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Auditory and visual information do not affect self-paced bilateral finger tapping in children with DCD

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Abstract

Children with Developmental Coordination Disorder (DCD) are more variable in timing their fingers to an external cue. In this study, we investigated the intrinsic coordination properties of self-selected anti-phase finger tapping with and without vision and audition in children with and without DCD and compared their performance to that of adults. Ten children with DCD (Mean age = 7.12 ± 0.3 years), ten age- and sex-matched typically developing (TD) children, and ten adults participated in this study. Participants tapped their fingers in anti-phase at a self-selected speed under four different sensory conditions: (1) with vision and audition, (2) with vision but no audition, (3) with audition but no vision, and (4) without vision and audition. We assessed intertap interval (ITI), variability of ITI, mean relative phasing (RP) between the fingers and the variability in RP. Children with DCD adopted a similar mean frequency, but were less accurate and more variable than the other groups. The different sensory conditions did not affect performance in any of the groups. We conclude that visual and auditory feedback of tapping are not salient information sources for bilateral self-selected tapping and that children with DCD are intrinsically less accurate and more variable in their tapping frequency and coordination.

Keywords

Developmental Coordination Disorder; Bimanual tapping; Sensory feedback; Timing; Motor skills

1. Introduction

Children with Developmental Coordination Disorder (DCD) have difficulty with motor tasks that require coordination, rhythm and timing, such as skipping, playing an instrument, or writing. Individuals with DCD have an impairment of motor coordination and performance severe enough to affect activities of daily living and their academic performance, which is not explicable by their age, IQ or any neurological condition (APA, 1994). Studies have suggested that these deficits in motor coordination could be related to

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visual (Zoia, Castiello, Blason, & Scabar, 2005), visual perceptual (Schoemaker et al., 2001; van Waelvelde, de Weerd, de Cock, & Smits-Engelsman, 2004) and/or kinesthetic (Coleman, Piek, & Livesey, 2001) deficits. On the other hand, rhythm and timing of the motor system is strongly influenced by auditory information (Repp & Penel, 2004; Thaut, 2003; Thaut, Kenyon, Schauer, & McIntosh, 1999) and the inability to use auditory information effectively may also contribute to the deficits. Indeed, several studies have shown that children with DCD are not able to synchronize well with external auditory cues (de Castelnau, Albaret, Chaix, & Zanone, 2007; Geuze & Kalverboer, 1987; Volman & Geuze, 1998; Whittall et al., 2006; Williams, Woollacott, & Ivry, 1992). Little is known about whether children with DCD show similar deficits without the presence of an external auditory cue or without preceding auditory pacing signal (Geuze & Kalverboer, 1987). It is also not known if they are able to use intrinsically available visual and auditory information to enhance their performance. In this study, we investigate these questions using bilateral anti-phase finger tapping.

Bilateral finger tapping is a useful paradigm to study sensorimotor coupling because it is a rhythmic task with repetitive discrete movements, where spatial coordination demands are minimized and auditory-motor coupling prioritized. The task requires temporal coordination between the two fingers in addition to a timing response if a driving sensory stimulus is involved. Low inertial properties of the fingers reduce the biomechanical influences on timing suggesting that there is a possible linear relationship between the conscious initiation of movement by the brain and the neural efferent and afferent signals that control the movement (Whittall, Forrester, & Song, 1999). Most studies of bilateral finger tapping have used either a synchronization or continuation paradigm.

A synchronization paradigm involves tapping in synchrony with an external beat. In studies using this paradigm, children with DCD were more variable and their synchronization was less accurate than typically developing (TD) children. Increased variability in children with DCD appears to be related, at least in part, to a lack of precise timing to the external driving stimulus (Whittall et al., 2008). The continuation paradigm entails tapping to an external beat and then trying to maintain the same frequency when the external stimulus is withdrawn. Studies using this paradigm in children with DCD (Lundy-Ekman, 1991; Williams, Woollacott, & Ivry, 1992) have shown that children with DCD were more variable in maintaining a set frequency of tapping (accounting for drift) than TD children. The variability, in general, is assumed to come from either processes of the central nervous system that determine when the next response should be made based on the remembered tapping rate (clock variability) or from processes involved in response implementation (motor variability) or both (Wing & Kristofferson, 1973). Lundy-Ekman et al., (1991) determined that in children with DCD who were poor at tapping, the variability seemed to come more from central processes.

