the capacity to inhibit movements of the left and right hand’s movements in 7–10 years old children with Developmental Coordination Disorder (DCD). Children with DCD represent 5–6% of the school-aged children and manifests principally by clumsiness and slowness, which is not due to the child’s age or intellect or to a known neurological disorder (DSM-IV, American Psychiatric Association, 1994; Blank, Smits-Engelsman, Polatajko, & Wilson, 2012). Among other hypotheses, one challenging neural mechanism explaining DCD relates to a deficit in inter-hemispheric inhibitory transfer (Wilson & Butson, 2007). First, children with DCD exhibit significantly more mirror movements than TD children (Licari, Larkin, & Miyahara, 2006; Licari & Larkin, 2008). Second, Sigmundsson and colleagues reveal that a subgroup of children with DCD exhibit more difficulties than TD children in target location using their left hand to match with their right hand and using their right hand to match with their left hand (Sigmundsson, Whiting, & Ingvaldsen, 1999). The authors conclude that children with DCD could suffer from a deficit either in inter-hemispheric transfer or in the right hemisphere controlling their non-dominant left hand. In addition, children with DCD present less hand preference. In TD children and adults, the right hand is preferentially used for manual movements (Oldfield, 1971) and the preferred hand is generally more stable than the non-preferred hand (Fagard, 1987; Peters & Durdig, 1978; Truman & Hammond, 1990). In DCD children, there is less difference in the right or left hand preference (Armitage & Larkin, 1993; Hill & Bishop, 1998). For example, the results of Hill and Bishop (1998) reveal that right-handed TD children from 7 to 11 years old use preferentially their right hand to locate cards whatever their spatial position (right or left of their body’s midline) whereas right-handed DCD reach spatial positions located to the right of their body’s midline predominantly with their right hand and spatial positions locate to the left of their body’s midline predominantly with their left hand. DCD children present the same pattern of results than younger right-handed TD children (5–6 years old), which lead the authors conclude that DCD children present an immaturity in the lateralization process. Taken together, these results and the cortical activation theory lead to the hypothesis that DCD children would exhibit less improvement in the capacity to inhibit the left hand movements compared to their TD peers.

We propose to test these hypotheses with a switching task from bimanual symmetrical tapping to unimanual tapping (Barral, De Pretto, Debú, & Hauert, 2010; Tallet, Barral, & Hauert, 2009). This task involves decoupling symmetric movements of right and left hands thanks to the inhibition of one finger’s tapping. Previous results suggest that switching induces a destabilization of the tempo of the continuing right hand whilst switching in adults (Tallet et al., 2009). Moreover, TD children increase their capacity to maintain the tempo of the continuing finger from 5 to 11 years old (Barral et al., 2010). These results suggest that motor perturbation induced by selective inhibition decreases during childhood. An alternative measure of perturbation could be the number of supplementary taps of the stopping finger after the instruction to stop. Given that supplementary taps lead to symmetric movements, we can reasonably postulate that inhibition of supplementary taps would require shared neural mechanisms with inhibition of mirror movements, i.e., inter-hemispheric inhibitory transfer. Previous distinct studies support this idea. In one hand, inhibition of mirror movements requires inter-hemispheric inhibitory transfer (e.g., Hoy et al., 2004). In other hand, a previous EEG study suggests that selective inhibition of symmetric movements leads to cerebral asymmetrization in functional couplings over the left and the right hemispheres that could reflect inhibitory transfer (Tallet et al., 2009). Hence, investigating behavioral perturbation of the stopping hand and continuing hand whilst switching from bimanual symmetric to unimanual movements would provide a complete experimental window to understand selective inhibition of symmetric movements. Thanks to a lateralized switching task that requires stopping selectively the left or the right finger’s tapping while continuing the other finger’s tapping, we can assess selective inhibition of right and left sides.
Operationally, we can first expect an age-related improvement of the capacity to stop (i.e., to inhibit) the left finger (right switching condition) in TD children only. Given the gradual improvement in the capacity to inhibit mirror movements during the first decade of life (Cohen, Taft, Mahadeviah, & Birch, 1967; Connolly & Stratton, 1968; de Auriaguerra & Stambak, 1955; Lazarus & Todor, 1987), we predict an age-related improvement in the capacity to inhibit selectively the left hand movements in TD children between 7 and 10 years old. Such changes are less expected in children with DCD. Second, we can expect an improvement of the capacity to continue (i.e., to maintain the stability of) the right finger with age (right switching condition), relative to the development of the left hemisphere dominance in right-handed TD children. Such changes are less expected in children with DCD. Third, a special interest is devoted on the possible evolution of performance over trials in order to assess possible general practice effect.

