ABSTRACT

Title of Dissertation: CONTINUOUS VERSUS DISCONTINUOUS DRAWING: POSSIBLE CEREBELLAR INVOLVEMENT IN THE DEVELOPMENT OF TEMPORAL CONSISTENCY

Jin Bo, Doctor of Philosophy, 2006

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The capability to generate drawing and writing movements of high spatial and temporal qualities is one of the most important developmental achievements during the early school years. Recently, Spencer et al., (2003) proposed that the cerebellum controls the ‘explicit timing’ underlying temporal consistency during discontinuous drawing, but not ‘implicit timing’ during continuous drawing. Alternatively, the cerebellum might be involved in the control of limb dynamics, which differ between continuous and discontinuous drawing (Bastian et al., 2000). In the current study, we examine the hypothesis that the developing cerebellum might play an important role in the development of temporal consistency in drawing skills in children. Specifically, we examined: 1) whether there were age-related differences between continuous and discontinuous circle drawing, 2) whether the children's performance in the circle drawing tasks was the same as their performance in the dynamically simpler line drawing tasks, and 3) whether children with Developmental Coordination Disorder (DCD) performed similarly to the children who were typically developing in these four types of movements.

Thirty-two children who were typically developing between the ages of five and eleven years[1] and ten children with DCD performed the continuous, discontinuous circle- and line-drawing tasks in random order. Participants were asked to move as consistently as possible for 20 seconds after synchronizing their movements with a metronome for 15 beats. Regression analysis in children who were typically developing showed that high temporal variability existed only in the discontinuous circling in the youngest children but not the older children. Children with DCD showed a similar pattern to their age- and gender-matched controls. However, individual comparison for each child with DCD and normal performance defined by children who were typically developing revealed that two of the ten children with DCD showed timing deficit in the discontinuous movements, an additional three children had timing problem in the discontinuous line drawing. Limb dynamic control played an important role in the development of drawing skills in children. The possibility of a compromised cerebellar function may only exist in a subgroup of children with DCD supporting others observation of the heterogeneous nature of this population.

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[1] Ten of these thirty-one were gender- and age-matched controls for the comparisons with the children with DCD.

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by

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CHAPTER I

INTRODUCTION

To reach successfully for an object is one of the most important developmental achievements in infancy. The attainment of this milestone represents the infant's ability to coordinate the perception of the world with the body's action. In the ensuing years, this rudimentary hand-eye coordination develops into more precise and complex movements. By the end of their first year, infants can successfully reach and grasp visually presented toys. Soon after, children are able to grab writing implements (e.g. crayons) and produce random scribbles, which will in a few years result in meaningful and organized forms and symbols leading eventually to tool use, the use of gesture movements and the production of complex hierarchical motor behaviors. How children develop the ability to produce these exquisitely timed complex hand movements is the focus of this dissertation.

The child's first attempt at drawing usually occurs around the age of 15 month with spontaneous scribbling (Kellogg, 1969). By the age of two, children can crudely draw circular, vertical, and horizontal lines that follow the appropriate direction (Knobloch & Pasamanick, 1974). However, the quality of the performance may vary considerably. It is not until the late school years that consistent drawing and writing patterns emerge (Hamstra-Bletz & Blote, 1990). From these random scribblings to consistent writing patterns, we see that children's motor skills dramatically change. How do these changes occur? What underlies these changes?

In the last half-century, there have been several hypotheses in the motor control literature offered to explain the development of drawing and writing skills. The first explanation offered was by Hay and her colleagues (Hay, 1984; Hay, Bard, & Fleury, 1986). They argued that what changed between the ages of five and ten years was how children used movement feedback. In their studies (Hay, 1979; Hay et al., 1986), they found that children around seven and eight years of age were more feedback dependent than children older or younger who depended less on feedback information. On the other hand, Van Galen and colleagues (van Galen, Portier, Smits-Engelsman, & Schomaker, 1993) argued that it was the continuously decreasing neuromuscular noise that caused the writing pattern to change developmentally. A third argument, and one offered by our research group emphasized the progressive and adaptive 'fine-tuning' that resulted in these developmental changes (Contreras-Vidal, Bo, Boudreau, & Clark, 2005). While differing in emphasis, two of the explanations (Hay's and our group's) point to the developing ability of the child to use sensory information to better control limb movements. This focus on fine-tuning the sensorimotor relationship might implicate developmental changes in the cerebellum.

Fine-tuning and coordination have been considered one of the major functions in the cerebellum (Thach, 1998). A number of behavioral and brain imaging studies (Ghilardi et al., 2000; Imamizu et al., 2000) have shown that the cerebellum is heavily involved in sensorimotor tasks which require fine-tuning and online adjustment, such as required in gradual adaptation tasks. Robertson and Miall (1999) have reported that adaptation to gradual visual distortion is blocked by inactivation of the dentate nucleus, one of the cerebellum's deep nuclei. Tasks in which the adaptation is sudden, however, may employ different neural circuits. Contreras-Vidal and Buch (2003) have argued that the basal ganglia is involved more in sudden adaptation tasks whereas the cerebellum plays a more central role in the fine-tuning seen in gradual adaptation tasks. In healthy adults, it has been shown that gradually increasing perturbations of visual feedback allows for a more complete adaptation than a large, sudden distortion onset (Kagerer, Contreras-Vidal, & Stelmach, 1997). In a previous study (Bo, Kagerer, Contreras-Vidal, & Clark, 2004), we examined the adaptation to sudden and gradual visuomotor distortions in children between the ages of 4 and 10 years in a point-to-point drawing task. For the children, no differences were observed between gradual and sudden adaptation. These findings led us to question a possible role of the cerebellum in motor skill development in childhood.

Indeed, there is support for the role of the developing cerebellum in the development of sensorimotor skills in animal studies. For example, under-nutrition during the brain growth spurt period in rats lead to a smaller cerebellum containing less neuronal and glia cells, less synapses and decreased myelination, whereas other parts of the brain were less seriously affected (Gramsbergen & Westerga, 1992). In addition, the rats had retarded and prolonged transition from immature locomotion and showed long-lasting signs of clumsiness. In another study (Gramsbergen, 2003), dexamethasone injected into young rats during the last-trimester (cerebellum maturation stage) induced long-lasting abnormalities during the development of walking including postural tremor and clumsiness. These results from animals suggest that disturbed cerebellar development may be an important factor in clumsiness in motor development.

In humans, it has been shown that the cerebellum develops slower and later than most other brain areas. Anderson (2003) has reported that the cerebellum and hippocampus have longer maturational cycles than the sensory cortices. Longitudinal cerebral magnetic resonance imaging of 259 subjects from age 4 to 20 years revealed that the cerebellum volume matures later than other brain areas (Giedd et al., 1996). Cerebellar volume peaks at approximately age 19 compared to a peak in total cerebral volume at approximately age 16 years. These anatomical studies suggest that cerebellar function is not fully developed during childhood.

While there are several extant theories of cerebellar function in motor control, the focus in the current study is on the 'timing' hypothesis. The cerebellum is proposed as the generator of temporal patterns (Llinas, Leznik, & Makarenko, 2002; Yarom & Cohen, 2002). The high synchronous discharge in the inferior olive during rhythmic, coordinated movement suggests that the inferior olive organizes movement in time, by entraining motor neuronal firing through rhythmic activation of the cerebellum (Welsh, Lang, Sugihara, & Llinas, 1995). Braitenberg (1997) has proposed that the long parallel fiber beams are the fundamental structures of the cerebellum that control the timing sequence during coordinated movements. Ohyama and Mauk (2001) have reported corresponding activations between Purkinje cells and the interpositus nucleus in eye-blinking. The cerebellar cortex appears to be required for the precise timing of the conditioned response. Permanent or reversible disconnection of the cerebellar cortex severely disrupts response timing. These neuronal-based findings suggest that the cerebellum is very critical for timed movements.

Numerous studies have reported that patients with cerebellar lesion have a deficit in various timing tasks (Franz, Ivry, & Helmuth, 1996; Ivry & Hazeltine, 1995; Zelaznik, Spencer, & Ivry, 2002). Recently, Spencer et al., (2003) have reported that patients with cerebellar damage have deficits in performing fast circle drawing movements. Interestingly, their reports showed that these deficits were restricted to discontinuous movements, which required initiation and termination for each circle. However, when these patients produced continuous, rhythmic movements, they had no difficulty (as measured by temporal variability). They argued that the discontinuous circling movement required an ‘explicit’ representation of the temporal goal (i.e. when to start and stop), and that the lesion of the cerebellum played a key role in this movement deficit (Spencer, Zelaznik, Ivry, & Diedrichsen, 2002; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). They hypothesized that there are separate timing mechanisms for drawing tasks: an ‘explicit timing’ process involved in the timing of the occurrence of events (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002) and ‘implicit timing’ that is an emergent property of the trajectory throughout a drawing. Based on this hypothesis, continuous drawing would require implicit timing while discontinuous drawing would require explicit timing process.

Similarly, higher variability in discontinuous movements is also reported in the development of writing in children. Wann et al., (1991) reported that children from 2nd to 6th grade have more difficulties in the discontinuous writing pattern. They asked children to perform discontinuous loops (i.e. garlands: counter-clockwise circling, similar to the letter ‘u’, and arcades: clockwise circling, similar to the letter ‘n’) and continuous loops (similar to the letter ‘l’). The discontinuous garlands and arcades showed much higher irregularity and movement time than the continuous loops (Wann, Wing, & Sovik, 1991). Similarly, Thomassen (1983) reported that 7-year-olds could write continuous loops (the letter ‘e’) better than writing waves (the letter ‘w’) and sawtooth shapes (similar to the letter ‘u’). These behavioral similarities between cerebellar patients and children give rise to questions as to whether there is a relationship between the development of 'explicit timing', as proposed by Spencer et al (2003), and the development of drawing and writing skills in children? Unfortunately, while many drawing and writing studies have been done for teaching purposes, few studies have addressed the issue of how these behavioral changes relate to the development of brain function in childhood.

In addition, a number of studies have been reported that children who are classified as 'clumsy' have deficit in multiple cerebellar timing tasks (Geuze & Kalverboer, 1987; Lundy-Ekman, Ivry, Keele, & Woollacott, 1991; Williams, Woollacott, & Ivry, 1992). Clumsy children were significantly more variable than normal children in maintaining a set rate of tapping and in accurately judging time intervals (Williams, Woollacott, & Ivry, 1992). A subtype of children with Developmental Coordination Disorder (DCD[2]) were also reported to have higher timing variability in repetitive hand tapping, foot tapping, and jumping in place (Parker, Larkin, & Wade, 1997). Interestingly, although numerous findings have pointed to the contribution of cerebellar timing function to developmental problems, few studies have evaluated the role of timing on motor skill development. Smits-Engelsman and colleagues (Smits-Engelsman, Niemeijer, & van Galen, 2001) have claimed that writing difficulties are the most common problem in children with Developmental Coordination Disorder. To our knowledge, no studies have examined the timing in drawing and writing tasks in children with and without DCD.

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[2] I use this term: Developmental Coordination Disorder (DCD) in this dissertation. This is a diagnosis based on American Psychiatric Association's Diagnostic and Statistical Manual of Mental Disorders IV or the DSM IV (1994)

An alternative to the ‘explicit timing’ explanation is the hypothesis that limb dynamics between continuous and discontinuous drawing are different such that discontinuous movement is biomechanically more difficult. It is more challenging to turn on and off certain muscle groups in a movement requiring intermissive initiation and termination compared to continuous movement. This dynamic difficulty becomes even more challenging during multiple-joint movements, such as in discontinuous circle drawing. The complex dynamics (e.g., the interaction torques in controlling multijointed movements) have also been proposed as one of major cerebellar functions (Schweighofer, Arbib, & Kawato, 1998; Schweighofer, Spoelstra, Arbib, & Kawato, 1998). Patients with cerebellar lesion can make almost normal single-jointed movements, but they have problems in multiple-jointed movements (Bastian, Zackowski, & Thach, 2000). In a recent study (Bo, Block, Clark, & Bastian, 2005), we found that cerebellum patients showed higher temporal and spatial variability in discontinuous circling compared to continuous circling, but both types of circling were more impaired on temporal consistency when compared to age-matched controls. Does the ‘dynamics’ of the movement play a partial role in children? This alternative hypothesis, which is also proposed as a major function of cerebellum, may also help us understand the development of temporal consistency in children.

The purpose of this dissertation

The purpose of this dissertation was to examine the development of temporal consistency in continuous versus discontinuous drawing in children 5 to 10 years of age. The current research provided a ‘developmental landscape’ for typically developing children (i.e. a characterization of children’s performance over this age range) as well as examined and compared the performance of children with Developmental Coordination Disorder (DCD) to the typically developing children. This research was motivated by the hypotheses about the role of the cerebellum in discontinuous and continuous drawing tasks. While our approach was behavioral, we expected our results to provide a foundation for understanding better the possible role of cerebellar development in the development of temporal consistency in drawing and writing skills. In addition, as a first step to examine the hypothesis that cerebellar dysfunction might be a major contributor for the timing deficit in some children with DCD, we used the continuous versus discontinuous drawing paradigm (Spencer et al., 2003) to explore the linkage between ‘explicit timing’ and temporal control in drawing and writing movements.

This dissertation had three specific aims:

Specific Aim 1. To determine whether there were age-related differences between continuous and discontinuous circle drawing.

Spencer et al., (2002) have proposed that the temporal control of hand movements can be achieved in two different ways: an explicit timing process which guides the movements by maintaining a representation of the temporal goal, and an emergent implicit timing process that arises from trajectory formation. It has been found that patients with cerebellum lesions have deficits in discontinuous circling, which require an ‘explicit timing process’, but not continuous circling (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). Will children maintain temporal and spatial consistency in the discontinuous circle drawing compared to the continuous circle drawing as adults do? The first aim established a developmental landscape for temporal and spatial controls in these two types of drawing movements.

Hypothesis 1: Younger children will have higher temporal and spatial variability than older children in the discontinuous but not the continuous circling; with increasing age, children will maintain their temporal and spatial variability in both movements.

Specific Aim 2. To determine whether the children's performance in the circle drawing tasks (Aim 1) was the same as their performance in the dynamically simpler discontinuous and continuous line drawing tasks.