In both paradigms (synchronization and continuation), there is a given timing rate, which is implicated in the increased movement variability. However, in adults, there is evidence that a preferred rate of tapping is associated with the least performance variability (Whittall, Forrester, & Song, 1999). Previous studies with either paradigm, typically did not try to match an individual's preferred rate of tapping. Given this knowledge gap, we chose to determine whether children with DCD would still be more variable if they produced a self-selected rate of tapping.

Conceptually, producing an accurately coordinated, consistent, anti-phase tapping at a self – selected frequency requires at least four developmental processes. First, an individual must have a cognitive understanding of what anti-phase and comfortable tapping means. In this study, we ensured that participants understood the concept so the remaining three

developmental processes are examined. These processes comprise what has come to be called the internal model that specifies the relationship between motor commands and their sensory consequences (Wolpert & Ghahramani, 2000). Over developmental time, (1) the motor system must produce relatively equal muscle contractions of the two fingers (given similar inertial properties), with equal time spaces and at a perceived comfortable frequency, (2) the sensory system needs to recognize whether the fingers are accomplishing the intended task, and (3) subsequently, the muscle contraction amplitude and timing are modified if errors between the intended and actual movements are detected. Initially, setting the amplitude, spacing and frequency of muscle contractions may be considered as utilizing a task-specific sensorimotor map (an inverse model in the language of internal models) (Davidson & Wolpert, 2003, 2004). Adjusting the map according to feedback and error detection can be considered as tuning the map to an optimal task-related setting (i.e., producing a good forward model and using feedback processes to modify). Note that the initial choice of self-selected frequency does not rely on tuning as much as the inertial properties of the fingers, a perception of comfort or some form of intrinsic CNS oscillation. Tuning the map for amplitude and spacing, however, would require sensory information which, in a self-selected frequency task, could come from four possible sensory sources: proprioception of muscle and joint action position during the tap, somatosensory information from touching the surface, auditory information from hearing the taps, and visual information from looking at the spatial pattern of the taps.

In the present study, we systematically removed the available auditory and visual feedback to determine if either of these sources of information contributed to the overall motor response. We reasoned that intrinsic auditory information might be important because, as an external source of information, it has been shown to have a greater effect on increasing the consistency of tapping than either a visual display or tactile information in adults (Aschersleben & Bertelson, 2003; Kolers & Brewster, 1985; Repp, 2006; Repp & Penel, 2004; Semjen & Ivry, 2001). Since adults have constructed a stable “map” for producing accurate and low variability anti-phase tapping (Whitall, Forrester & Song, 1999), children and, particularly, children with DCD are likely to be more affected by the lack of this source of intrinsic feedback. Visual information gained from looking at the finger positions when tapping might also be a source available for tuning motor responses. In the presence of intact proprioception during synchronization or continuation paradigms, however, visual information does not improve accuracy of tapping in adults suggesting that it is not typically a salient source of information for this temporally constrained task (Billon, Semjen, Cole, & Gauthier, 1996; Stenneken, Aschersleben, Cole, & Prinz, 2002; Stenneken, Prinz, Bosbach, & Aschersleben, 2006; Stenneken, Prinz, Cole, Paillard, & Aschersleben, 2006). It is plausible that children with DCD may give preferential weighting to visual information particularly since they appear to be more dependent on visual information in motor tasks such as walking (Deconinck et al., 2006) and reaching (Smyth, Anderson, & Churchill, 2001). Therefore, we reasoned that children with DCD may be more affected by removing vision than adults and TD children.