2. Methods

2.1. Participants

Twelve TD (4 girls) and 12 DCD (4 girls) volunteer children participated in the study. For TD children, mean age was 107 months (SD = 14; range: 88–125 months). For children with DCD, mean age was 109 months (SD = 15; range: 84–128 months). All children were right-handed as assessed with the Oldfield questionnaire (handedness quotients > 70%; Oldfield, 1971). TD children were solicited from local schools. These children did not experience any observable perceptivo-motor disorder and did not meet the criteria for DCD. Children with DCD were recruited from psychomotor therapists and met the criteria of DSM-IV (American Psychiatric Association, 1994). Children with DCD and probable DCD (score lower than percentile 15) in a French version of Movement ABC have been included in the DCD group (Blank et al., 2012; Henderson & Sugden, 1992; Soppelsa & Albaret, 2004). Before the experiment, the children's parents or a legal guardian signed an informed consent. The study was in agreement with the University guidelines and the ethical standards laid down in the declaration of Helsinki.

2.2. Materials

The experiment was conducted in a dimly lit room. A computer screen was placed 1 meter in front of the participant and delivered visual instructions and auditory tones of a metronome using Presentation software version 0.81 (Neurobehavioral System Inc., Albany, CA). Two red-colored ‘‘Ctrl’’ keys of a keyboard were used for tapping tasks. Each key pressing was recorded with the Presentation software.

2.3. Tasks and procedure

2.3.1. Pre-test

A pre-test was carried out prior to the proper switching task in order to evaluate the self-selected tempo of children (period of the right or left index). After a familiarization, children were asked to produce bimanual symmetrical fingers tapping by pressing the two red-colored keys with their both index fingers simultaneously. They were instructed to tap with their self-selected tempo, as stably as possible during 20 s. This task was designed to ensure that the self-selected tempo corresponded to 600 ms in accordance with previous results of Stambak (1958) and did not evolve with age.

2.3.2. Switching task

In the switching task, the same participants were asked to synchronize their index finger(s)’ tapping on the beat of the metronome. The tempo of the metronome was fixed at 600 ms for all children and remained the same during all the trial. Two switching conditions were required: In the left switching condition, children had to switch from bimanual symmetrical tapping to unimanual tapping by stopping the right index while continuing the left index tapping in synchrony with the metronome. The right switching condition corresponded to the opposite task requirements.

Procedure was designed as follows: participants sat comfortably in front of the computer screen, their index positioned on each red-colored key in order to perform the fingers’ tapping task. Each trial was designed as follows. A visual stimulus “Press START to continue” was presented on the screen until the participant pressed the space key at the middle of the keyboard. Then, a green cross appeared in the center of the screen. Participants were preliminary instructed to fix their gaze on this cross during the whole trial. The auditory metronome started to produce iso-frequency low-pitched tones (500 Hz), requiring the participant to synchronize bimanual symmetrical fingers tapping with the metronome. After varying delays (9, 11 or 13 low-pitched tones), the metronome changed to high-pitched tones (4000 Hz), prompting the participant to switch to unimanual left or right tapping. At the end of the trial, a visual stimulus (“STOP”) was presented for 2 s on the screen. The participant triggered the next trial to her/his like. Each trial lasted 20 s and each experimental condition corresponded to a block of 5 trials. Some familiarization trials in which participants could repeat the task were proposed at the beginning of the experiment. The children were told that they could familiarize as many times as they wanted. On average, they

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1 One trial of one TD participant has not been realized in the left-switching condition.
performed two trials for each condition. Participants were informed about the left or right switching condition before each block and the order of the blocks was pseudo-randomized across participants.