It has been found that the timing process for line and circle drawing is the same in adults (Spencer & Zelaznik, 2003). Based on the 'explicit timing' hypothesis, we should expect to replicate the same results between line and circle drawing in children. Alternatively, the temporal differences between continuous and discontinuous circling could be due to the more difficult dynamics of discontinuous movements (Bo, Block, Clark, & Bastian, 2005). In Aim 2, we tested the age-related differences in line drawing movements, which were considered dynamically simpler than circle drawing. Experimentally, we controlled the number of joints so that only the elbow was involved in the line drawing. If the movement dynamics were also playing a role, the performance in the line drawing would be different from that observed in the circle drawing.

Hypothesis 2: The temporal variability between the discontinuous line and circle drawing will not be significantly different based on the 'explicit timing' hypothesis. Alternatively, if the 'dynamics' hypothesis plays a role, the temporal variability in the discontinuous circle drawing would be higher than that in the discontinuous line drawing. The temporal variability in continuous circle drawing will be higher than that in the line drawing.

Specific Aim 3. To determine whether the pattern of results found in children who were typically developing, for continuous, discontinuous circle and line drawing (Aim 2) were the same for age-matched children with DCD.

A body of research has shown that the cerebellum is linked to a number of developmental disorders. It has been reported that children classified as ‘clumsy’ show much higher variability in maintaining a set rate of tapping and in accurately judging time intervals, which would indicate possible cerebellar timing control problems (Dewey, 1994; Williams, Woollacott, & Ivry, 1992). Moreover, ‘clumsiness’ is applied to a heterogeneous population. It is very possible that cerebellar dysfunction might be present in one subgroup of clumsy children and absent in other subgroups. While most of these studies have simply compared children with developmental disorders to age-matched controls, few studies have tested their developmental level individually. In Aim 3, we examined whether children with DCD perform similarly to children who were typically developing in continuous, discontinuous circle and line drawing (Aim 2) and tested with regression techniques their developmental level compared to children who were typically developing.

Hypothesis 3a: We predicted that children with DCD would have much higher temporal and spatial variability in discontinuous circling and line drawing than children who were typically developing at the same age level.

Hypothesis 3b: Due to the heterogeneous population of children with DCD, we expected that some of the children with DCD would demonstrate higher temporal and spatial variability than the children who were typically developing while others would not. A confidence interval will be calculated to define the range of normal performance using regression analysis on children who were typically developing.

Summary

In summary, the current study examined the development of temporal consistency in drawing and writing skill and the possible implication of these results for cerebellar functional development in childhood. The reported difficulty in performing discontinuous movements in cerebellar patients may shed some light on children's performance in writing discontinuous and continuous patterns. This work is one of only a few studies to provide behavioral evidence that would point to a possible relationship between brain development and motor skill development. It also sets a foundation for understanding the underlying mechanisms of children with DCD.

In the following chapters, a comprehensive literature review is presented in Chapter II. The first experiment is reported in Chapter III, "Continuous and discontinuous circle and line drawing: High temporal variability exists on in discontinuous circling in young children". The second experiment is described in Chapter IV: "Temporal consistency in children with Developmental Coordination Disorder during continuous and discontinuous drawing: Possible cerebellar involvement". The last chapter (V) is a general discussion of the results of this dissertation and the future directions for this line of research.

CHAPTER II

REVIEW OF RELEVANT LITERATURE

Soon after birth, infants demonstrate well-coordinated sensory-motor behaviors. For example just a few days after their birth, newborn human babies consistently turn their heads toward a patterned visual stimulus rather than toward a plain gray stimulus (von Hofsten, 1992). Later, other more complex sensory, motor, and temperament patterns emerge. By about one year, the infant is able to walk independently as well as feed him/herself. From an infant who can barely lift his/her head to an adult driving a car on a snowy road, our motor skills dramatically changed. These changes across the lifespan and how these changes occur are the central focus of motor development (Clark & Whitall, 1989).

In this dissertation, development of visuomtor coordination during childhood is used as a window to understand not only what changes during development (i.e. the product), but also the processes underlying these changes. Our daily activities contain many skills based on the visuomotor coordination, e.g. reaching, pointing, drawing, tracking, painting, writing, and catching. All these skills require the fundamental ability to coordinate the sensory information (e.g. vision) with the motor action. Therefore, an important question is how the elementary visuo-motor coordination "develops" into skillful complex movements?

In this chapter, a comprehensive literature review is presented. The first section is a brief overview of motor control for visuomotor coordination, with emphasis on the development of hand-eye coordination in children. The second section is a general review of brain development. In particular, the focus is on cerebellar development, including its structure, function and the role it might play in motor development. In the third section, the correlation between cerebellum and movement disorders is presented with a focus Developmental Coordination Disorder (DCD) in visuomotor coordination tasks. In the last section, the significance and the conceptual framework for the current study are discussed.

Development of visuomotor coordination in children

Many concepts on visumotor coordination have been proposed in last century. For the purpose of this dissertation, we only briefly outline the essentials as a background to introduce the development of visuomotor coordination in childhood. In this section, three main approaches related to the development of visuomtor coordination are briefly introduced first. Then, we have detail reviews on each of these three approaches. At the end, some other studies that are also related to the visuomotor coordination are reviewed.

Among extant theories on motor control and development, the control system perspective is one of the predominant behavioral perspectives addressing how the nervous system produces coordinated movement. There are two principal control mechanisms on this perspective: one is a feedforward, the other is a feedback mechanism. It has been proposed that that two subcomponents on movement velocity time series during aimed reaches reflect these two processes: 1) the initial ballistic phase (primary movement) based on movement planning that guides the movement toward the target (feedforward mechanism) , and 2) the final corrective phase (secondary movement) based on feedback where adjustments are made (feedback mechanism) (Meyer, Kornblum, Abrams, Wright, & Smith, 1988). Comparing the velocity profiles between children and adults, adults have a smooth bell-shaped profile while children have a shorter, more variable ballistic phase and a longer corrective phase (Yan, Thomas, Stelmach, & Thomas, 2000).

The concepts of forward/inverse internal model are another way to describe the relationship between motor planning and control. Within these conceptual frameworks, internal models are neural mechanisms that can mimic the input/output characteristics, or their inverses, of the motor apparatus (Kawato, 1999). Forward internal models predict sensory consequences from efference copies of issued motor commands. Inverse internal models, on the other hand, calculate necessary feedforward motor commands from desired trajectory information. In order to achieve a skillful level of visually directed arm movements, a transformation of visual information about hand and target positions into appropriate motor commands is required. This transformation can be conceptualized as an internal model or map of the relationship between ‘visual space’ and ‘motor space’. We have focused on this approach to understand the development visuomotor coordination in children (Contreras-Vidal, Bo, Boudreau, & Clark, 2005).

Along the same line of control system theory, van Galen et al. (1990) have proposed that there are three processes to control drawing and writing movements. First, the motor program defines the appropriate motor planning. Once certain motor program is selected, the system needs to calculate certain kinematic and dynamic variables to control the movement. This is called parameterization (e.g. force, speed, size). After the motor program and the parameterization, the neuromuscular system needs to implement previous planning and control variables to make the final movement. This is called muscular initiation. In the handwriting literature, this three-step model has been used to test the development of drawing skills. It is claimed that children's performance is limited by high neuromuscular noise level (Smiths-Engelsman et al., 1997).

Although there are other concepts in control system theory that may relate to the visuomotor coordination, these three approaches (1. feedforward/feedback; 2. forward/inverse internal model; 3. neuromuscular noise) are the most influential ones on understanding the development of visuomotor coordination in children. In the following paragraphs, we will have a detailed review on each of these approaches.

Feedforward/feedback mechanism

With respect to the feedforward/feedback concepts, Hay and her colleagues (1979; 1984; 1991) have argued that there is a discontinuity in the development of feedback control in childhood. Children around seven and eight years of age are more feedback dependent while children older or younger depend less on feedback information. In a prism adaptation study, Hay (1979) reported that 5-year-olds demonstrated more programmed movement, whereas 7-year-olds used feedback corrections, 9- and 11- year-olds demonstrated an integration of both modes of control. In 1991, Hay et al. (1984) studied the velocity patterns of aimed movements to visual targets in children aged 6, 8 and 10 years of age. The results showed that the 8-year-olds had a greater propensity to use feedback control while children older or younger than 8-year-olds used more ballistic movements. In a computer-manipulated adaptation study, Ferrel et al. (2001) suggested that children at 8 years of age showed a shift from unidirectional to bi-directional representation in the development of visual-guided reaching. Therefore, it has been argued that development is non-monotonous with a transition at age around eight. Interestingly, in their recent study (Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002), results showed that 5-, 7- and 9-year-olds made more corrections than 11-year-olds and adults, which would suggest that children from 5 to 9 years of age relied more on visual feedback than older children. They did not explain the disagreement between their previous and current results as well as their claim of discontinuity of feedback control in childhood.

Others have also challenged Hay's specific interpretation because they were unable to reproduce the alleged predominance of the ballistic mode in 5-year-olds compared to the older children. Pellizzer and Hauert (1996) argued that the drop in accuracy between 7 and 8 years reflected a reorganization of the sensorimotor mapping associated with cortical maturation and that it occurred only in open-loop conditions. Indeed, comparison between 7-year-olds and adults revealed a monotonic decrease in movement time suggesting that the amount of online programming and feedback processing did not change from age 7 onwards.

Several other reaching studies (Thomas, Yan, & Stelmach, 2000; Yan, Thomas, & Thomas, 1998; Yan et al., 2000) on movement subcomponents support the linear improvement in development of visuomotor coordination in childhood. A recent study (Thomas et al., 2000) on the effect of practice on the movement subcomponents of children found that: younger age children had less initial planning of the primary movement than older children between age 6 and 9 years of age. All participants increased the primary movement as a function of practice; however, the increases were substantially larger in the children (25-30%) than in adults. These findings indicated that practice could help younger children become less depend on visual feedback and improve the planning of the primary movements. With practice, the primary movement was lengthened so that it ended nearer the target in children. The increment in distance and duration of ballistic primary sub-movements and decrement in distance and duration of corrective secondary sub-movement were related to the improved programming occurred with practice.

Inverse/forward internal model

With respect to the concepts of inverse/forward model, we focused on the questions how children were able to adapt (i.e. update their internal model) to make accurate straight movements when the relationship between the visual space and motor space is manipulated (Contreras-Vidal et al., 2005). Children between 4 and 8 years of age were asked to draw a straight line between two points in the horizontal plane under normal (pre-, and post-exposure), and rotated (exposure) visual feedback on a computer monitor in the vertical plane. The older children moved straighter and less variably than the youngest children in the baseline condition. When the relationship between hand path and visual feedback was rotated 45°, all age children were able to adapt after 60 trials of practice. However, the after-effects were only significant in the eight-year-olds. This led the investigators to suggest that the youngest children had broadly tuned visuo-motor mapping while older age children had more finely-tuned visuo-motor mapping between the visual-spatial signals and motor commands. In other words, the visuo-motor internal representation was not yet fully developed in the younger children. For example, when children performed in the 45° visual distortion conditions, targeted movements fell well within the width of the children's visuo-motor directional 'range' for a particular target direction. Thus, in the younger children, it is very possible that the directional errors were not "detected" and remained uncorrected. Only older children (the 8-year-olds) were able to update their visuo-motor mapping between indirectly presented visual information and initial trajectory planning. These results suggested that the acquisition of fine-tuned visuo-motor relationships were a developmental achievement in tasks requiring indirect transformations between a visual display and movement.

In our follow-up study (Bo, Contreras-Vidal, & Clark, 2003), we want to further understand whether the same developmental trend presents in more familiar environment rather than a relative “novel” setup, where the sensory information is not directly presented in front of the children. The purpose of this study was to examine age-related effects on arm movements when the complexity of the visuo-motor transformation increases. Children did the same “center-out” task under three different conditions in terms of spatial relationship between movement space and visual feedback space: a) Normal transformation: Participants made arm reaches with the target, line path and hand position fully visible. (b) Aligned transformation: Participants saw the target and line path through a mirror mounted on the horizontal level without vision of their arm/hand positions. And (c) Vertical transformation: Participants saw the target and their movement paths presented on a computer monitor in the vertical plane, but their arm/hand movements were not visible. As expected, with increasing age, the children’s movements became faster, less variable, and smoother. The length and time of the first sub-movement also increased with age. With increasing complexity of the visuo-motor transformation, movement planning as measured by initial directional error (IDE) revealed that all participants made more errors in directional planning in the vertical transformation than in the other two conditions. However, the variability of the

IDE revealed age-related differential effects across the three transformation conditions indicating that with increasing age, participants were less variable in their initial reach direction.

Similarly, less well tuned internal models were also reported in a study on the development of dynamic control, using force adaptation (Jansen-Osmann, Richter, Konczak, & Kalveram, 2002), thirty children from 6-year-olds to 10-year-olds and ten adults performed 30° elbow flexion movements under two conditions of external damping (negative and null). The study examined how learning a force field in one hemifield of the right arm workspace affected the force adaptation in the other hemifield. Younger age children had prolonged re-adaptation back to a null-force condition after they showed aftereffects, which suggested that neural representation of limb dynamics (e.g. inverse dynamic model) in children lacked precision.

Taken together, these results suggest that with increasing age, visuomotor tuning is progressively sharpened and children's ability to perform visuomotor transformations improves, which further support the gradual improvement interpretation on development of visuomotor coordination in childhood.

Neuromuscular noise

Recently, the importance of the neuromuscular noise in development of visuomotor coordination has been reported. Using the concepts of internal model, Takahashi et al, (2003) claimed that children's motor performance was limited by an inherently higher level of movement variability, but that their motor adaptive ability was robust to this variability. They examined motor adaptation of 43 children (ages 6–17) and 12 adults as they reached while holding the tip of a lightweight robot. The robot applied either a predictable, velocity-dependent field (the “mean field”) or a similar field that incorporated stochastic variation (the “noise field”), thereby further enhancing the variability of the subjects’ movements. It was found that children exhibited greater initial trial-to-trial variability in their unperturbed movements but were still able to adapt comparably to adults in both the mean and noise fields. Furthermore, the youngest children (ages 6–8) were able to reduce their variability with practice to levels comparable to the remaining children groups although not as low as adults. However, performance after adaptation is still more variable than in adults, indicating that movement inconsistency, not motor adaptation inability, ultimately limits motor performance by children and may thus account for their appearance of in-coordination and more frequent motor “accidents” (e.g., spilling, tripping). Based on these findings, the authors claimed that the decreasing neuromuscular noise is one of the key factors in the development of visuomtor coordination.