The purpose of this study was to determine the timing and coordination deficits of finger tapping at a self-selected frequency in children with DCD with and without availability of auditory and visual information. We compared their performance to that of TD children and adults. We hypothesized that the lack of specific external timing cues in this study would result in children with DCD having greater timing and coordination deficits than TD children who would have greater deficits than adults (Getchell, Forrester & Whitall, unpublished). We also predicted that children with DCD and possibly TD children would be adversely affected in timing and coordination by a lack of auditory information since we assumed that the auditory information would provide sensory tuning for a less well-developed initial motor map of anti-phase tapping. We did not expect that a lack of vision

would adversely affect adults or TD children. Finally, based on studies of walking (Holt, Ratcliffe, & Jeng, 1999), we expected that there would be a differential choice of self-selected frequency because adults have larger fingers and therefore might adopt a slower frequency. We expected that children with DCD would adopt a slower frequency than TD children despite the similar inertial properties.

2. Methods

2.1 Participants

Ten adults (aged between 21–35 years), ten typically developing children (Mean = 7.08 ± 0.6 years) and ten children with DCD (Mean = 7.04 ± 0.4 years) participated in this study. TD children were age- and gender-matched within 6 months to the DCD group. The adults were gender-matched to the DCD group. In each group, there were 7 males and 3 females. One male in each group was left dominant. Children with DCD were recruited from local occupational therapy clinics and schools for children with special needs. Once recruited into the study, potential subjects were screened using the following: a) Movement Assessment Battery for Children (MABC) (Henderson & Sudgen, 1992) administered by trained testers, to screen for motor problems; b) Physical and Neurological Examination of Subtle Signs (PANESS) (Denckla, 1985) and a clinical neurological exam by a pediatrician (AWF); and c) the Woodcock-Johnson Psycho-Educational Battery (WJ III) (Woodcock, McGrew, & Mather, 2001) administered by an education specialist. Hand dominance was established using the Annett handedness questionnaire (Annett, 1991). The inclusion criteria for the DCD group were: 1) age between 6–8 years; 2) no neurological disorder present including pervasive developmental disorder (PDD); 3) an independent diagnosis of DCD from the pediatrician; 4) MABC total impairment scores less than or equal to the 15th percentile; and, 5) no cognitive impairment as assessed by the WJ III. Ten out of the 15 children, who were evaluated, met all inclusion criteria. Control children were also screened with the MABC and WJ III. They were included in the study if their total MABC impairment scores were equivalent to the 20th percentile or higher; their WJ III scores were within normal ranges indicating age-appropriate cognitive function and they had no known neurological condition. Characteristics of the DCD and control group are summarized in Table 1. Adults were included if they were between 21–35 years, had no known neurological or sensory condition and if they were non-musicians (not professional musician or advanced amateur with 10 or more years of training). All adults and guardians of the children in the study gave informed consent to the experimental protocol, which was approved by the Institutional Review Board of the University of Maryland, Baltimore.

2.2 Experimental set up and apparatus

The participants were seated in a quiet area with their forearms resting comfortably on the table. The elbows were slightly flexed and the forearms pronated. The hands were strapped to the table at the forearm and along the metacarpals to reduce associated movements. Hard plastic caps were placed on the tip of the fingers so that when the participant tapped the finger on the table, they could clearly hear their taps. However, they were not specifically directed to listen to this feedback. Minibirds™ sensors were attached on the fingernails of the non-dominant index finger and the dominant middle finger. A cotton swab was taped to the finger across the metacarpophalangeal joint to restrict movement. The positional data of the sensors were captured by a 3D magnetic tracking system (Minibirds™ Ascension system, Burlington, VT) at a sampling rate of 100 Hz. A set of headphones provided white noise during the conditions where the tapping sound was occluded. White noise was generated by a Hewlett Packard waveform generator. A blindfold was used to occlude vision during the no vision conditions. Each session was videotaped for later verification.

2.3 Experimental protocol

Participants were instructed to alternately tap their non-dominant left finger and dominant right finger at their preferred comfortable speed, which they could sustain for a long time. This non-homologous pattern tends to have lower phasing values compared to symmetrical homologous patterns (Whitall, Forrester, & Song, 1999). We reasoned, therefore, that the mixed pattern would be easier to perturb with changes in available visual or auditory information.