2.4. Data processing

Seven dependent variables were analyzed for each switching condition and each participant. We divided each trial in two epochs (Fig. 1): the pre-switching epoch corresponded to the 3 taps before the switching (bimanual condition) and the switching epoch to the 3 taps following the switching (unimanual condition). The switching was identified by the stopping of the required finger’s tapping after the change of the metronome tonality.

First, to analyze data of the pre-test, we computed the mean period of the right index finger tapping ($T_{\text{mean}}$) and corresponding standard deviation ($T_{\text{sd}}$) for each participant during the pre-test dedicated to evaluate the self-selected tempo. $T_{\text{mean}}$ reflected the tempo adopted by the right index finger and $T_{\text{sd}}$ its variability, both expressed in milliseconds.

Second, to test whether participants actually performed symmetrical tapping before switching, we calculated the relative phase (RP) of the bimanual tapping during the pre-switching epoch. The computation corresponded to:

$$\text{RP} = \left( \frac{IT}{T_{\text{mean}}} \right) \times 360$$

where $IT$ was the inter-tapping temporal delay between the tapping of the right and left index for all the taps before the switching and $T_{\text{mean}}$ was the period of the right finger’s tapping. When the left finger led the right one, RP was corrected to be distributed between 0° and 180°.

RP was expressed in degrees. Theoretically, for symmetrical tapping, $IT = 0$ ms and $T_{\text{mean}} = 600$ ms, leading to $\text{RP} = 0°$. The mean of the produced RP ($\text{RP}_{\text{mean}}$) informed about the accuracy of the produced tapping mode and SD of RP ($\text{RP}_{\text{sd}}$) on its stability.

In order to evaluate the difficulty to inhibit one finger tapping, we identified the number of supplementary taps of the stopping finger after the change of metronome tonality for each trial performed by each participant for each condition.

In order to evaluate the changes in the produced tempo of the continuing finger and its variability before and after switching, we computed the difference between the mean period of the right (or left) index finger tapping during the pre-switching and the switching epochs ($\text{diff}T_{\text{mean}}$) and corresponding standard deviation ($\text{diff}T_{\text{sd}}$) for each participant in each condition and each trial. For all trials, participants and conditions, 13% of trials were excluded because participant produced unimanual taps during the pre-switching epoch or did not switch with the required finger. Excluded values have been replaced by the mean of the corresponding trial, group and condition. Global $\text{diff}T_{\text{mean}}$ corresponded to the average of $\text{diff}T_{\text{mean}}$ over the 5 trials in each condition. Similarly, global $\text{diff}T_{\text{sd}}$ corresponded to the average of $\text{diff}T_{\text{sd}}$ over the 5 trials in each condition. Positive $\text{diff}T_{\text{mean}}$ reflected deceleration whereas negative $\text{diff}T_{\text{mean}}$ reflects acceleration due to switching. Positive $\text{diff}T_{\text{sd}}$ reflected an increase in variability of the tempo (destabilization) whereas negative $\text{diff}T_{\text{sd}}$ reflected a decrease in variability of the tempo (stabilization) due to switching.

2.5. Statistical analyses

First, two-sample tests were carried out in order to compare the mean differences in each of the 7 variables ($T_{\text{mean}}$ and $T_{\text{sd}}$ for the self-selected tempo, $\text{RP}_{\text{mean}}$ and $\text{RP}_{\text{sd}}$ for the bimanual tapping, $\text{diff}T_{\text{mean}}$ and $\text{diff}T_{\text{sd}}$ and the number of supplementary taps).

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2 The self-selected tempo of one participant with DCD has not been recorded so that we have replaced her data by the mean of the DCD group.
taps produced after the switching instruction) between the two groups of children (TD and DCD), independent of age, for both conditions (left-switching and right-switching). Complementary t-tests were performed in order to ensure that the self-selected tempo produced during pre-test was not significantly different from 600 ms.