The argument of neuromuscular noise can be also found in the drawing and handwriting literature. The three-step process was one of approaches used to understand the development of drawing skills as well as children with writing difficulties. Van Galen’s three step model (1. motor program, 2. parameterization (e.g. force, speed, size), and 3. muscular initiation) was proposed to understand which control process is more critical to the development of drawing skills. It is based on the method of the power spectrum density (PSD) analysis in the kinematic velocity time series. The high frequency band in the PSD analysis was found in the younger children but not in the older children (van Galen, Portier, Smitsengelsman, & Schomaker, 1993). The authors claimed that performance changes in children were related to the neuromuscular noise rather than the previous planning period. Smiths-Engelsman (1997) tested two groups of children between 7- and 11- year-old (poor and proficient writers) writing ‘mmm’, ‘eeee’, versus ‘meme’, ‘eenn’ tasks. Results showed that younger children moved much slower in strings of varying letters than same letters. PSD analysis on velocity profiles showed higher noise level between 5.5 to 8 Hz in the poor handwriters suggesting the muscular initiation problem during the writing processing. One-year follow up showed that poor writer had not improved compared to age-matched controls. Similarly Van Galen (1993) reported that the children with poor handwriting had higher noise frequency. Using their model, the major processes that caused writing problems were neuromuscular noise.

Besides handwriting, Smits-Engelsman et al., (2001) reported the fine motor deficiencies in children with DCD (more details in the later section) in ‘flower-trial drawing’ task, one of the items in Movement ABC test. The results revealed that 34% of the group of 125 children displayed handwriting problem using concise assessment method for children’s handwriting (BHK) and school questionnaire for teachers (SQT). The kinematic analysis showed that serious handwriting problems were accompanied by fine motor deficits. Again, they claimed that an enhanced level of neuromotor noise was compensated for by enhanced phasic stiffness of the limb system, which resulted in higher movement velocity and fewer velocity peaks in children with DCD.

Besides the studies focusing on these three approaches under the control system perspective, there are other approaches in the motor control literature. For example, optimization control models are also very common in the studies of development of visuomotor coordination (Berthier, 1996; Bourgeois & Hay, 2003; Jordan, Flash, &

Arnon, 1994; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002). Other major perspectives in this area are dynamic system perspective, perception-action perspective, information-processing perspective. In current review, we only list some of them that relate to my dissertation focus.

<u>Others: descriptive studies</u>

Beyond the studies on developmental processes, descriptive studies may also shed some light on the understanding of both the product and the process of the development of visuomotor coordination. In the handwriting literature, many studies have been done with the goal to improve the teaching methods. However, there are some interesting patterns that may also help us to understand what change and how these changes occur.

Hamstra-Bletz and Blote (1990) reported a longitudinal study describing the development of handwriting in primary school children. One hundred and twenty-seven pupils were rated yearly starting in 2nd grade, and then followed-up for 3, 4, or 5 years. The BHK scale (Hamstra-Bletz & Blote, 1993) for children's handwriting was used for rating the scripts on 13 characteristics. These 13 characteristics were clustered into different aspects: 1) development of fine motor ability including bad letter/word alignment, irregularities in joins, inconsistent letter size and unsteady writing trace; 2) stylistic preference including absence of joints, collision of letters; 3) structural performance including insufficient word spacing, acute turns in connecting joints to letters, and ambiguity letter forms. Results showed that the handwriting was poor in dysgraphic children with respect to the structural performance but not the others (Hamstra-Bletz & Blote, 1990; Hamstra-Bletz et al., 1993). Based on these 13 characteristics, two major aspects could be identified: temporal variability and spatial variability that were unique to the writing movement. Within temporal variability, acute turns in connecting joins to letters, irregularity in joins and absence of joins could be considered lack of smoothness during conjunctions. Within spatial variability, three sub-categories could be identified: 1). Writing size/scaling included writing too large, inconsistent letter size, and incorrect relative height of the various kinds of letters; 2). Writing orientation included bad letter/word alignment, collisions of letters, unsteady writing trace, insufficient word spacing and collisions of letters; 3). Word form included letter distortion, ambiguous letter forms, and corrections of letter forms. The results suggest that the temporal and spatial consistencies are two important characteristics for developing skilled writing.

Some other drawing and writing studies focus on how different types of writing pattern could affect the temporal and spatial measures. Wann et al., (1991) reported that children from 2nd to 6th grades had more difficulties in the discontinuous writing pattern. They asked children to perform discontinuous loops (i.e. garlands: counter-clockwise circling, similar to the letter ‘u’, and arcades: clockwise circling, similar to the letter ‘n’) and continuous loops (similar to the letter ‘l’). The discontinuous garlands and arcades showed much higher irregularity and movement time than the continuous loops (Wann, Wing, & Sovik, 1991). Similarly, Thomassen (1993) reported that 7-year-olds could write continuous loops (the letter ‘e’) better than writing waves (the letter ‘w’) and sawtooth shapes (similar to the letter ‘u’). Further, it has been reported that these fundamental writing units could in principle be drawn either clockwise (e.g. discontinuous arcades, letter n) or counter-clockwise (e.g. continuous and discontinuous garlands, letter e and u) (Moject, 1991; Sovik & Arntzen, 1991). Meulenbroek and van Galen (1986) found that counter-clockwise rotating patterns without acute angles (continuous garlands, letter e) were written at the highest speed and with a relatively high quality. The most difficult movement patterns were those where the direction of rotation alternated frequently, resulting in combinations of clockwise and counter-clockwise movements. All these evidences supported that continuous writing pattern seemed easier than the discontinuous writing pattern for children when they needed to stop during an ongoing movement.

Summary

In summary, different approaches have been used to answer the question what the underlying processes relate to the motor behavior change. Hay and her colleagues (1984) have argued that there is a discontinuity in the development of visuomtor coordination on feedback control in childhood. Children around seven and eight years of age are more feedback dependent while children older or younger depend less on feedback information. Van Galen and colleagues (1990) argue that it is the continuously decreasing neuromuscular noise that causes the writing pattern to change developmentally. We argue that the progressive ‘fine-tuning’ processes (i.e. refined sensory-motor relationship) is a developmental achievement since the young children can make accurate point-to-point drawing movement but with larger planning variability (Bo et al., 2003; Contreras-Vidal et al., 2005). All these arguments suggest that the development of visuomotor coordination is a complex process that may relate to multiple factors.

The role of cerebellum in movement control

Sensory-motor fine-tuning and coordination have been considered one of the major functions in cerebellum (Thach, 1998). Damage to the cerebellum disrupts the spatial accuracy and temporal coordination of movement. The cerebellum, in general, is considered to influence the motor systems by evaluating disparities between what movement plan and movement outcome, and by adjusting the operation of motor centers in the cortex and brain stem while a movement is in progress, as well as during repetitions of the same movement (Ghez & Thach, 2000). There are multiple theories and arguments existed on the role of cerebellum on movement control. Due to the interest of this dissertation, we start with the structure and function of cerebellum as well as current four major theories of cerebellum function. Then, brain development in childhood, especially the development of cerebellum is the focus.

Structure and function of cerebellum

Since neurons in the cerebellum are arranged in a highly regular manner as repeated units, the function of the cerebellum has been thought relating to its different connections using similar computational operation among each unit.

The cerebellum can be divided into four parts. Two longitudinal furrows distinguish three mediolateral regions that are functionally important: vermis, intermediate cerebellar hemisphere, and laterally hemisphere. The flocculonodular lobe is separated from the hemisphere.

The cerebellum connects to the dorsal part of brain stem by three symmetrical pairs of tracts: inferior cerebellar peduncle, middle cerebellar peduncle, and superior cerebellar peduncle. The inferior cerebellar peduncle carries input from the ipsilateral spinal cord, inferior olive and vestibular nuclei. The middle cerebellar peduncle accepts the corticopontine fibers contralaterally (from pontine nuclei). Cerebellum output flows through the superior cerebellar peduncle to the contralateral red nucleus and VL and VPL thalamic nuclei. Cells in the flocculonodular lobe project to the lateral and medial vestibular nuclei in the brain stem.

The output of the cerebellum projects to almost all components of the voluntary and postural motor systems. It is generated by the deep cerebellar nuclei and by the vestibular nuclei. There are three sets of cerebellar nuclei: Fastiguis, Interpositus (including two sets) and Dentates. Fastiguis receives inputs mainly from the vermal cerebellar cortex. Single unit recordings in the fastiguius and vermal cerebellar cortex in cats have shown neural discharge to be correlated with both walking and scratching movement (Andersson & Armstrong, 1987) suggesting that fastiguius nucleus is specific for the control of stance and gait. Further, the rostral fastigius might help control head orientation and combined eye-head gaze shifts. The caudal fastigius appears to be involved in oculomotor functions including saccade generation and smooth pursuit. Interpositus accepts inputs mainly from intermediate cerebellum. It’s firing is related to the antagonist muscle group being used. Monkey’s lesion studies showed that interpositus is most concerned with the balance of agonist-antagonist muscle activity of the limb as it moves. It is believed that anterior and posterior interpositus are involved in coordinating distal and proximal musculature together via climbing fiber input to Purkinje cells (Mason, Miller, Baker, & Houk, 1998). Dentate accepts major input from lateral cerebellum. Its cells preferentially fire at the onset of movements that are triggered by mental associations with either visual or auditory stimuli. It has been found that the dentate helps to initiate movements that are triggered by stimuli, which are mentally associated with the movement, while the interpositus is more involved in compensatory or corrective movements initiated via feedback from the movement itself (Thach , 1978). Further, both dentate and interpositus activity has been speculated to relate more to movements involving multiple joints than to movements involving single joints (Thach, Goodkin, & Keating, 1992).

As mentioned at beginning, the structures of cerebellar neurons are arranged in a highly regular manner as repeated units. And each part of the cerebellum hemisphere repeats with common three layers in all parts of the cerebellum: 1). Molecular layers: parallel fibers (excitatory axons of granule cells), dendrites of inhibitory Purkinje cells, inhibitory stellate cells and basket cells. 2.) Purkinje cell layer: Purkinje cell bodies. Output is entirely inhibitory GABA mediated. 3). Granular layer: granule cells (excitatory), Golgi cell (inhibitory).

Purkinje cells receive two afferent excitatory inputs and inhibited by three local interneurons. Two inputs are climbing fiber and mossy fiber. Mossy fibers carry sensory information from both periphery and cerebral cortex. They terminate as excitatory synapses on the dendrites of granule cells in the granular layer. The axon of the granule cells travel along in the molecular layer, thus exciting large numbers of Purkinje neurons (many-to-many connections). Purkinje cells receive a massive convergence of mossy fiber input (via parallel fibers), suggesting that they integrate or combine inputs from a variety of sources. Climbing fibers originate from inferior olivary nucleus and convey somatosensory, visual or cortical information. They wrap around the cell bodies and proximal dendrites of Purkinje neurons. The connection ratio is 1:1-10 between climbing fibers and Purkinje cell. The role of complex spikes during limb movements is currently a subject of debate. More discussion about these arguments will be introduced in the section of theories related to cerebellum function.

In summary, the different function in different parts of the cerebellum is related to different anatomical connections. But the role of the mossy fiber and climbing fiber across all parts of the cerebellum is debatable. In general, the major function for flocculonodular lobe is to regulate balance and eye movements. The major function for spinocerebellum (include vermis and intermediate) is to modulate the descending motor systems in brain stem and cerebral cortex. Vermis lesion produces disturbances principally in the control of axial and truck muscles during attempted antigravity posture, slow speech. Intermediate lesion produces action tremor of the limbs. The major function for the cerebrocerebellum (lateral cerebellum) is involved in movement planning and evaluating sensory information for action. Lesion of the cerebrocerebellum disrupts motor planning and prolongs reaction time. Lesion interferes with the time of serial events, it also affects the ability of judge elapsed time in purely mental or cognitive tasks (Bastian, Mugnaini, & Thach, 1999).

Theories related to cerebellum function

The wide breath of cerebellar function is somewhat surprising in view of the simplicity and homogeneity of the cerebellar cortex. Interestingly, multiple theories that related to cerebellum function have been proposed and debated for decades. I focus on four major theories of cerebellum function in current review.

Learning

According to the Marr-Albus-Ito motor learning theory, the cerebellum is the controller of movements that are made automatically (Albus, 1971; Ito, 1972; Marr, 1969). In general, the cerebellum gains this control through trial-and-error practice, linking a certain behavioral context to the movement response. Thach (1998) proposed that the learning process would entail stimulus-response linkage through trial and error learning, and would consist of groupings of single-response elements – motor and cognitive – into large combinations. After practice, the occurrence of a sensory or experiential ‘context’ would automatically trigger the combined response. The parallel fiber is the proposed agent of stimulus-response linkage and of combining the response elements. And the climbing fiber circuitry helps the modulation of parallel fiber circuitry activity. As new movement learnt, the selected/strengthened activity would drive the appropriate movement with the context.

Based on learning theory, two main cerebellar input system: the highly divergent-convergent mossy-fiber/parallel-fiber/Purkinje cell system brings information from most parts of the nervous system, and approximately one-to-one climbing-fiber/Purkinje-cell system arises exclusively from inferior olive, are playing very important roles. The mossy fibers bring vestibular, somatic, visual and auditory sensory information, and signals from sensorimtor cerebral cortex. Others carry information from prefrontal, premotor, and parieto-occipital association cortex. Mossy fiber information is conveyed to granule cells and their parallel fibers. The parallel fibers are so long that any one Purkinje cell could conceivably receive, via parallel fibers, accept information from all three medio-lateral zones. Such many-to-many input structure allows cerebellum detecting all sensory modalities including feedback and feedforward each element of movement. The fast frequent simple spikes found in Purkinje cells were proposed to set certain sensitivity as background to adjust movement. The climbing fiber input is very different from mossy fiber. A climbing fiber normally fires irregularly at very slow frequency. When a new movement needs to be learned or an old one adapted, the cerebellar learning theories predict that the climbing fiber would fire immediately after an error occurs, but only once, and that it would do this reliably each time the error occurs. The evidence of cerebellum learning is that the low-frequency but synaptically powerful climbing-fiber firing is found to reduce the strength of the synapse on the Purkinje cell of those parallel fibers that were active at the time (Albus, 1971). What would be left unaltered after practice, and repeated firing, would be those parallel fibers whose action caused a correct movement. In this way, the ‘corrected/learned’ parallel fibers were strengthened and remain strong in the appropriate movement context, while the climber fiber would returned to its slow maintained background firing after the previous error would be eliminated after learning.