We chose to use anti-phase or alternating finger tapping rather than in-phase or simultaneously finger tapping. We reasoned that anti-phase tapping is likely to be more susceptible to altered sensory feedback since there are 2 taps per cycle and anti-phase tapping is possibly more unstable than in-phase tapping (Kelso, Scholz, & Schöner, 1986; Yamanishi, Kawato, & Suzuki, 1980). Participants were instructed to tap as evenly and steadily as possible. They were given practice trials to ensure that they understood the task and the concept of even vs. uneven taps. Formal trials began once the ability of the participant to produce uniform, alternating beats at a comfortable speed was established. Participants were presented with four blocks consisting of four 15-s trials, for a total of 16 trials. Each block had four different sensory conditions presented in random order. The sensory conditions included were: (1) Tapping with eyes open and with no occlusion of tapping sound (Vision and audition present; VA); (2) Tapping with eyes closed and no occlusion of tapping sound (No vision but audition present; NVA); (3) Tapping with eyes open, but with occlusion of the tapping sound using headphones with white noise (Vision present but no audition; VNA); and, (4) Tapping with eyes closed and occlusion of the tapping sound with white noise (No vision and no audition; NVNA). Short breaks were given between blocks. In order to sustain motivation of the children in the study, rewards (such as stickers) were given intermittently. Small tokens of appreciation (such as small toys) and a small financial compensation were given after the completion of the study.

2.4 Data reduction

The data were filtered using a recursive low pass 4th order Butterworth filter with a cut off frequency of 10 Hz and then processed using a custom-written Matlab™ program. The program derived the following variables: mean intertap interval (ITI), coefficient of variation of the intertap interval (CVITI), mean relative phase between the fingers (RP) and the variability of the relative phasing within a trial (*SDrp*), for both dominant and non-dominant fingers. The ITI was defined as the onset-to-onset times of the taps with each trial. CVITI was defined as the standard deviation of ITI divided by the mean ITI. RP represents the temporal relationship between the two fingers and indicates the accuracy of coordination. RP between the two fingers was taken as the ratio of the time between the left finger's touchdown and the touchdown of the right finger. If the participant tapped in perfect anti-phase, then the right finger touchdown would occur when the left side is at 180° (or 50%) of its cycle. The following formula was used to calculate the relative phase between the fingers:

$$RP = \frac{(ND_n - D_n)}{(ND_{n+1} - ND_n)} \times 100$$

where ND_n indicates the finger tap of non-dominant hand and D_n indicates the finger tap of dominant hand for the n th cycle in the time series. The phase then was normalized with a value of 50% corresponding to precise anti-phase between two fingers. Variability of the relative phase within a trial (*SDrp*) is the standard deviation of the mean relative phasing within a trial. *SDrp* is a method of expressing the variability (and therefore the stability) of

coupling between the fingers (Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980). Greater stability would be indicated by lower *SDrp* values. Paired t-test was performed between dominant and non-dominant ITI and CVITI. There were no significant differences between the values ($p > .05$). Once it was established that there was no effect of dominance on the variables, the dominant and non-dominant finger data for ITI and CVITI were collapsed for use in inferential statistical analysis.

2.5 Statistical analysis

All statistical analyses were performed using SAS (SAS Institute, Cary, NC, USA; version 9.1). Repeated measures ANOVA (using the linear mixed model) was carried out for each of the dependent variables with group (3 levels) by condition (4 levels). Goodness-of-fit statistics (such as Akaike's Information Criterion Correction (AICC)) were recorded from different covariance structures to find the best-fitting variance-covariance structure. Post hoc analysis (Tukey's HSD) was carried out when main or interaction effects were found. The overall alpha level was set at .05.

DCD is known to be a heterogeneous group. Therefore, to understand differences between the children, a z-score (or standard score) was calculated for each child with DCD. Z-score indicates how many standard deviations away from the mean an observation is. Z-score is calculated using the following formula:

$$z = \frac{x - \mu}{\sigma}$$

where x = the value of a DCD child's performance μ = the mean value of the TD children's performance σ = mean standard deviation of TD children Z score is dimensionless.

For the variables of CVITI and *SDrp*, we considered performance of children with DCD with z-scores below the mean + 1 standard deviation of the TD children as performance in the normal range because this range includes 84 % of TD children. For the variable of RP, we considered normal range as mean $\pm$ 1 standard deviation of the TD children, which included 68.2 % of the TD children. In this case, the phasing values are present on either of the mean. Chi square test with a Yates correction was done to see the frequency differences between the DCD and TD group. We present the number of DCD children who had mean performance greater than 1 *SD* and 2 *SD* (children with greater performance severity) of the TD mean. This analysis of the children with DCD permitted closer inspection of the heterogeneity found in this population.