Second, in order to assess age-related changes in the two groups of children, we used the following linear regression for each dependent variable and each group:

\[ y = \alpha \times \text{age} + \beta + \epsilon, \]

where \( \alpha \) and \( \beta \) are estimated slope parameters and intercept respectively, and \( \epsilon \) represents the residuals. To assess age-related changes within groups, we tested the significance of the slopes parameters (i.e., \( \alpha \)) in each group for each dependent variable and each condition.

Third, to assess the possible evolution of performance over the 5 experimental trials, a Group (2) \( \times \) Trials (5) ANOVA with repeated measures on Trials was performed on each variable.

For all analyses, the \( p \) value was fixed at \( p \leq 0.05 \). The Cohen’s effect size (\( d \)) is also reported for significant group effects on t-tests. \( \eta^2 \) was reported for significant effects on ANOVA.

3. Results

3.1. Pre-test and pre-switching

3.1.1. Self-selected tempo during pre-test

Results revealed that the mean self-selected tempo produced by children was 634 ms (SD = 160 ms) with no effect of group (\( t(11) = 0.719, p = 0.48 \)). The produced tempo was not significantly different from 600 ms (\( t(23) = 1.398, p = 0.08 \)). Moreover, the variability of the tempo was 92 ms (SD = 137 ms) and did not differ between groups (\( t(11) = 1.705, p = 0.11 \)).

3.1.2. RP\text{mean} and RP\text{sd} during pre-switching

The RP\text{mean} of the bimanual symmetrical tapping produced before switching differed for TD and DCD groups in the right switching condition only. As shown in Table 1, the mean RP was higher in children with DCD than in TD children in the right switching condition (\( t(11) = 2.414, p = 0.03, d = 0.817 \)). It was not the case for the left switching condition (\( t(11) = 1.206, p = 0.252 \)). The RP\text{sd} did not differ between groups whatever the condition (\( t(11) < 2.107, p > 0.058 \)).

3.2. Switching

3.2.1. Number of supplementary taps after the change of the metronome tonality

As represented in Table 2 and illustrated in Fig. 2, in TD children, the number of supplementary taps decreased significantly with age for the left finger’s tapping only (\( t(11) = -2.251, p = 0.02 \)).

In children with DCD, the number of supplementary taps did not significantly evolve with age whatever the finger stopped.

### Table 1

Mean relative phase (RP\text{mean}, in degrees), variability of the relative phase (RP\text{sd}, in degrees), number of supplementary taps, global difference between the mean tempo of the continuing finger before and after the transition (global diff\text{temp}, in ms) and global difference between the tempo variability of the continuing finger before and after the transition (global diff\text{var}, in ms) produced by TD children and children with DCD in the right and left switching conditions. Values in parentheses are standard deviations.

<table>
<thead>
<tr>
<th></th>
<th>Right switching</th>
<th>Left switching</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>TD children (N = 12)</td>
<td>DCD children (N = 12)</td>
</tr>
<tr>
<td>( \text{RP}\text{mean} ) (( \circ ))</td>
<td>16.6 (±6)</td>
<td>25.4 (±14)</td>
</tr>
<tr>
<td>( \text{RP}\text{sd} ) (( \circ ))</td>
<td>14.7 (±7)</td>
<td>22.1 (±13)</td>
</tr>
<tr>
<td>Number of supplementary taps</td>
<td>2.23 (±1.3)</td>
<td>3.60 (±1.1)</td>
</tr>
<tr>
<td>Global diff\text{temp} (ms)</td>
<td>240.7 (±437)</td>
<td>-63.4 (±682)</td>
</tr>
<tr>
<td>Global diff\text{var} (ms)</td>
<td>-357.1 (±479)</td>
<td>-706 (±804)</td>
</tr>
</tbody>
</table>

\( d \) is the value of the effect size of each significant effect.

* \( p < 0.05 \).
Table 1

Results of *t*-tests for the number of supplementary taps, the global difference between the mean tempo of the continuing finger before and after the transition (global $\text{Diff}_\text{mean}$, in ms) and the global difference between the tempo variability of the continuing finger before and after the transition (global $\text{Diff}_\text{sd}$, in ms) as a function of age in TD children (left panel) children with DCD (right panel).