In summary, the cerebellum gains this motor control through trial-and-error practice, and reaches the automaticity of skilled movement without worrying every single element of the movement. This theory is based on the climbing fiber system’s long-term depression on synaptic strength. Mossy fiber carries sensory motor information as a background while climb fiber carries the error signals to guide the appropriate activation to initiate and control the movement. As learnt, appropriate granule/parallel-fiber/Purkinje-cell synapses were strengthened and climbing fiber went to normal suggesting the automaticity of the movement without constantly think about the movement elements.

Dynamics-coordinator

The cerebellum was proposed to "coordinate" movements. Kawato and colleagues have proposed that the intermediate cerebellum learns an internal model of body mechanics, allowing the cerebellum to adjust for the complex dynamics (interaction torques) inherent in multijointed movement (Schweighofer, Arbib, & Kawato, 1998; Schweighofer, Spoelstra, Arbib, & Kawato, 1998). This model is based on the behavioral study that cerebellar patients are impaired in adjusting for interaction torques that occur during fast reaching movements (Bastian, Martin, Keating, & Thach, 1996).

Bastian and colleagues have focused on the question about the underlying mechanisms of cerebellar ataxia. Is the cerebellar ataxia caused by torque deficiency or torque mismatch (Bastian, Zackowski, & Thach, 2000)? In other words, is ataxia due to a general inability to generate sufficient levels of phasic torque inability or due to an inability to generate muscle torques that predict and compensate for interaction torques? Will reducing the number of moving joints by external mechanical fixation improve cerebellar subjects' targeted limb movements?

In order to answer these questions, Bastian et al (1996) have tested cerebellar patients reaching movement in two conditions: shoulder free and shoulder fixed. If the cerebellum plays the key role in the generation of muscle torque that predicts and compensates for interaction torques caused by other moving joint, the patients should have difficulty with fast movements that produce greater interaction torques because they cannot precisely activate multiple muscles to offset or accommodate the anticipated interaction torques. In this case, patients should perform better in the shoulder fixed condition because there is less compensation needed to worry about to make the better movement. Alternatively, if the cerebellum plays key role in quickly generating the appropriate muscle torque levels, patients should have a general deficit in producing phasic torques, which would account for their inability to offset interaction torques. In this case, the patients should have equally deficit in the fast reaching movement no matter whether the shoulder is free or fixed.

The results showed that the patients had greater endpoint error in the shoulder free condition than controls did. Cerebellar patients overshoot errors were largely due to unwanted flexion at the shoulder. The excessive shoulder flexion resulted from a torque mismatch, where larger shoulder muscle torques were produced at higher rates than would be appropriate for a given elbow movement. In the fixed condition, endpoint errors of cerebellar patients and controls were comparable. The improved accuracy of cerebellar patients was accompanied by reduced shoulder flexor muscle activity. The correct cerebellar trials in the shoulder fixed condition were movements made using only muscles that flex the elbow. The findings suggest that cerebellar subjects' poor shoulder control is due to an inability to generate muscle torques that predict and compensate for interaction torques, but not due to a general inability to general sufficient levels of phasic torques. In addition, reducing the number of muscles can help improve the cerebellar ataxia.

It is interesting that the cerebellar patient can improve their movement through slowing down the movement speed and decreasing the number of involved joints. The reason for slowing down explained in dynamic coordinator approach is to decompose the interaction torques. But there are other hypotheses to explain the speed issue in cerebellum e.g. timing for cerebellum is from millisecond to one second fast range but not for longer time range (Ivry & Spencer, 2004). It might be hard to tease apart these two possibilities because it is possible that the patients also use the decomposition strategy when slowing down.

The idea of control the dynamic interaction torques is in line with the automaticity idea in learning theory. In order to make an automatic skilled movement, one should not have to consider all the elements of the whole movement. In order to achieve such automaticity, the cerebellum should link certain behavioral contexts and multiple movement components through trial-and-error practice. When the cerebellum is impaired, such automaticity is compromised. One has to concentrate for each movement element, which is similar to the early stage of learning a new pattern of movement. The cerebellar deficit in interaction torque during multiple joint movement fits quite well into the learning theory.

Predictor

Prediction is very fundamental to many aspects of motor behavior, e.g. postural adjustment, tracking movement, rhythmic movement, and reach-grasp movement. It can be embedded in other functions as well, e.g. learning a new movement. One should be expected to make quite good prediction to achieve an automatic skill movement through learning. In the rhythmic movement, one should make quite planning prediction in order to follow the rhythm. Both parietal lobe and the cerebellum have been proposed to play important role in making sensorimotor prediction. Most of the modeling works are focus on the prediction in cerebellum. It has proposed that the CNS implements prediction by internal model: inverse models calculate the motor commands required to achieve a certain goal based on the desired state, forward models make predictions about the behavior of the motor system and its sensory consequences (Kawato & Wolpert, 1998; Wolpert, Miall, & Kawato, 1998). When a movement is made, an efference copy of the motor command, in combination with state variables such as the configurations of parts of the body, is used to make a prediction of the sensory consequences of the movement. This sensory prediction can be compared with the actual sensory feedback from movement and used to optimize motor control.

The cerebellum is acting as a component of a forward model system that provides rapid predictions of the sensory consequences of motor actions, which are compared with the actual sensory consequences. The main input in cerebellum, the climbing fibers from the inferior olive, has been proposed to act as a comparator between expected and achieved movement, signaling errors in motor performance (Thach, 1998). Then, how is the prediction related to motor learning in cerebellum? Motor learning can be achieved by comparing predicted consequences of an action to the actual results of the action adapting the prediction accordingly (Wolpert et al., 1998). In the learning tasks, the function brain imaging studies have consistently showed the increased activation in cerebellum suggesting that the heavy involvement in motor learning phases. The activation in early learning might correspond to the error signals originating from the comparison between the predicted and actual outcomes of movements, which are used to refine the forward model’s predictions and guide the acquisition of new internal models. In late learning phase, the massive activation in cerebellum is decreased after repeated trials, but there are certain subregions of the cerebellum near the posterior superior fissure, continuing to be activated even after subjects had learned to use novel tools. The author has interpreted as that remain activity represents an internal model that is acquired during the repeated test trials, which defines the new relationship between movement of the cursor and of the mouse (Kawato, 1999). Through learning and internal model built up, one can make both sensory and motor prediction in diversity of environmental context.

The parietal cortex is also proposed involving in predictions. It plays a central role in combining sensory and motor information within common reference fame. According to this view, different subregions within posterior parietal areas contain maps of intention related to the planning of different movements such as eye movements, reaching and grasping movements. But it is somehow difficult to differentiate the roles of the parietal cortex and cerebellum in motor prediction, it is highly likely that these two regions work as a functional loop for estimating the current status of the motor system throughout movement execution. There are anatomical connections from parietal cortex to cerebellum via pone and from cerebellum to parietal cortex via thalamus (Blakemore & Sirigu, 2003). It has been proposed that the differential roles of the cerebellum and the parietal cortex may occur at the level of awareness ascribed to the prediction. The cerebellum is normally involving in unconscious prediction and learning while the parietal cortex is more consciously. Beyond the cerebellum and parietal cortex, some other brain areas might also involved in the prediction in different ways, e.g. premotor area in imagining movement, basal ganglia in learning novelty etc.

In summary. The role of cerebellum in prediction is fundamental to motor learning. It is believed that prediction is acquired first before control the movement.

Timing

The concept of timing is proposed to be involved in almost all the different functions attributed to the cerebellum. For example, in learning, precise timing of the two input systems- parallel fibers and climbing fibers is essential; in dynamics, precise timing is required to turn on and off certain muscle activities in order to solve the complexity of the force and torque; in prediction, precise timing determines the accuracy of movement planning; in controller, precise timing helps the fine adjustment of motor output and sensory expectation. Because of the importance of timing, the cerebellum is proposed as the generator of temporal pattern (Llinas, Leznik, & Makarenko, 2002; Yarom & Cohen, 2002).

The motor clock function for the cerebellum was proposed in 1971 on the basis of periodic discharge in the inferior olive (Lamarre et al., 1971). The assumption was founded on the effects of harmaline, a substance which induced a whole-body 10Hz tremor in experimental animals and a correlated synchronous discharge in inferior olive cells in slice preparations (Llinas et al., 1986). Because ablation of the olive then abolished the tremor, it was assumed that the olivary discharge caused the tremor. A number of other findings seemed to uphold the interpretation, such as a tendency in undrugged animals for the olive to fire periodically and in synchrony, and gap junctions in the live which might synchronize cell discharge. The generalization had been questioned by others, who found non-periodic olivary discharge in awake monkey.

Although there is a general agreement as to the importance of the powerful input to the cerebellar cortex provided by the climbing fibers, there are fierce debates regarding its role in cerebellar function. One focus of debate is the question of rhythmicity of the climbing-fiber input. Complex spike activity, as recorded continuously from a single Purkinje cell does not appear to be rhythmic. However, such activity recorded simultaneously from a population of Purkinje cells exhibits a clear rhythm of 5-10 Hz (Yarom et al., 2002).

The predominant evidence of rhythmic coordinate movement is synchronous discharge in inferior olive using multiple-microslectrode recordings by Llinas and colleagues in rats (Welsh, Lang, Sugihara, & Llinas, 1995). They propose that the motor coordination depends upon the integrity of the inferior olive, a major cerebellar afferent. They used the multiple-microelectrode recording and found that the activities in Purkinje cells were generated by olivary input during skilled tongue movement and such activities were highly rhythmic and time-locked to movement. Patterns of synchronous olivocerebellar activity are geometrically complex and can change during a sequence of movements. Their results support that the inferior olive organizes movement in time, by entraining motor neuronal firing through rhythmic activation of the cerebellum, and in space, by synchronously activating cell ensembles that allow the use of individual muscles. The pattern of olivocerebellar timing pattern is dynamic which allow dealing with movement complexity (Welsh et al., 1995).

But how can we explain the relationship between high frequency simple spike and low frequency of complex spikes? How the information is coded in the neuronal activities? Some previous studies of olivocerebellar system have generally not indicated a strong relation between single neuron activity and movement. It seems that there is no clear time-lock relationship between all the spikes and movements. Evidence has showed that the coding scheme in IO and Purkinje system is not local coding but population coding scheme. Population coding refers to the information that is conveyed in the relative amounts of activity across multiple neurons or neural system. However, a deeper type of population coding refers to the information conveyed in the specific temporal patterns of neurons' action potentials with respect to one another. Approaches toward this analysis are electrophysiological recording of many single neurons using multiple microelectrodes or high-resolution voltage imaging (Welsh, 2002). Multiple-microelectrode method demonstrates that the olivocerebellar contribution to movement is uniquely coded in the population activity. During a train of licks, multiple Purkinje cell recordings revealed a 270% increase in the incidence of complex spikes due to a doubling of the number of Purkinje cells firing complex spikes. While only 36% increase in the number of complex spikes fired by single Purkinje cells during each lick train (Welsh et al., 1995). Results suggested that if just look at the relationship between simple spike and complex spike individually, one might easily miss the coding information that were embedded in a group of related neuronal population. Using population coding scheme, the olivocerebellar system can dynamically tune to certain temporal pattern in varies environmental context. While local coding could restrict the system's ability to deal with different movement tasks. It is impossible to store all possible combination of activities in brain using local coding as well as to explain the adaptation and learning using local coding. Unfortunately, most others who oppose timing hypothesis are automatically describing the oscillation of IO as rigid timer and assume the individual spike frequency should present the movement timing which do not take account of dynamically population coding.

Yaron et al., (2002) has proposed that the olivocerebellar system as a dynamic temporal generator. Multiple groups of electrically coupled olivary neurons generate synchronous sub-threshold oscillations that occasionally elicit action potentials. These oscillations propagate causing different phase shift among these groups. Since the sub-threshold oscillation in each olivary group is synchronized, the summation of the corresponding group of Purkinje cells shows rhythmic complex spike activities, which generates dynamic complexity of the temporal pattern in cerebellum.

Ivry and colleagues (1988) have proposed “clock” functions for the cerebellum based on other evidence. Patients with lateral cerebellar injury are impaired in their ability to perceive differences in intervals between tone pairs of the order of 0.5s. This has been interpreted as indicative of a general clock, not only for movement but also for perception. Houk (1988) has proposed that motor programs are encoded as tonic reverberating activity within several closed-loop systems that make up the basic movement program generators. In voluntary movement, the loops are excited by a higher cerebral input, and continue to reverberate closed loop (all the while generating movement) until they are turned off. The cerebellar cortex is supposed to turn them off: upon recognizing (through trial-and error learning) the ‘context’ in which` movement should stop, the Purkinje cell output flipflops from a low bistable condition of no discharge to one of high maintained discharge. This is purported to inhibit the maintained activity in the deep nuclei and to stop the activity reverberating in the movement program generator circuits.

Most of the evidences for timing hypothesis are from the rhythmic movement, e.g. rats lick movement (Welsh et al., 1995), human rhythmic movement (Spencer et al., 2003). As I can think of, we need to pay attention to couple of points about timing: first, different types of timing (rhythmic anticipatory timing and temporal planning for discrete movement, on-line temporal adjustment); second, the temporal requirement for different types of tasks, in other words, task-dependent temporal requisition. The internal timing system is a task-dependent and dynamic system. The requirement of the internal timing becomes essential when the movements have high temporal demands, for example, the timing in activation agonist and antagonist, or the ability to differentiate the auditory interval and perform rhythmic movement. The above evidences about population coding of simple and complex spikes match the task-dependent dynamics timing system quite well.