3. Results

3.1 Individual performance

Table 2 illustrates the individual performance of the children for each variable at 1*SD* and 2*SD* above the mean of the TD children. The analyses of these non-parametric data are referred to after the parametric group by condition analyses for each variable. Fig. 4 illustrates the individual matched comparisons for one variable, *SDrp*, to illustrate how the determinations were made.

3.2 Intertap Interval (ITI)

There were no significant differences found for main effects or interactions. The overall mean was 0.89 ± 0.24 s. Analyses of individuals also confirmed that children with DCD chose frequencies comparable to the TD children. However, one child with DCD tapped slower in all four sensory conditions (z-score range from 2.07–3.34) and another faster (z-

score range from -1.21 to -1.55) than the average frequency of the TD children in all four sensory conditions. Removal of these children from the analysis did not change the statistical result for ITI.

3.3 Coefficient of Variation of intertap interval (CVITI)

A significant group main effect was found, $F(2, 26) = 22.70$, $p < .0001$, but no condition main effect or group by condition interaction effect was found. Fig. 1 shows the CVITI of the 3 groups collapsed across sensory conditions. Post hoc analyses showed that the adults had a lower CVITI value than typically developing (TD) children ($p = .012$) and children with DCD ($p < .0001$). TD children also had lower values than children with DCD ($p = .0054$). Chi square test showed significantly more children with DCD during vision available conditions (VA and VNA) at > 1 SD over the TD mean and all conditions at > 2 SD over the TD mean (Table 2A). Three children with DCD (#2, #6, #9) had similar timing consistency to TD children under normal sensory conditions.

3.4 Mean relative phasing between fingers (RP)

The group main effect was significant, $F(2, 26) = 7.83$, $p = .0022$, with no main effect for condition or interaction effect. Fig. 2 illustrates the RP of the 3 groups collapsed across sensory conditions. Post hoc tests revealed that the DCD group differed from the adults ($p = .0023$) and TD children ($p = .0226$) both of whom tended to tap very close to 50% RP and did not differ from each other. Chi square test showed significantly more children with DCD under normal sensory conditions (VA) at > 1 SD over the TD mean and all conditions at > 2 SD over the TD mean (Table 2B). Two children (#6 & #9) with DCD had similar coordination accuracy to TD children under normal sensory conditions.

3.5 Variability of the relative phase within a trial (SDrp)

There was a significant group main effect, $F(2, 26) = 27.36$, $p < .0001$, but no condition main effect or any interaction effect. Fig. 3 shows the SD of RP of the 3 groups collapsed across sensory conditions. Post hoc tests shows that DCD children were more variable than TD children ($p = .04$) and adults ($p < .0001$). TD children also were more variable than adults ($p = .0003$). Chi square test showed significantly more children with DCD during all conditions but only at > 2 SD over the TD mean (Table 2C). Five children with DCD (#2, #3, #4, #5, #9) had similar coordination stability to TD children under normal sensory conditions.

4. Discussion

Our study was designed primarily to determine the effect of visual and auditory information on the timing consistency (CVITI), the coordination accuracy (RP), and the coordination stability (SDrp) of a self-selected frequency anti-phase finger tapping task in children with DCD. We were also interested in which frequency was self-selected and in whether children with DCD were still more variable without an external cue. Unexpectedly, we found that the absence of visual and/or auditory information did not alter tapping performance in any of the 3 groups. There were expected differences in RP, CVITI and SDrp between adults, TD children and children with DCD, regardless of the sensory conditions. Self-selected frequency did not differ across groups. Finally, an analysis of individuals demonstrates that not all children with DCD perform poorly in this task and also that a sub-set of these children appear to perform better without vision.