<table>
<thead>
<tr>
<th>Age-related changes</th>
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<th>Left switching</th>
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<tbody>
<tr>
<td>in TD children</td>
<td>Number of supplementary (left) taps</td>
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<td>Global $\text{Diff}_\text{sd}$</td>
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</tr>
<tr>
<td>$t(11)$ = -2.751; $p = 0.02$</td>
<td>$t(11)$ = -1.148; $p = 0.278$</td>
<td>$t(11)$ = -0.800; $p = 0.443$</td>
<td>$t(11)$ = -0.485; $p = 0.638$</td>
<td>$t(11)$ = -0.048; $p = 0.299$</td>
</tr>
<tr>
<td>Age-related changes in children with DCD</td>
<td>$t(11)$ = -0.865; $p = 0.408$</td>
<td>$t(11)$ = -1.313; $p = 0.219$</td>
<td>$t(11)$ = 0.283; $p = 0.783$</td>
<td>$t(11)$ = 1.023; $p = 0.33$</td>
</tr>
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</table>

Table 2

Results of *t*-tests for the mean number of supplementary taps, the global difference between the mean tempo of the continuing finger before and after the transition (global $\text{Diff}_\text{mean}$, in ms) and the global difference between the tempo variability of the continuing finger before and after the transition (global $\text{Diff}_\text{sd}$, in ms) as a function of age in TD children (left panel) children with DCD (right panel).

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* $p < 0.05.$

As shown in Table 1, the number of supplementary taps was significantly higher for the DCD group than for the TD group when they had to stop their left finger (right switching condition; $t(11) = 3.29, p = 0.007, d = 1.137$). It was not different when they had to stop their right finger.

3.2.2. Changes in the global mean tempo of the continuing finger after switching

In regards to the tempo of the continuing finger, statistical analyses indicated that the global $\text{Diff}_\text{mean}$ of the right and the left finger did not significantly change with age, neither in TD children nor in children with DCD (Table 2).

As indicated in Table 1, *t*-tests indicated that, whatever the continuing finger, the global $\text{Diff}_\text{mean}$ was not significantly different for TD compared to DCD children.

3.2.3. Changes in the global variability of the tempo of the continuing finger after switching

As indicated in Table 2, statistical analyses indicated that the global $\text{Diff}_\text{sd}$ of the left finger significantly change with age in TD children only ($t(11) = 4.523, p = 0.001$). Fig. 3 clearly shows an age-related increase of the global $\text{Diff}_\text{sd}$ which tends toward zero millisecond in TD children only.

As indicated in Table 1, *t*-tests indicated that, whatever the continuing finger, the global $\text{Diff}_\text{sd}$ was not significantly different for TD compared to DCD children.

3.3. Evolution of performance over trials

3.3.1. $\text{RP}_\text{mean}$ and $\text{RP}_\text{sd}$ during pre-switching

Whatever the condition, ANOVA did not reveal any significant effect or interaction of $\text{RP}_\text{mean}$ or $\text{RP}_\text{sd}$.

3.3.2. Number of supplementary taps after the change of the metronome tonality

ANOVA revealed a significant effect of Trials on the number of supplementary left taps (right switching condition, $F(4,88) = 2.904, p = 0.026, \eta^2 = 0.117$). As illustrated in Fig. 4, whatever the Group, the mean number of supplementary left taps decreased from the first (0.92 taps ± 0.83, i.e., near one supplementary tap per trial) to the last trial (0.33 taps ± 0.38). The ANOVA also revealed a significant effect of Group on the number of supplementary left taps (right switching condition, $F(1,22) = 6.673, p = 0.017, \eta^2 = 0.233$). Whatever the Trial, the number of supplementary left taps was globally higher in children

![Fig. 2](image-url). Individual data of the mean number of supplementary taps of the left finger produced by TD (white diamonds) and DCD (black squares) children after the change of the metronome tonality. Thin solid and dotted lines represents the developmental trajectories of the mean number of supplementary taps of the left finger with age in TD and DCD children respectively.
with DCD (0.72 taps ± 0.86) compared to TD children (0.44 taps ± 0.62). The interaction Group × Trial was not significant ($F(4,88) = 0.911, p = 0.461$).