Regardless of the convincing evidence of oscillation and their relationship to the movement, there seems some pieces missing between the neuronal characteristics of olivary system and behavior: how is rhythmic activity translated into a sequential firing pattern? What determines that amplitude of the response? How are these patterns learned, stored, and recruited by specific input? And how many combinations of temporal patterns need to be stored in brain to cover all the complexity of environment?

Recent work from Kawato and colleagues has combined the timing hypothesis and learning hypothesis based on their finding of ‘chaotic resonance’ in inferior olive. They reported that there are high-rate components within the low-frequency oscillation in inferior olive suggesting that IO cells allow information-rich but low firing-rate error signals to reach individual Purkinje cells, thereby providing the cerebellar cortex with essential information for efficient learning without disturbing on-going motor control (Schweighofer et al., 2004). Based on their interpretation, the basic temporal component determines the movement onset while the error signal in the complex spikes elicits the learning mechanism.

Beyond timing in the cerebellum, we also need to realize that there are other brain areas heavily involved in temporal information processing. Parkinson’s patients have large variability when they perform repetitive movement, they are also reported to have abnormalities in their ability to estimate temporal interval and tend to underestimate time. The activation of Gpi besides cerebellar nuclei were found in the fMRI studies also suggested the importance of the basal ganglia in timing (Gerwig et al., 2004). The frontal lobe appears to be essential for memory and attentional operations required in may timing tasks, especially those with long intervals (Kagerer, Wittmann, Szelag, & Von Steinbuchel, 2002). Because of these diversity structures of timing, Ivry (1996) has proposed that cerebellar research has focused on relatively short intervals, usually under 1s, and emphasis has been on variability. In contrast, intervals spanning many seconds characterized most of the basal ganglia research, and the emphasis has been on clock rate (i.e. bias) rather than variability.

Several models on cerebellar timing have been proposed e.g. Oscillator models (an oscillator and a calibration unit), Interval-based model (distribute timing mechanism), Multiple timer model (a bank of oscillators or hourglass timers), spectral timing model (Bullock, Fiala, & Grossberg, 1994) etc. With all these different models proposed, the focus of current dissertation is the ‘explicit timing’ hypothesis.

Recently, Spencer et al (2003) have reported that patients with cerebellar damage have deficits in performing fast circle drawing movements. Their reports have showed that these deficits are restricted to discontinuous movement, which requires initiation and stop each circle during circle drawing. These patients have no deficit in temporal variability when producing continuous, rhythmic movement. Their interpretation is that because the discontinuous circling movement requires an explicit representation of the temporal goal (i.e. when to start and stop), the lesion of cerebellum plays a key role on the deficit performing the movement (Spencer, Zelaznik, Ivry, & Diedrichsen, 2002; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). It has been hypothesized that there are separable timing mechanisms for drawing tasks: explicit timing process is involved in the timing of the occurrence of events and has been lined to event timing (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002); and implicit timing is an emergent property of the trajectory throughout a drawing. Continuous drawing requires implicit timing while discontinuous drawing requires explicit timing process, which involves cerebellum. Therefore, in the current project, we use this ‘explicit’ timing hypothesis as a basis to examine the role of cerebellar timing on development of drawing skill in children.

In summary, I think that timing is one of important aspects in cerebellum, however, there is no rigid clock in cerebellum but a dynamically task specific temporal controller. The timed responses are generated at granule cell-Golgi cell circuit covering a spectrum of activity that related to all the possible timing intervals. The outputs are adaptively filtered to derive an accurately timed response through both LTD/LTP mechanism and baseket/stellate cell inhibitory circuits. The temporal response for different movement needs to be linked to certain context through learning process.

After a review of several important theories of cerebellum function, it is not hard to find out that all these theories focus on one aspect of the multiple cerebellum roles e.g. temporal control, dynamic torque control, error detection and automaticity of the movement, and training of predictor and controller. The example based on one theory can be normally interpreted into another. There are evidences support one theory might also support the other although sometime they looks like opposite. Sometime, lack of evidence does not mean it not exists. In summary, we need to realize the diverse function of the cerebellum and it is important to look at the same question from different angles. When we using one of the theories to test the role of cerebellum, we need ask ourselves whether it can be explained in other way? Disapproved results might embed positive answers.

Development in cerebellum

Numerous deprivation, enrichment lesion and developmental studies have consistently reported that brain development is the product of dynamic processes involving interaction among all different kinds of constraints from genetics to environment (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990; Cotman & Engesser-Cesar, 2002; Dawson, Ashman, & Carver, 2000; Dorris, Pare, & Munoz, 2000). The behavior changes and brain development are shaping each other across life span. Following birth, the mass of brain increases 30% between 3 and 18 months. This is followed by 5% to 10% for each period between age 2 to 4, 6 to 8, 10 to 12 years, and 14 to 16 years (Kolb, Gibb, & Dallison, 1999). White matter volume increases linearly throughout childhood reflecting increasing myelination, and gray matter volume increases until early adolescence before decreasing during late adolescence, presumably from continued synaptic pruning (Giedd, Blumenthal, Molloy, & Castellanos, 2001). The cerebellum develops slower and later than most of other areas of brain (Griffiths et al., 2004). The cerebellum appears to start its significant growth at 16.5 weeks with a rate of 16mm/week throughout pregnancy, while the cerebral hemisphere appeared to commence significant growth at 13 weeks at a rate of 184/week throughout pregnancy. Anderson (2003) has reported that the maturation of the cerebellum, and the hippocampus occurs later than sensory cortices. The subcortical structures (including basal ganglia) develop earlier than cortical structures.

There is a sequential order in cerebellar development (Bastian, Mugnaini, & Thach, 1999): output structures develop first, and cerebellar cell types develop at different times and at different places. The first cells to be formed are the neurons of the deep cerebellar nuclei. They are followed soon after by the Purkinje cells. Golgi cells, basket cells, stellate cells, astrocytes, and glia migrate to their final positions after the migration of the Purkinje cells. Input structure develops next: Once Purkinje, Golgi, basket and stellate cells have formed, climbing fibers enter the cerebellum from the inferior olive and begin to innervate the Purkinje cells. Later, after the Purkinje cells have begun to receive synapses from parallel fibers, most of the climbing fiber contacts with Purkinje cells will be eliminated. Mossy fibers also enter the cerebellum and grow to the level just below the Purkinje cell layer. They will ultimately synapse on granule cells, which have yet to arrive. The granule cells first develop at a very distant site, they then crawl over the Purkinje cells to an external granule cell layer. The granule cells extend their axons, which branch to form parallel fibers that run as coronal beans through the dendrites of the Purkinje cells. Only then do the granule cells descend, guided by the Bergmann glia, to form the internal granule cell layer. In general, the ‘motor’ side of the cerebellar circuit (deep nuclear cells and Purkinje cells) forms first, the ‘sensory’ side (mossy fiber) then arrives in place, and the ‘matrix’ that connects the two (the granule cells and intrinsic inhibitory neurons) is the last to develop (Bastian, Mugnaini, & Thach, 1999).

In humans, the first cerebellar structures develop at approximately 32 days after fertilization, and the development is not completed until after birth. The mammalian cerebellum is known to be in a vulnerable state around the time of birth, since this is a period of active proliferation and migration of the cerebellar granule cells. It has been shown that individuals born pre-term had significant reduced cerebellar volume compared with term-born controls (Allin et al., 2001; Gramsbergen, 2003). The last trimester prenatal period to 2 years postnatal is the critical time for cerebellum development. However, cerebellum does not stop developing afterwards, brain imaging studies have shown that development of cerebellum continuous throughout childhood. Recent cerebral magnetic resonance images study on 259 subjects, longitudinally studied the development of cerebellum. Results have showed that the cerebellum volume is mature late than other brain areas. It peaks at approximately 19 years of age, compared to a peak in total cerebral volume at approximately 16 years of age. Twin data indicate that the cerebellar volume is the least heritable of the other structures (Giedd et al., 2001). Similar late cerebellar activation in children compared to adults is also reported in individuals between 8 and 30 years old (Luna et al., 2001). Other MRI studies have showed that significant changes in gray matter density occur during adolescence in multiple brain areas including cerebellum (Frangou, Chitins, & Williams, 2004).

Besides brain imaging studies on cerebellar volume development, P-magnetic resonance spectroscopy is also used to examine the maturation of human brain

(Hanaoka, Takashima, & Morooka, 1998). Age related changes in multiple values have been reported in 37 normal children aged 4 months to 13 years 8 months. The component of long relaxation time, contained in the PME peak (reflecting richness of lipids and phospholipdis), decreases more and more depending on age. It is plentiful in the early postnatal period, especially before the age of 2 corresponding to that of the most active myelination. Then, the age-related changes become slower during the childhood. Finally it reaches to a plateau after age of 8. Age-dependent changes are also seen in PME/PDE reflecting the general brain development. The group of values before 1 year of age and those after 8 years of age are significantly different. PME/PDE value is constant higher in the cerebellum than cerebrum. The results suggest that development of cerebellum is slower than cerebrum in childhood. The myelination in cerebellum is still developing although the rate of changes is much slower than 2 years of age. Chugani (1987) examined the developmental changes of metabolism in both the cerebrum and the cerebellum by the use of positron emission tomography and have reported that the mean cerebral metabolic rate for glucose for most cerebral cortical regions was higher than the mean metabolic rate in cerebellum between 3 to 8 years of age, which again supported the late development of the cerebellum.

In summary, the cerebellum develops slower and later than most of the other areas of brain. The myelination in cerebellum is still continuous after birth. However, the rate of change in cerebellum development is much slower after 2 years old, and it lasts till adolescence. With the focus on cerebellum development in this review, we also need to realize couple of points in brain development. First, besides the continuous changing in cerebellum, other brain areas, including almost all the cortical and subcortical areas are also developing during the children and adolescence (Paus et al., 1999). Second, Constraints, including experience, dynamically influence the development of brain. There are huge variability existed in human brain suggesting that behavior changes cannot be explained by a single factor. Third, although the brain volume increases, the rate of change is quite small. The most important changes in brain development during childhood might relate to the detail brain circuit fine-tuning process (Caviness, Jr., Kennedy, Richelme, Rademacher, & Filipek, 1996). And lastly, the correlation between brain development and behavior changes does not determine the causal effect. Human brain is so plastic that structural difference might not necessary show the behavioral differences. We are trying to understand the development of drawing development from one angle to examine whether slow development of cerebellum correlate to behavior changes in childhood.

Cerebellum and movement disorders

A body of research has showed that the cerebellum has been linked to a number of developmental disorders. In this section, I start with the general overview of the relationship between the cerebellum and movement disorders. Then, a brief introduction of the Developmental Coordination Disorder (one of the movement disorders) is followed. Lastly, I focus on the relationship between the cerebellar timing and the children with movement difficulties, especially children with DCD.

Cerebellum and movement disorders

Most evidence on the relationship between the cerebellum and movement disorder is based on the analysis of high-resolution MRI scans. In addition, imaging and behavioral studies have led researchers to consider functional contribution of the cerebellum beyond that associated with motor control.

Courchesne and colleagues (1988) reported the pronounced cerebellar hypoplasia in children with autism. In that study, 18 autistic individuals and 12 age-matched controls were tested. Interestingly, no other brain region showed a difference between the two groups except the cerebellum. Subsequent studies involving larger sample sizes have confirmed that cerebellar abnormalities are consistently associated with autism. A reduced cerebellar volume is the most consistent structural marker of autism.

Cerebellar hypoplasia has been associated with other developmental disorders. MRI evidences on children with ADHD (Castellanos et al., 2002; Giedd et al., 2001) indicate that cerebellar abnormalities co-exist with structural differences in the cerebral cortex. For example, children with ADHD show approximately 10% reduction in total brain volume (including the cerebellum) compared to children who are typically developing (Giedd et al., 2001).

Researchers also use behavioral methods to study the relation of the cerebellar function to the developmental disorders. Children with developmental dyslexia have marked impairments on tests of coordination, and their problems resemble those exhibited by patients with acquired cerebellar lesions (Zeffiro & Eden, 2001).

Recently, animal studies have shed light on the relationship between clumsy and disturbed cerebellum development. Under-nutrition during the brain growth spurt period in rats leads to a smaller cerebellum containing less neuronal and glia cells, less synapses and decreased mylination, whereas other parts of the brain are less seriously affected (Dobbing, 1981). A retarded and prolonged transition from immature locomotion is found and the sign of clumsiness is long-lasting (Gramsbergen & Westerga, 1992). Dexamethasone (corticosteroid treatment for lung maturation) injected into young rats at a maturational stage comparable to that of prematurely born human babies of 27-34 weeks postmenstral age, induces neurological abnormalities discernible as a retarded development of vestibular reflexes and long-lasting abnormalities during the development of walking as postural tremor and clumsy (Gramsbergen, 2003). These results suggest that a disturbed cerebellar development should be considered as an important etiological factor in clumsiness in human children.

To summarize this brief review, cerebellar abnormalities, either anatomically or behaviorally defined, have now been linked to developmental disorders like autism, ADHD, and dyslexia. It is very possible that a disturbed cerebellum development is one of the key players in the motor development.

Children with Developmental Coordination Disorder

Developmental Coordination Disorder (DCD) was introduced in the revised third edition of Diagnostic and Statistical Manual of Mental Disorder (DSM III-R) to identify motor coordination problems in children not caused by any known physical disorder. A number of terms have been used to children with DCD, for example developmental dyspraxia (Ayres, 1972), clumsiness (Henderson & Hall, 1982), physical awkwardness, poor coordination (Cratty, 1994), perceptual-motor dysfunction and motor delay (Henderson, Barnett, & Henderson, 1994). While existing for years under a variety of labels, these children are now classified in the DSM IV (APA, 1994) as having Developmental Coordination Disorder (DCD). Criteria for diagnosis of DCD include (a) performance in daily activities that require motor coordination is substantially below that expected given the person's chronological age and of daily living; (b) the motor disturbance (significantly) interferes with academic achievement or activities of daily living; and, (c) the motor disturbance is not due to a general medical condition (e.g. cerebral palsy, hemiplegia, or muscular dystrophy) and does not meet criteria for a pervasive Developmental Disorder (APA, 1994). The prevalence of DCD has been estimated to be as high as 6% for children in the age range of 5-11 years (APA, 1994).