4.1 Children with DCD have timing and coordination (but not frequency) deficits in self-paced tapping under normal sensory conditions

During self-paced tapping, children with and without DCD (Mean ITI ~ 1 Hz) and adults (1.2 Hz) had comparable tapping frequencies; a finding we did not expect. The fact that tapping frequency is similar between adults and children reinforces the idea that tapping is relatively uninfluenced by inertia. If inertia did influence finger tapping, adults would adopt a slower frequency based on increased moments of inertia, as observed during self-paced walking (Holt, Ratcliffe, & Jeng, 1999). The finding that the TD and DCD groups did not differ indicates that the slow motor performance often reported in DCD children (O'Brien, Williams, Bundy, Lyons, & Mittal, 2008; Raynor, 1998) does not apply to self-paced bilateral finger tapping. This suggests that deficits seen in performance are not due to a slowing of the movement. There may be an intrinsic CNS process that constrains finger tapping and rhythmic isometric pulses (Harabst, Lazarus, & Whittall, 2000) to a limited range of perceived comfortable frequencies. However, the lack of an external cue did not substantively alter the coordination and variability characteristics of tapping in these children (see Whittall et al., 2008 for comparison at a comparable frequency of external cueing).

In this study, children with DCD are less accurate than adults and TD children in their ability to achieve anti-phase tapping. On average, they were 3.3 % (11.8 deg) away from the target coordination (50%). It is not clear whether this inaccuracy is due to 1) an inability to initially correctly space the muscle contractions of the fingers, 2) a lack of awareness that the phasing relationship is not accurate or, 3) an inability to correct and attain the accurate relationship, or any combination. If they cannot initially equalize output from the two fingers, it would suggest that the children with DCD have not built a good sensorimotor map of reciprocal movements (that is, the initial process in this conceptual model). If they are not aware of the inaccuracy then they are not using sensory information to detect the error and if they are "aware" but still cannot correct then they cannot couple the sensory information to the motor actions. However, if the latter hypothesis is true, we speculate that the phasing error would be bidirectional; that is, the absolute error from 50% (180 deg) would occur on both sides of the ideal phasing. Since the phasing error is unidirectional, it appears that the initial sensorimotor plan is not reciprocal.

The phasing relationship was not only inaccurate, but more variable in children with DCD when compared to TD children. A similar observation was reported by Volman and Geuze (1998). DCD children also had variable intertap intervals. Geuze and Kalverboer (1987) also reported a similar finding in clumsy children during a self-paced task. However, they used a unilateral tapping protocol that involved tapping between two goals. Furthermore, we found that TD children were more variable than adults. These results indicate that children need to develop across time, the ability to fine-tune the sensorimotor map and that children with DCD are delayed in this process. The developmental effect, alone, is possibly due to the combination of developmental processes such as myelination of the corpus callosum (Keshavan et al., 2002; Muetzel et al., 2008; Pujol J, 1993; Yakovlev & Lecours, 1967) and the effect of experience with rhythmic tasks, though not necessarily finger tapping. However, we do not know whether the increased variability in performance of children with DCD is related to amount of experience, a and/or sensorimotor coupling (Apps & Garwicz, 2005).

Lesion studies have suggested that damage to the lateral and medial cerebellum causes deficits in time production (clock variability as opposed to the motor implementation variability). Ivry, Keele & Diener (1988) reported that damage to the lateral cerebellum causes deficits in central processes (i.e. production of time regardless of the motor execution) while lesions of the medial cerebellum impairs the implementation of correctly

timed responses. In a study using the inhibitory r-TMS (repetitive TMS) over the medial cerebellum, which causes a transient disruption, there was an increase in variability during paced finger tapping. This response was not found during r-TMS of the lateral cerebellum (Theoret, Haque, & Pascual-Leone, 2001). However, in a study on patients with essential tremor, r-TMS on the lateral cerebellum caused the ITI and CVITI to have similar values as the controls (Avanzino et al., 2009). Thus, it appears plausible that the lateral and medial regions of the cerebellum are likely areas of the brain involved in DCD. From our study, it is not possible to draw a conclusion about which specific area might be involved.

Inspection of the individual data of children with DCD for the two sources of variability (CVITI and *SDrp*) in the VA condition shows that two children were better than the average for TD children (#2 & 9), two were comparable (#5 & 6) and the rest were substantially worse than their matched controls. The four children with DCD who had age-appropriate variability also were more accurate with phasing than the other six children. These results highlight the fact that this is a heterogeneous diagnosis and that speculations of underlying problems for specific tasks may not apply to all. Note that the discussion above refers only to the condition of “normal” sensory information where vision and intrinsic auditory feedback are not altered.