The ANOVA did not reveal any significant effect or interaction of the number of supplementary left taps (right switching condition).

3.3.3. Diff$T_{\text{mean}}$

Whatever the condition, the ANOVA did not reveal any significant effect or interaction of Diff$T_{\text{mean}}$.

3.3.4. Diff$T_{\text{sd}}$

Whatever the condition, the ANOVA did not reveal any significant effect or interaction of Diff$T_{\text{sd}}$.

4. Discussion

The aim of this experiment was to investigate the development of the capacity to selectively inhibit bimanual symmetrical movements in right-handed 7–10 years old TD children and children with DCD. After ensuring that the self-selected tempo of the children was around 600 ms (Stambak, 1958), we used a lateralized motor switching task in which participants first produced a bimanual symmetrical tapping and then were asked to selectively inhibit the tapping of left finger while continuing the tapping of the right one (right switching) and conversely (left switching). Three major results are discussed.

4.1. Improvement in control (inhibition and maintain) of the left finger in TD children

In regards to the results of TD children, the number of supplementary taps decreased for the left finger’s tapping only. This result suggests an age-related improvement in inhibiting the left finger’s movements in order to decouple symmetrical movements. This finding is in accordance with our hypotheses based on the cortical activation theory that predicts that the non-dominant (left) finger is less and less prone to mirror movements with age (Todor & Lazarus, 1986). Moreover, TD children increase their capacity to maintain the stability of the tempo of the left continuing finger. This finding is in
accordance with previous results using a similar experimental task (Barral et al., 2010) and comforts the results of Roy, Bryden, and Cavill (2003) who found that the control of non-preferred hand improves during typical childhood.

These results highlight an age-related increase in the role of the non-dominant (left) hand in bimanual coordination and motor switching in the normal time course of development. A previous developmental study of Pellegrini, Andrade, and Teixeira (2004) tests the effect of attentional focus on the dominant or non-dominant hand on the production of bimanual tapping tasks in children, 5–8-years and 9–12-years old. Results suggest that bimanual coordination is improved when children focused attention on their non-preferred hand (reduced movement time and less errors). The crucial role of the non-dominant hand is also supported by behavioral findings showing that the non-dominant hand is more prone to this phase shift than the dominant hand during bimanual coordination (Agnew, Zeffiro, & Eden, 2004; Aramaki, Honda, Okada, & Sadato, 2006; Semjen, Summers, & Cattaert, 1995). Other findings show that intentional switches between bimanual coordination patterns are primarily triggered by the non-dominant hand in adults (De Poel, Peper, & Beek, 2006). At a neurophysiological level, EEG findings show that bimanual movements are mainly mediated by the non-dominant (right) hemisphere controlling the left hand (Serrien, Cassidy, & Brown, 2003). Moreover, bimanual movements are associated to interactions from the dominant (left) to the non-dominant (right) primary sensorimotor cortex (Serrien et al., 2003). One possible explanation of our results is that the development of inhibition of the non-dominant hand could relate to the development of left-to-right inter-hemispheric inhibitory transfer advantage during childhood.

Finally, given that some recent studies found that girls exhibit superior performance in fine motor control (Gasser, Rousson, Caflisch, & Jenni, 2010; Roeder et al., 2008) and present less mirror movements than boys (Connolly & Stratton, 1968; Gasser, Rousson, Caflisch, & Largo, 2007; Larson et al., 2007; MacNeil, Garvey, Ranta, Denckla, & Mostofsky, 2011), further studies could be devoted to investigate a possible girls’ advantage in the capacity to inhibit and to maintain their left finger tapping during childhood.

4.2. Persistent difficulties in inhibiting the non-dominant (left) finger’s tapping in children with DCD

First, children with DCD produced globally more left supplementary taps than TD children with no improvement with age. This result suggests persistent difficulty to inhibit left finger’s movements in children with DCD. Given the crucial role of the non-dominant hand in bimanual coordination described above, this finding may in part explain difficulties in bimanual coordination of children with DCD, especially for asymmetric coordination that requires to inhibit symmetric movements in order to decouple movements of right and left hands (e.g., Volman & Geuze, 1998).