A number of researchers think that motor coordination problems of children with DCD are the result of sensory processing problems (Ayres, 1972; Hulme, Moran, & Smart, 1982), or kinesthetic processing problem (Coleman, Piek, & Livesey, 2001). Interestingly, few studies have questioned whether there are other processes that relate to this group of children. In one of our previous studies, we examined the ability of seven children with DCD to adapt to a novel visuomotor relationship by exposing them to a 45 degrees visual feedback rotation while they performed a center-out drawing task, and compared their performance with that of seven normally developing children. The results showed that the children with DCD were less affected by the feedback distortion than the control children, and did not show aftereffects, suggesting they had a less well-defined internal model. A principal component analysis of the performance variables during early and late exposure showed that the variables accounting for most of the variance in the trajectories were different between the groups, suggesting that underlying control processes might operate differently in the two groups of children (Kagerer, Bo, Contreras-Vidal, & Clark, 2004).

In our second experiment, we examined whether children with DCD between the ages of 6 and 10 years were able to perform the gradual and sudden visumotor distotion at their comparable age level. Contreras-Vidal et al. (2003) has argued that there may different neural circuits be involved in these two types adaptation with the basal ganglia being more involved in sudden adaptation tasks and the cerebellum playing a greater role in gradual adaptation tasks. Participants (n=10) performed the same center-out task. The two adaptation tasks were administered separately and counterbalanced across subjects: 1) Sudden Adaptation: Three conditions included 30-trial baseline with normal feedback, 126-trial exposure with the visual feedback rotated abruptly by 60° clockwise, and lastly 9-trial post-exposure with normal visual feedback for after-effects indicative of learning. 2) Gradual Adaptation: the same three conditions - 30-trial baseline, 126-trial exposure with the visual feedback rotated in 6 steps of 10º each up to 60° clockwise (21 trials each step), and 9-trial post-exposure. At baseline, children with DCD performed comparable to their age. During exposure, children with DCD showed larger changes on spatial variability and movement distance in both adaptation tasks. Significant aftereffect in movement planning measured as initial directional error (IDE), computed at 80 msec post-movement after onset, was found in typically developing children at comparable age but not in children with DCD under either of the two tasks. Regression analysis during post-exposure in gradual adaptation showed that the IDE aftereffect in 8 out of 10 children with DCD were lower than 95% low confident limit (LCL) at their age level. The aftereffect in sudden adaptation showed that only 7 out of 10 DCDs were lower than 95% LCL. The results suggested that the children with DCD were not able to learn the visuomotor distortion at their age level and such lack of learning was quite different across individuals in the gradual distortion task. The results of these studies suggest that some of the children with DCD may have a possible cerebellum dysfunction in children (Bo, Contreras-Vidal, Kagerer, & Clark, 2005). Of course, the linkage of cerebellum dysfunction needs to be further tested.

Handwriting is the most frequently mentioned problems in children with Developmental Coordination Disorder (Smits-Engelsman, Niemeijer, & van Galen, 2001). The common feature of a writing problem (i.e. dysgraphia) is that even with the proper amount of instruction and practice, children fail to make sufficient progress in the acquisition of the fine motor task of handwriting. Dysgraphic handwriting lacks consistency (Keogh & Sugden, 1985). The observed inadequacies are typically of a motor nature and not due to carelessness or ignorance, nor are poor spelling or other psycholinguistic problems (Smits-Engelsman & van Galen, 1997; Wann et al., 1991).

Among few studies on handwriting in children with DCD, Smits-Engelsman et al., (2001) reported that poor drawing and poor handwriting are closely related to each other. The fine motor deficiencies in children with DCD in ‘flower-trial drawing’ task, one of the items in Movement ABC test was highly correlated to the writing problems. The kinematic analysis showed that serious handwriting problems were accompanied by fine motor deficits. Using Van Galen’s model, they suggested that an enhanced level of neuromotor noise was compensated by enhanced phasic stiffness of the limb system in children with DCD since the high frequency band in PSD analysis did not show a big differences between children with and without DCD. The higher movement velocity and fewer velocity peaks were found in this study.

In general, not many studies have been done to understand the motor coordination problems of children with DCD. Besides the claims of sensory processing problems or kinesthetic processing problem, the integration among different processes may play more important role. Due to the interest of current dissertation, the relationship between the cerebellar ‘timing’ function and children with movement problems will be discussed in the following.

Cerebellum timing and movement disorders

Quite a number of studies have been reported that children who are classified as ‘clumsy’ have deficit in various cerebellum timing tasks (Geuze & Kalverboer, 1987; Ivry, 2003; Lundy-Ekman, Ivry, Keele, & Woollacott, 1991; Williams, Woollacott, & Ivry, 1992). Williams et al., (1992) examined whether children diagnosed as clumsy showed deficits on the motor and perceptual timing tasks similar to those in adult patients with cerebellar lesion. The children were categorized as clumsy if they were between the 40% and 50% percentile on the Bruininks-Osertesky test and scored between 0.5 and 1.5 SD below normal on at least 6 of the 9 items in the clinical battery. The control group consisted of individuals who were at or above the 50% on Bruininks-Osertesky test and scored above 0.4 SD below the mean on at least 6 of the 9 items in the clinical battery. Results showed that children classified as clumsy on standard clinical assessment instruments were impaired on tasks that required precise timing. However, the normal performance of the clumsy children on the loudness task demonstrated that this group did not perform poorly on all tasks. The author interpreted that there might be a general deficit in the function of the entire motor system, with the cerebellar timing problems just one particular manifestation of this generic impairment.

Since ‘clumsiness’ is applied to a heterogeneous population, it is very possible that cerebellar dysfunction might be present in one subgroup of clumsy children and absent in other subgroups. Lundy-Ekman (1991) used the soft neurological sign of basal ganglia or cerebellar dysfunction (Touwen, 1979) screened ‘clumsy’ children into two subgroups: basal ganglia group and cerebellum group. The timing tasks including tapping, duration and loudness discrimination and a force control task. The results revealed that children with cerebellar signs were significantly more variable than controls and children with basal ganglia sign in finger tapping tasks. In other hand, the basal ganglia group was unimpaired on the tapping and discrimination tasks but showed larger variability in the force control task. The author interpreted that clumsiness did not reflect a generalized dysfunction across the motor system but a dysfunction in a particular neural system (Lundy-Ekman et al., 1991).

Subtype groups of children with DCD were also reported to have higher timing variability in other timing tasks, e.g. repetitive hand tapping, foot tapping and jumping in place (Parker, Larkin, & Wade, 1997). Different from Lundy-Ekman, the children were sub-grouped into two based on the motor impairment in fine and gross motor skills. Children with both fine and gross motor coordination impairment would have significant lower timing stability on all tasks, whereas children with gross motor impairment would have significantly lower timing stabilities in jumping. Results showed that children with both fine and gross impairment showed higher variability in all tasks, particularly in hand tapping. But the results in other group were not so clear.

Summary

In summary, previous studies have shown the behavioral difficulties in multiple timing tasks in children with motor problems. Interestingly, while numerous evidences have pointed out the contribution of cerebellum function to developmental problems, few studies have evaluated the role of timing function in children with and without DCD. The temporal consistency is one of the most important characteristics in skilled writing. To our knowledge, no study has been done to evaluate the ‘timing’ in drawing and writing tasks. Therefore, current study examines the timing function in continuous and discontinuous drawing tasks, which may have insight of the relationship between the cerebellar function and the motor problems in children with DCD.

Significance and conceptual frameworks

In this last section, three parts are included. The first part is the significance of the current study. The second part discusses the conceptual framework that guides this dissertation. The last part lists the knowledge gaps that relate to the current study.

Significance

1) The development of drawing skills is linked with school-related activities, such as reading, or writing skills. Numerous studies have shown that there is a very close relationship between drawing and reading, writing performance (Barnett & Henderson, 1992; Hamstra-Bletz et al., 1993; Karlsdottir & Stefansson, 2003; Smits-Engelsman et al., 2001). It is common to use the drawing product to evaluate the handwriting motor ability in children, e.g. Movement ABC (Henderson & Sugden, 1992), and the Developmental test of Visual Motor Integration (Beery, 1997) etc. The development of drawing skills is the building block for other complex motor skills, e.g.

handwriting, which influence children's academic achievement and long-term career development.

2) Developmentally identify children with motor difficulties (e.g. DCD) may avoid other long-term complications. Several studies have shown that most children identified at ages five or six years as having motor coordination problems still exhibit motor difficulties 10 years later (Cantell, Smyth, & Ahonen, 1994; Losse et al., 1991). It has been reported that older clumsy children show much more delayed than younger children (Barnett & Henderson, 1993). A number of studies suggest that children with motor difficulties not only demonstrate poor academic achievement, but also experience socio-emotional difficulties including low self-esteem (Shaw, Levine, & Belfer, 1982), low competence (Rose, Larkin, & Berger, 1997; Skinner & Piek, 2001), and behavior problems (Losse et al., 1991), early identification of these children becomes very important to improve their performance with less prolonged problems.

2) Teaching methods and intervention should match the brain function development. Many handwriting studies have been done with children in order to improve the teaching of handwriting (Burns, 1962; Freeman, 1914). These studies revealed the progression of movement proficiency over years of practice. Most intervention studies show positive effects over no-intervention controls with no significant advantage for widely differing approaches (Sugden & Chambers, 1998). These patterns suggest that there might be other factors along with pure motor practice that result in the observed changes. While numerous studies focus on the behavior changes, few studies have addressed the issue how motor performance changes relate to the development of brain function in childhood. In current project, we propose that the

development of cerebellar function is playing a key role on the development of drawing skill. The introduced teaching methods and intervention program should be appropriate to the developmental level of brain function.

Conceptual framework

A large body of developmental studies on visuomotor coordination focus on the movement components between a programmed ballistic part (feedforward mechanism) and visually guided correction (feedback mechanism) during simple spatially oriented movement (Hay, 1979; Hay, 1984; Hay, Bard, & Fleury, 1986; Thomas et al., 2000; Yan et al., 2000). In drawing and writing literature, progression of movement proficiency: from high variability to more consistent drawing/writing products, are consistently reported (Hamstra-Bletz et al., 1990; Meulenbroek & van Galen, 1986; Wann, 1987). Recently, adaptation paradigm, where the discrepancy (rotation or gain changes) between visual space and motor space is experimentally manipulated, are commonly used to understand the developmental process how children update their visuomotor map in changing environment (Contreras-Vidal et al., 2005; Ferrel-Chapus et al., 2002). Conceptually, a number of these approaches are based on the control system perspective that a fast and accurate movement depends on precise motor planning and control. Beyond these approaches, an important developmental question emerges: what, in the developing brain, may relate to these changes?

Currently, more evidences have shown the close relationship between brain development and behavior changes. Numerous deprivation, enrichment, or lesion studies have consistently reported that brain development is the product of dynamic processes involving interaction among all different kinds of constraints from genetics to environment (Black et al., 1990; Cotman et al., 2002; Dawson et al., 2000; Dorris et al., 2000). The behavioral changes and brain development are shaping each other across the life span. Following birth, the mass of brain increases 30% between 3 and 18 month. This is followed by 5% to 10% for each period between age 2 to 4, 6 to 8, 10 to 12 years, and 14 to 16 years (Kolb et al., 1999). It has been shown that cerebellum develops slower and later than most of other areas of brain. Anderson (2003) has reported that the maturation of cerebellum, hippocampus is later than sensory cortices. Recent cerebral magnetic resonance images study showed that the cerebellum volume is mature late than other brain areas. It peaks at approximately 19 years of age compared to a peak in total cerebral volume at approximately 16 years of age (Giedd et al., 2001). Do the developing brain structure, especially the slower cerebellar development play a role on the motor development? These studies lead us question the relationship between developing cerebellum and the motor skill development in childhood.

A body of research has shown that the cerebellum has been linked to a number of developmental disorders: for example, pronounced cerebellar hypoplasia in autism (Courchesne et al., 1988), reduced cerebellar volume related to ADHD (Berquin et al., 1998) and schizophrenia (Nopoulos et al., 1999). Quite a number of studies have reported that children who are classified as ‘clumsy’ have deficit in various cerebellar timing tasks (Geuze et al., 1987; Ivry, 2003; Lundy-Ekman et al., 1991; Williams et al., 1992). Clumsy children were significantly more variable than normal children in maintaining a set rate of tapping and in accurately judging time intervals (Williams et al., 1992). Subtype groups of children with DCD are also reported to have higher timing variability in repetitive hand tapping, foot tapping and jumping in place (Parker et al., 1997). Interestingly, while numerous evidences have pointed out the contribution of cerebellar timing function to developmental problems, few studies have evaluated the role of cerebellar timing function on motor skill development. In addition, wider age range of children included in current study will create a developmental landscape for us to better evaluate children with DCD. In other words, we can test not only whether children with DCD perform higher timing variability than age-matched controls, but also measure which age level these children perform, for example, two years or three years lower than their age level?

Thus, in current proposal, I focus on age-related difference in continuous versus discontinuous drawing movements, which might have some insight of developing cerebellar timing, in children with and without DCD. Recently, Spencer et al., (2003) have reported that patients with cerebellar damage have deficits in performing fast circle drawing movements. Their reports have shown that these deficits are restricted to discontinuous movement, which requires initiation and stop each circle during circle drawing. These patients have no deficit in temporal variability when producing continuous, rhythmic movement. Their interpretation is that because the discontinuous circling movement requires an explicit representation of the temporal goal (i.e. when to start and stop), the lesion of cerebellum plays a key role on the deficit performing the movement (Spencer et al., 2002; Spencer et al., 2003). It has been hypothesized that there are separable timing mechanisms for drawing tasks: explicit timing process is involved in the timing of the occurrence of events and has been lined to event timing (Ivry et al., 2002); and implicit timing is an emergent property of the trajectory throughout a drawing. Continuous drawing requires implicit timing while discontinuous drawing requires explicit timing process, which involves cerebellum. This hypothesis may provide us a more comprehensive understanding of underlying mechanism of normal motor skill development as well as developmental coordination disorder.