4.2 Auditory feedback is not critical for finger tapping at a self-selected frequency

Many studies have shown that auditory information has a greater effect on finger tapping performance than visual information. A single source of external auditory information had a greater effect on increasing the consistency of adult unilateral tapping than visual or tactile information (Kolers & Brewster, 1985) and auditory rhythms were a stronger attractor of rhythmic movement than visual rhythms in musicians (Repp, 2006; Repp & Penel, 2004). Thus, we speculated that auditory feedback of rhythmic movement would be an important source of sensory information. In our paradigm, we did not manipulate the external source of information or give external feedback, but enhanced the natural intrinsic feedback from the finger tapping. We then eliminated this feedback in two conditions but none of the groups, including children with DCD, were affected by the loss of auditory feedback. This suggests that the effect of the auditory feedback is different from the potentially entraining effect of external auditory cueing. Evidently, this type of intrinsic auditory feedback is not typically used by adults or TD children, or even if it is, it does not override the intrinsic coordination pattern. We had speculated that children with DCD might use this salient auditory feedback more than the other groups because it would augment their poorly formed sensorimotor map for anti-phase movements. Children with DCD are less accurate at judging auditory time intervals than TD children (Williams, Woollacott, & Ivry, 1992) and it has been shown that those who have difficulty with timing perception also have difficulty with producing temporally accurate movements (Ivry, 2003). Thus, we speculate that implicit temporal perception of the anti-phase map may be needed even for a non-constrained rhythmic task such as self-selected anti-phase finger tapping and that children with DCD seem to have a fundamental difficulty in tuning their sensorimotor relationships resulting in a noisy or distorted map, regardless of available enhanced auditory information.

4.3 Visual feedback is not critical for finger tapping at a self-selected frequency although individual analysis demonstrates exceptions

While studies with adults (Gentilucci, 2003; Jakobson & Goodale, 1991; Jeannerod, 1984) and older children (Smyth, Peacock, & Katamba, 2004) have shown that lack of visual feedback causes decrement in performance in discrete movements with spatial accuracy demands such as reaching and grasping tasks, our results suggest that observing one's own fingers when tapping is not important for self-selected frequency bilateral finger tapping, a rhythmic task with low spatial accuracy demands. For the children with DCD, who may

have a less well developed sensorimotor map for anti-phase tapping, we had hypothesized that eliminating this source of information might have a detrimental effect on their performance. However, individual analyses suggest that most of the children with DCD were actually substantially more variable when they have visual feedback (VNA) or when they have both visual and auditory feedback (VA). That is, available visual information interfered with the sensorimotor mapping required of the anti-phase tapping task for some children with DCD. One plausible explanation is that visual information is distracting to these children with DCD. In fact, those children that appeared to have the most benefit from lack of vision did not have the diagnosis of attention deficit and hyperactivity disorder (ADHD). An alternative explanation is that these children were unable to integrate visual with auditory or proprioceptive/somatosensory information to improve their performance. Further systematic investigation will be necessary.

4.4 Implications and Future directions

We can conceptualize the sensorimotor map or internal models for self-paced anti-phase finger tapping as driving the initially produced motor commands to the finger muscles as well as continuously utilizing feedback relationships between visual, auditory, proprioceptive and somato-sensory information sources of information in comparison to the map and tuning motor commands to the finger muscles. It is hypothesized that these relationships are learned with experience (Kording & Wolpert, 2004) since infants cannot accomplish this task. The map is dynamic and continually updated by feedback, becoming more fine-tuned through childhood. Our results suggest that accurate coordination is first to develop since TD children are as accurate as adults. However from our data, we cannot determine whether individual finger or coordination variability develops first.