Our finding is not suitable to be explained by a difference in the preferential tempo between DCD and TD children because both groups exhibited similar preferential tempi (600 ms in accordance with Stambak, 1963). However, children with DCD performed less accurate symmetrical tapping in the right switching condition. This result extends previous results of Volman and Geuze (1998) who found that 7–12 years old children with DCD produced less stable bimanual symmetrical coordination. It is possible that the lack in accuracy of the symmetric tapping in the right switching condition found in our study is associated to difficulty to inhibit left finger’s movements. A first interpretation is that performing less accurate symmetrical tapping led to a difficulty to inhibit the left finger’s tapping (more supplementary taps). This interpretation is in accordance with previous findings suggesting that decoupling bimanual movements is facilitated when pre-existing coordination is accurate and stable (Tallet, Kostrubiec, & Zanone, 2008). An alternative interpretation is that right switching would require supplementary attentional resources to prepare switching in children with DCD, which could have led to less accurate symmetric tapping. Even if this interpretation should be tested experimentally, it is in accordance with previous findings suggesting a tight relationship between attention and bimanual coordination stability (Monno, Temprado, Zanone, & Laurent, 2002).

All in all, our results provide new elements to discuss Sigmundsson et al.’s (1999) hypotheses, suggesting that children with DCD would suffer from a lack in inter-hemispheric transfer or a deficit in the right hemisphere function. The lack of (left-to-right) inter-hemispheric transfer would explain why children with DCD present difficulties to inhibit their left finger’s movements in our study. The deficit in the right hemisphere function would predict that children with DCD would present difficulties to continue their left finger’s movements, which is not the case in our study. Hence, our findings are more in accordance with a lack in inter-hemispheric transfer rather than with a deficit in the right hemisphere function.

4.3. General practice effect on selective inhibition of the left finger’s movements in both groups

Despite their global difficulty to inhibit their left finger’s tapping, we found that children with DCD present a decrease in supplementary left taps over trials comparable with TD children. This suggests that although DCD children do not reach the performance of TD children, they demonstrated comparable task practice effects. We cannot exclude that practice effects may be due to the fact that we included both severe and less severe DCD. However, previous findings suggest that children with severe DCD also present an intact capacity to improve their performance over practice although specific learning deficits (Gheysen, Van Waervelde, & Fias, 2011). It is important to note that there was no learning requirement in our study (no feedback about the switching performance). Improvement may just relate to a greater experience of the switching task. The general improvement to inhibit the left finger’s movements is in accordance with previous findings of Roy et al. (2003) who show that the performance of non-preferred hand presents larger improvements than the right hand over typical childhood because of a greater experience with using their non-preferred left hand from 5 to 24 years old. One could suppose
that children with DCD have poorer experience with using their left hand, which could explain their difficulty to inhibit (and maintain) this hand’s movements, but increased experience would lead to improvements in inhibiting their left hand. This finding opens new perspective therapies based on exercises to control the left hand’s movements in children with DCD. Whether the capacity to inhibit the left hand is related to the capacity to decouple both hands’ movements, it would be interesting to test possible transfer of such a training on asymmetric bimanual coordination.

5. Conclusion

To conclude, our results show an improvement in the capacities to inhibit the left finger’s tapping in TD children. On the contrary, children with DCD exhibit persistent difficulties in both inhibiting and maintaining their left finger’s tapping unless all children present improvements in inhibiting their left hand with general practice. The lateralized motor switching task seems to provide a fine measure to assess developmental deficits in selective motor inhibition of right or left hand’s movements. Given that inhibition of mirror/symmetric movements is considered as a marker of neural development (Wolff et al., 1983), complementary neuroimaging studies including analyses of inter-hemispheric coherence with EEG (see Castelnau, Albaret, Chaix, & Zanone, 2008; Tallet et al., 2009) would be necessary to test whether behavioral changes found in the present study are associated to an increase in left-to-right inter-hemispheric inhibitory transfer advantage during typical development that could be absent or delayed in children with DCD.

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References