Knowledge gaps

1) A large body of researches in development of visuomotor coordination has reported improvement of temporal and spatial variability in childhood. The progression of movement proficiency: from large variability to consistent performance, has been reported in the developmental literature. Our previous studies consistently showed that the older children moved straighter, faster and less variably than the youngest children in point-to-point drawing task (Bo et al., 2003; Contreras-Vidal et al., 2005). Similar findings were also found in drawing/handwriting studies (Hamstra-Bletz et al., 1990; Smits-Engelsman et al., 1997). It was found that besides the variability improvement over age, children performed different types of movements differently. Wann et al., (1991) reported that children from 2nd to 6th grades have more difficulties in the discontinuous writing patterns than the continuous writing patterns. Thomassen (1983) reported that 7-year-olds could write continuous loops (letter ‘e’) better than write waves (letter ‘w’) and sawtooth shapes (similar to letter ‘u’) with more consistent spatial and temporal controls. These studies pointed out the common difficulties in children, no matter in reaching or writing movements, that initiation and stop an ongoing hand movements at appropriate time was very challenging. Unfortunately, few studies have connected these behavior changes to the development of brain function.

2) To our knowledge, no studies have systematically examined the cerebellar timing in children who are typically developing in development of drawing skills. It has

been shown that the cerebellum develops slower and later than most other areas of the brain. The cerebellum volume matures later than other brain areas. With the cerebellum continuously developing in childhood, few behavioral studies have examined whether the developing cerebellar functionality relates to the development of motor skills. Recently, the developmental studies on timing have examined finger-tapping and duration-perception tasks in childhood, but no studies have been done to specifically examine the cerebellar ‘explicit’ timing on development of drawing skills in children.

3) While a number of studies have reported the cerebellar timing deficit in developmental disorders, to our knowledge, no studies have systematically examined the timing function in children with DCD and compared their developmental level to children who are typically developing. Quite a number of studies have reported that children who are classified as ‘clumsy’ have a large temporal variability in various timing tasks, e.g. finger tapping (Geuze et al., 1987), bimanual movement (Geuze & Kalverboer, 1993), duration-perception tasks. To our knowledge, there are no studies, which examine the cerebellar timing in drawing task in children with and without DCD. It is a big knowledge gap that how the developing cerebellar function affects the drawing skill development in children with and without DCD. Current study is one of few studies that attempt to understand such relationship developmentally.

In summary, proficiency in drawing and writing skills is one of the most important advances in motor development during the preschool and school years. The current study has the potential to make a contribution to our understanding of motor skill development in children. First, this work provides behavioral evidence that one of the important underlying mechanisms in motor skill development is the development of brain function. Second, this work contributes to the existing literature on the role of cerebellum timing in children with Developmental Coordination Disorder using drawing movements – a task that affects every day living and academic performance. And finally, we contribute the debate on subtypes of DCD by evaluating individual performance using regression technique with wider range of children who are typically developing.

CHAPTER III

EXPERIMENT I

CONTINUOUS AND DISCONTINUOUS CIRCLE AND LINE DRAWING: HIGH TEMPORAL VARIABILITY EXISTS ONLY IN DISCONTINUOUS CIRCLING IN YOUNG CHILDREN

Abstract

An important milestone in early school years is the capability to generate drawing and writing movements of high spatial and temporal quality. This is intrinsically linked to fine temporal control and coordination of the effectors and the drawing or writing tools. Recently, Spencer et al., (2003) proposed that the cerebellum controls the ‘explicit timing’ underlying temporal consistency during discontinuous drawing, but not the ‘implicit timing’ during the continuous drawing. Alternatively, the cerebellum might be involved in the control of limb dynamics (including tool use), which differ between continuous and discontinuous drawing (Bastian et al., 2000). In the current study, we examined whether there were different developmental trends in children’s discontinuous versus continuous circling. Further, we tested whether similar differences also existed in a dynamically simpler line drawing task. Thirty-one children who were typically developing between the ages of five and ten years performed the continuous, discontinuous circle- and line-drawing tasks in random order. They were asked to move as consistently as possible for 20 seconds after synchronizing their movements with the metronome for 15 beats. The target speed was 550 ms for completion of one circle or one back-forth line. Regression analysis showed an age by condition interaction. The younger children showed much higher temporal variability, as measured by the coefficient of variation, than the older children in the discontinuous but not in the continuous circling. Contradictory to the ‘explicit timing’ hypothesis, we found that there were no age-related differences between the continuous versus discontinuous line drawing in children. Results suggested that decreasing the complexity of limb dynamics could improve the temporal variability in young children, indicating that limb dynamics may play an important role in the development of drawing skills in children.

Introduction

Handwriting is a tool-using skill that is linked with graphic-related drawing movements. Proficiency in writing is one of the most important developmental achievements during the preschool and early school years. Children first attempt to draw around the age of 15 month with spontaneous scribbling (Kellogg, 1969). By the age of two, children can crudely draw circular, vertical, and horizontal lines that follow the appropriate direction (Knobloch & Pasamanick, 1974). However, the quality of the performance varies considerably. It is not until the late elementary school years that consistent drawing and writing patterns emerge (Hamstra-Bletz & Blote, 1990). Previous research (Williams, Woollacott, & Ivry, 1992) suggests that consistent temporal control is a fundamental component in producing skillful writing.

It has been argued that the consistency of writing speed is one of the important criteria in evaluating handwriting skills (Wann, 1987). Handwriting studies indicate that the regularity of movement speed and the smoothness improve from the 2nd to 6th grades

(Hamstra-Bletz et al., 1990; Hamstra-Bletz & Blote, 1993). Furthermore, Wann et al., (1991) have reported that children from 2nd to 6th grades have more difficulties in performing discontinuous loops (i.e. garlands: counter-clockwise circling, similar to the letter ‘u’, and arcades: clockwise circling, similar to the letter ‘n’) than continuous loops (similar to the letter ‘l’). The discontinuous garlands and arcades show much higher irregularity and inconsistent movement times compared to continuous loops (Wann, Wing, & Sovik, 1991). Similarly, Thomassen & Teulings (1983) who were interested in the constancy in stationary and progressive handwriting, report that 7-year-olds can write the continuous loops (the letter ‘e’) better than writing the waves (the letter ‘w’) and the sawtooth shapes (similar to the letter ‘u’). The irregularity of timing and the duration of timing were better in the continuous loops. These behavioral findings led us to question why children showed more temporal difficulties in the discontinuous than the continuous writing patterns.

Recently, it has been proposed that there are separate timing mechanisms controlling the temporal consistency in continuous versus discontinuous drawing movements (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). Making discontinuous movement requires an explicit representation of the temporal goal (i.e. when to start and stop) while making continuous movement does not need an event-related explicit timing process. Support for this claim can be found in the behavioral studies of patients with cerebellar lesions (Spencer, Zelaznik, Ivry, & Diedrichsen, 2002; Spencer et al., 2003). Patients with cerebellar damage have deficits in performing fast circle drawing movements. Interestingly, these deficits are restricted to discontinuous movements, that require initiation and termination for each circle during circle drawing. These patients have no problem in their temporal variability when producing the continuous, rhythmic movements (Spencer et al., 2002; Spencer et al., 2003). Based on their finding, Spencer et al. (2003) proposed that timing emerged from the continuous drawing trajectory and is thus an “implicit timing” process. Discontinuous drawing, on the other hand, requires an “explicit timing” process that times the occurrence of specific events. This latter process involves the cerebellum.

Similarities in the behavioral difficulties with discontinuous movement in patients with cerebellar lesion and those of young children suggest that the developing brain function in childhood may be playing a role in the changes observed in the temporal consistency in drawing and writing movements. Support for the role of the cerebellum in motor skill development can be found in animal studies. For example, under-nutrition during the brain growth spurt period in rats leads to a smaller cerebellum containing less neuronal and glia cells, less synapses and decreased myelination, while other parts of the brain are less seriously affected (Gramsbergen & Westerga, 1992). Behaviorally, these rats have retarded and prolonged transition from immature locomotion and show signs of long-lasting clumsiness. Similarly, dexamethasone injected into young rats during the maturational stage of the cerebellum induces long-lasting abnormalities during the development of walking as postural tremor and clumsy (Gramsbergen, 2003). In humans, it has been shown that the cerebellum develops slower and later than most of the other brain areas. Anderson (2003) has reported that the cerebellum and hippocampus have longer maturational cycles than the sensory cortices. A cerebral magnetic resonance imaging (MRI) study of 259 children has longitudinally studied the development of the cerebellum (Giedd et al., 1996). Results show that the cerebellum volume matures later than other brain areas. It peaks at approximately the age of 19, compared to a peak in total cerebral volume at approximately the age of 16 years. These anatomical studies suggest that it is possible that cerebellar function is not fully developed during childhood.

Is the developing cerebellar function in childhood playing a role in the development of drawing and writing skills in children? Coordination and fine-tuning fast and accurate movements have been considered one of the major functions in the cerebellum (Thach, 1998). Previous developmental studies suggested that the kinematic and dynamic limb control is not well tuned in children (Contreras-Vidal, Bo, Boudreau, & Clark, 2005; Jansen-Osmann, Richter, Konczak, & Kalveram, 2002). Therefore, an alternative to the ‘explicit timing’ hypothesis, the complexity of the limb dynamics may be more difficult in the discontinuous movements. The requirement of turning on and off certain muscle groups in multi-joint movements, e.g. discontinuous circle drawing, is reported to be very challenging for patients with cerebellar lesion (Bastian, Zackowski, & Thach, 2000). The cerebellar patients can make almost normal single-jointed movements, but they have problems in the multiple-jointed movements (Bastian et al., 2000). In a recent study, we have found that cerebellar patients showed higher temporal and spatial variability in the discontinuous circling compared to the continuous circling (Bo, Block, Clark, & Bastian, 2005). However, both types of circling were more impaired compared to the age-match controls suggesting that there are other control mechanisms underlying continuous and discontinuous movements besides ‘explicit timing’.

Thus, the current study examines the hypothesis that the developing cerebellar function might play an important role in the development of temporal consistency in drawing skills. We use a behavioral approach to investigate 1) the age-related differences in children performing continuous and discontinuous drawing movements, 2) whether children can maintain the temporal and spatial consistency in discontinuous drawing compared to continuous drawing, and 3) whether there are different developmental trends in children’s continuous and discontinuous circle and line drawing. Experimentally, we control the number of joints in line drawing so that the dynamic complexity of the line drawing is simpler than the circle drawing.

Methods

Subjects

Thirty-one typically developing children between the ages of five and ten years (mean age 7.93 ± 1.77, 16 male and 15 female), and five college age adults from the area surrounding a suburban university community were recruited as subjects. All children were screened on the Movement Assessment Battery for Children (MABC, Henderson and Sugden, 1992) test and the Beery–Buktenica Developmental Test of Visual-Motor Integration (VMI, 4th edition, Beery, 1997). The inclusion criteria for children participants were 1) a no lower than standardized VMI score 1½ standard deviations below the mean; and 2) the MABC score higher than the 40th percentile. One additional child was excluded because his score in the Movement Assessment Battery for Children (MABC) test was lower than the 30%ile. The handedness was determined using the MABC criteria. Children's parents or legal guardians were fully informed of the task purpose, and signed the consent forms prior to the child's participation in the study. Adult subjects provided their consent before the test started. All procedures were approved by the Institutional Review Board of the University of Maryland-College Park.

Apparatus

Participants sat comfortably at a table with a digitizing pen taped on their dominant hand's extended index finger (the hand used for handwriting). The height of the chair was adjusted so that the participants' hand could move freely in the horizontal plane, and the lower end of their sternum touched the tabletop throughout the experiment. A digitizing tablet (WACOM InTuos™, Vancouver) was placed on the table and centered at the participant's midline in front of the chest so that participants could directly look at their hand and a template during the whole experiment. The tablet was used to collect data on the pen position in the X-Y coordinates at 200 Hz sampling rate using custom software written in OASIS™ (Kikosoft, Nijmegen). A paper template, either a circle or a 45-degree slanted thin ellipse, was placed at the center of the tablet. The diameter for the circle template was 5 cm. The size for the ellipse template was $5\sqrt{2}$ cm in long-axis and 0.2 cm in short-axis. The participants were asked to move their finger along the template. We instructed participants to use the template as a guide rather than trying to strictly trace the circle or ellipse. The participants' movement trajectory was recorded on the tablet when they moved the finger. Data were collected and stored on a computer for off-line processing. Real-time visual feedback of the pen movements on the computer screen was available only for the experimenter during the experiment.

At the beginning of each trial for all conditions, a metronome (Quikwatz) was turned on to initiate the movement rhythm. The target cycle duration (the time to complete one circle or one thin ellipse) was fixed at 550ms. After approximately 10-15 beats when the participant got the rhythm, the metronome was turned off. The participants were asked to move as consistently as possible for 20 seconds till that trial ends.

Procedures

Before any test started, the purposes and procedures were fully explained to both parents and participants with appropriate language. All the children were assessed through the screening tests before the drawing tests.

Screening tests

All screening tests took place in a quiet testing area. The Movement Assessment Battery for Children (Henderson & Sugden, 1992) test was administered first to identify children who had movement difficulties. The Beery–Buktenica Developmental Test of Visual-Motor Integration (Beery, 1997) was administered to evaluate the fine motor skill level. A 5-minute break was taken between the two screen tests. If the child did not qualified as a typically developing participant, he/she was excluded for the drawing tests.

Drawing experiment

The participants were required to perform drawing movements on a template using their index finger in four different conditions presented in random order. The experimenter explained and demonstrated the movement before each condition. The participants had several trials to become familiar with the task before formal testing started. A formal trial began when the experimenter announced ‘ready, go’. The metronome was turned on, and the participants synchronized the movements with the metronome. Once the participant got the rhythm (approximately 10-15 beats), the metronome was turned off. All participants were asked to move as consistently as possible for 20 seconds until the experimenter said ‘stop’. If the participants could not get the rhythm within the first 15 beats, the trial was restarted. The instruction emphasized the temporal consistency instead of spatial accuracy throughout the tests. The experimenter emphasized the instructions between trials but not during the trials. After each one or two trials, the experimenter gave positive feedback, such as ‘good job’, to encourage the child to keep up the performance. There were five trials in each condition. The randomization was among four conditions not among trials.