Since intrinsic visual and auditory feedback do not have an influence on self-selected frequency finger tapping, other sensory modalities such as touch or proprioception must be critical in maintaining accurate and/or consistent rhythms. Studies of adults with somatosensory deafferentation (peripheral loss of tactile and proprioceptive afferents) support this view. These patients can produce desired values of ITI in unilateral repetitive tapping regardless of the visual or auditory feedback conditions but their performance is more variable when compared to the controls (Billon, Semjen, Cole, & Gauthier, 1996). Studies with this patient population also suggest that during bilateral repetitive tasks, temporal coupling between the hands compared to unilateral tapping, is achieved in the absence of somatosensory feedback (Spencer, Ivry, Cattaert, & Semjen, 2005) and this bimanual advantage was independent of additional somatosensory feedback (Drewing, Stenneken, Cole, Prinz, & Aschersleben, 2004). Thus, these deafferented patients had accurate coordination but were more variable. The above studies used synchronization or continuation paradigms which do not require that the subject match an internal template. Nevertheless, the results support a case for concluding that proprioceptive and/or somatosensory information is needed to fine-tune the sensorimotor mapping to achieve less variable performance. Further investigation is needed to establish whether children with DCD would benefit from enhanced tactile and proprioceptive information and/or whether the loss of this information causes a decrement in performance. In addition, further investigation is necessary to determine whether children with DCD can benefit from intense guided practice, indicating a developmental delay in fine-tuning a sensorimotor map or whether they will remain less accurate and/or more variable (atypical development) indicating an ill-formed map that will never acquire adult-like properties.

In conclusion, we demonstrated that children with DCD adopt similar frequencies but are less accurate and more variable in timing and coordination than TD children in bilateral self-paced finger tapping. We also determined that concurrent visual and/or auditory feedbacks are not critical to performance of this task in any group. A few children with DCD were

even less accurate and more variable when vision was available while others performed similarly to TD children.

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Fig. 1.
Coefficient of variability of the intertap interval (CVITI) collapsed across sensory conditions for Adults, TD control and DCD groups.

Fig. 2.
Mean relative phasing between the fingers (RP) collapsed across sensory conditions for Adults, TD controls and DCD groups.

Fig. 3.

Mean variability of phasing (*SDrp*) within a trial for each sensory condition each sensory condition for adult, TD control and DCD groups. Regardless of the sensory conditions, there was significant difference between the adults, TD controls and DCD groups.

Fig. 4.

Individual comparison between children with DCD and their matched controls on Mean variability of relative phasing (SD) across the different sensory conditions: 1. No visual but auditory feedback present (NVA), 2. No visual or auditory feedback (NVNA), 3. visual and auditory feedback present (VA), and 4. visual feedback but no auditory feedback (VNA). Dotted line represents $+1 SD$ while the dashed lines represent $+2 SD$ around the SD of the TD children.

Table 1

Age, gender, MABC impairment score and percentile for children with DCD and TD group

Subject	Children with DCD			Typically developing Children		
	Age	Sex	MABC	%ile	Age	Sex
1	6.73	F	25.5	<1	6.33	F
2	7.16	F	16	2	7.18	F
3	7.23	M	28	<1	7.28	M
4	7.59	M	23	<1	7.62	M
5*	7.57	M	13	6	7.71	M
6	6.92	M	11	11	6.90	M
7	6.98	M	20.5	<1	6.86	M
8	7.13	F	16.5	2	7.08	F
9	7.26	M	10.5	13	7.61	M
10	6.67	M	15.5	3	6.01	M
Mean	7.12		17.95		7.06	
SD	0.3		6.06		0.56	

* Denotes having ADHD in addition to DCD

Table 2

Frequency of children with DCD (total $n = 10$) with values greater than 1 and 2 SD of TD mean in the four sensory conditions: vision and audition both available (VA), Vision available, no audition (VNA), no vision but audition available (NVA) and no vision or audition available NVNA.

A. CVITI				
CVITI	VA	VNA	NVA	NVNA
> 1 SD	7*	7*	5	5
> 2 SD	5*	4*	2*	2*

B. RP				
RP	VA	VNA	NVA	NVNA
> 1 SD	8*	6	3	5
> 2 SD	5*	5*	3*	3*

C. SDrp				
SDrp	VA	VNA	NVA	NVNA
> 1 SD	5	5	5	2
> 2 SD	2*	2*	2*	2*

* Significant chi-square results are indicated with.