Condition 1: Continuous circle drawing: The participants were asked to start each trial with the pen tip on the top of the circle template. They then made continuous counter-clockwise movements around the circle and tried to coincide each of their circling with the metronome beats at the top of the template. Their wrist and fingers were not constrained, and the movements could be achieved by multiple-joints motions including elbow and shoulder.

Condition 2: Discontinuous circle drawing: The participants were asked to start each trial with the pen tip on the top of the circle template. They then made counterclockwise circle movement between two beats (one interval - 550ms), waited for the next beat (i.e. paused for one interval) before drawing the next circle. The participants attempted to initiate and stop one movement cycle, i.e. discontinuous circling, on the top of the circle template coincident with the beat of the metronome.

The discontinuous movements could be achieved by multiple-joints motions including elbow and shoulder.

Condition 3: Continuous line drawing: The participants started a trial at the upper end of the ellipse template and tried to pass the styles at the upper end of the ellipse coinciding with the beat of the metronome while moving back-and-forth between two ends continuously (550ms per up-and-down motion). Due to the thin short axis of the ellipse, the movement is basically a line drawing motion. In order to control the number of joints involvement, the participants wore a splint to keep the wrist and fingers rigid. The position of the elbow was supported so that the back-and-forth movements were controlled by the elbow motion.

Condition 4: Discontinuous line drawing: The participants were asked to draw a back-and-forth line on the thin ellipse template for each interval formed by two beats, then waited for the next beat (i.e. paused for one interval) before the next back-and-forth movement. They attempted to initiate and stop one movement cycle, i.e. discontinuous line drawing, at the upper end of template coincident with the beat of the metronome. The duration for drawing one back-and-forth line and that for pausing were one beat interval – 550ms. The participants wore a splint to constrain the number of joints involvement. The position of the elbow was supported in this condition.

The entire experiment lasted approximately 90 minutes including the screening tests. Children were allowed to take breaks between trials and conditions.

Data Analysis

The time series representing the *x/y* position of the pen movement were filtered through an eighth-order dual-pass Butterworth filter (cut-off frequency: 10 Hz). The position data were detrended before any analysis. A custom MATLAB program was used to mark each movement segment, i.e., one cycle or one back-forth line, based on the following criteria. For the continuous circle drawing, the starting and the ending of each movement segment were marked when the position in the y-axis was positive and the position in the x-axis passed the zero (equivalent to the top of the circle template). For the continuous line drawing, the starting and the ending of each segment were marked when the position in both x- and y-axis was positive and close to the top end of the ellipse. For the discontinuous circle and line drawings, the tangential pen velocity was first numerically obtained from the position data, and the maximum peak velocity was found. Then, the program searched the velocity time series, marked the starting points for each movement segment when the velocity rose higher than 5% of the maximum peak velocity and marked the ending points for each segment when the velocity dropped lower than 5% of the peak velocity. On the basis of these criteria, the experimenter visually inspected the data to verify that the identified starting and ending points for each segment were appropriate. In a few cases in which the algorithm failed to mark the starting or ending points, the experimenter manually adjusted the marks. Once all the segments were verified, the dependent variables were calculated.

Dependent Variables

Movement time (MT, sec) was defined as the time taken for completion of one segment. In other words, the time for completion one circle or one back-and-forth line.

Movement Time Coefficient of Variation (CVMT, unit free) was calculated using the standard deviation of the MT divided by mean of MT, then times 100 to measure the temporal variability of the movements.

Movement total distance (TD, cm) was the total movement length traveled by the pen for each individual segment, i.e. one circle or one back-and-forth line.

Total Distance Coefficient of Variation (CVTD, unit free) was calculated using the standard deviation of TD divided by mean of TD, then times 100 to measure the spatial variability of the movements.

Root mean squared error (RMSE, in cm) was calculated to assess the average deviation of the spatially re-sampled (to achieve equally-distant data samples) movement trajectory from the ideal traveling trajectory in each movement segment,

$$RMSE\ (in\ mm) = \sqrt{\frac{\sum_{i=1}^{N}\left[(x_a - x_i)^2 + (y_a - y_i)^2\right]}{N}} \qquad (1)$$

where (x_a, y_a) and (x_i, y_i) were corresponding points of the re-sampled trajectory and the mean trajectory, respectively, and N is the number of points in the path.

Statistical Analysis

A mixed model linear regression analysis was used for all the dependent variables (MT, CVMT, RMSE, TD, CVTD). The age was treated as continuous variable and condition (continuous circle, discontinuous circle, continuous line and discontinuous line) was treated as a categorical variable. The variance and co-variance structure were adjusted since the later independent variable was a repeated measure. Multiple contrasts among the four slopes were used to test the age-related differences in four types of drawing. The interactions in temporal variability (CVMT) between age and conditions are our particular interest.

Results

Overall, all children were able to successfully perform the task although their performance differed across age groups. Figure 3.1 shows the exemplars in each age group (from 5 to 10 years of age) during the continuous, discontinuous circle and line drawing. As expected, older children showed more consistent trajectories over repetitive circling, with the younger group showing more variable response in both conditions.

Since the cerebellar ‘timing’ was considered to be at the millisecond range (Handy, Gazzaniga, & Ivry, 2003; Ivry & Richardson, 2002), we first observed how long it took for children to complete one cycle. Individual data (Fig. 3.2) showed that the mean for all children in all conditions were lower than 1.1s, suggesting all participants were moving within the ‘cerebellar timing’ range. Regression analysis revealed a significant age by condition interaction for MT ($F_{(3,87)}=2.70$, $P=0.05$), that was due to the slope differences in the continuous circle, continuous line contrast, and the discontinuous circle, continuous line contrast. The mean difference for MT decreased approximately 0.2s from the continuous, discontinuous circle drawing to the continuous line drawing (both $P<0.05$) in the 5-year-olds while the MTs for the older age children were very close to each other (less than 0.1s).

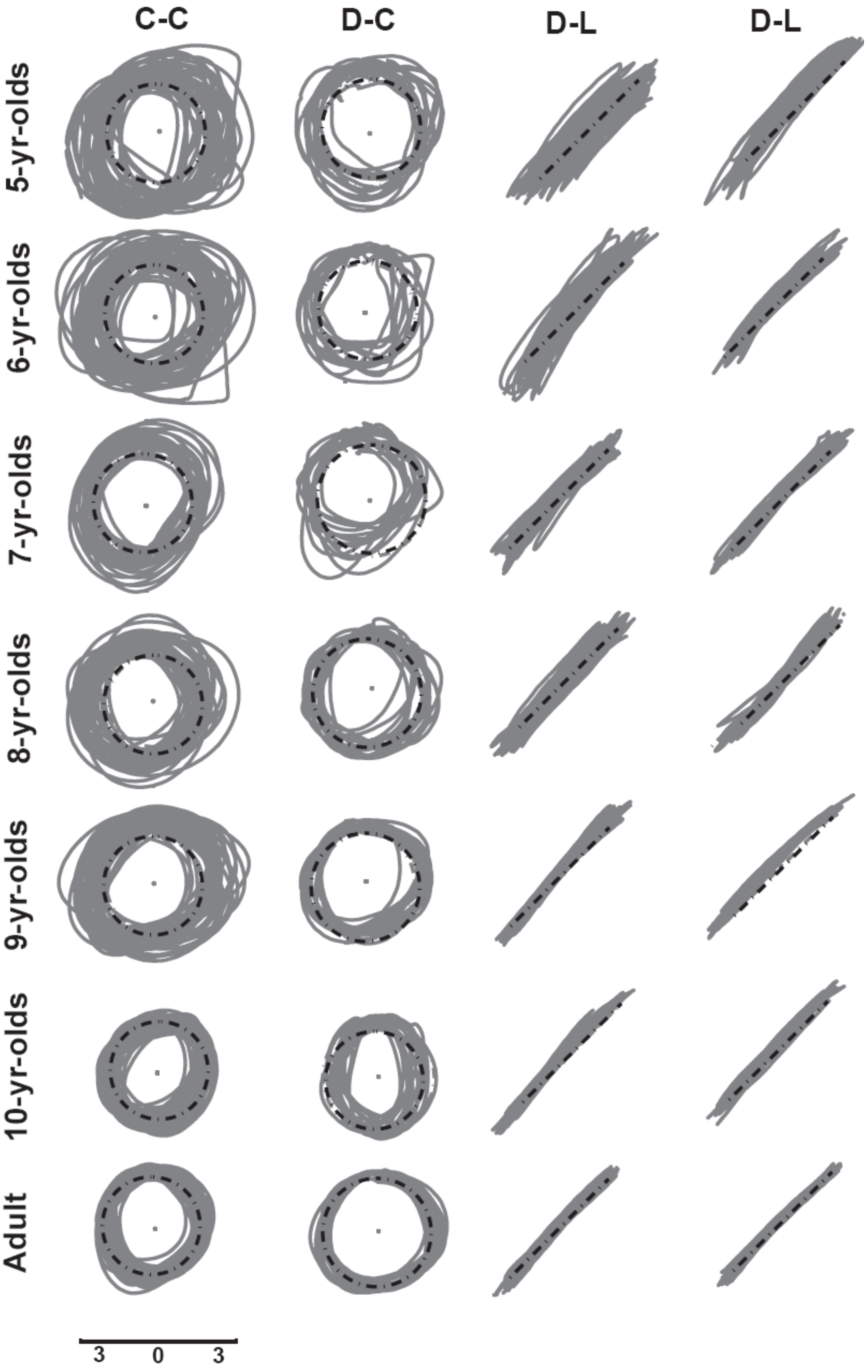
C-C
D-C
D-L
D-L
5-yr-olds
6-yr-olds
7-yr-olds
8-yr-olds
9-yr-olds
10-yr-olds
Adult
3
0
3

Figure 3.1 Movement path for the continuous, discontinuous circle and line drawing: paths shown are from one subject for each age group. Scale indicates centimeters.

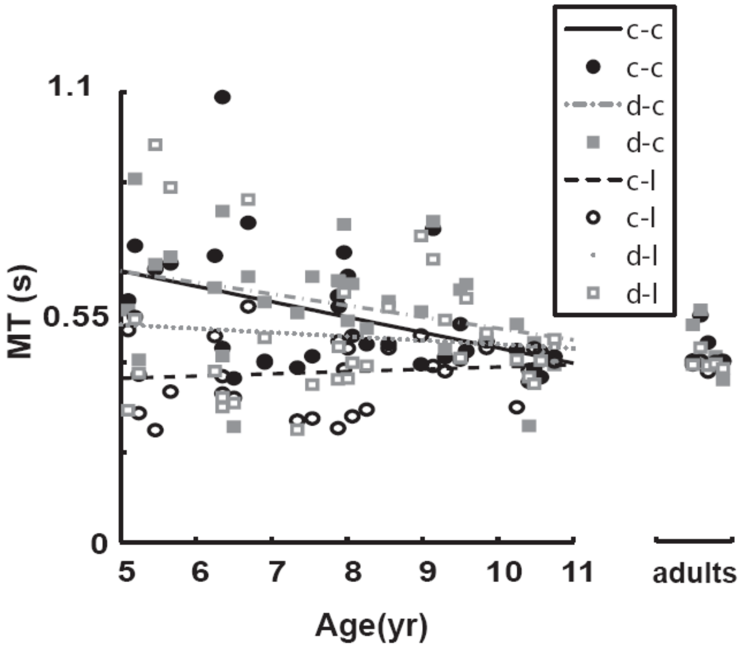

Figure 3.2 Age regression for movement time (MT). The solid line and circles show the linear regression and individual MT for the continuous circling. The dot-slash line and solid squares represent the linear regression and individual MT for the discontinuous circling. The slash line and empty circles show the linear regression and individual MT for the continuous line drawing. And the dotted line and empty squares represent the linear regression and individual MT for the discontinuous line drawing.

The ideal travel distances for completion one circle and one back-forth line are about 15cm and 14cm respectively. Significant age ($F_{(1,29)}$=4.61, P<0.05) and condition effect ($F_{(3,87)}$=26.59, P<0.01), revealed that younger children draw much longer compared to the older children (Fig. 3.3). All children traveled longer in the circle than lines drawing (all P<0.05).

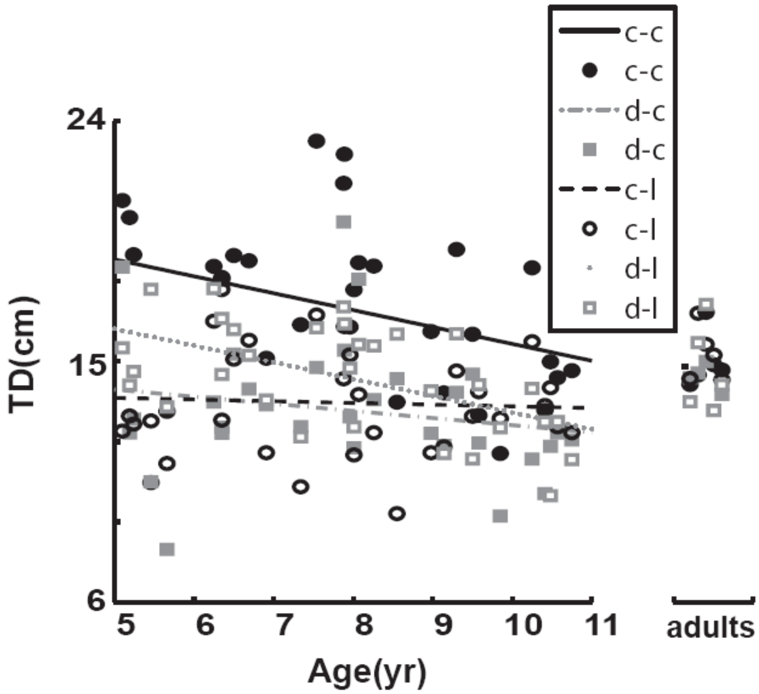

Figure 3.3 Age regression for movement distance (TD). For explanation of legends see Figure 3.2.

The CVMT is the key measure for the current study since it is thought to reflect the temporal consistency in repetitive movements. All slope coefficients were significantly different from zero (all $P<0.05$) suggesting that the temporal variability decreased with increasing age in all four types of movements. A significant age by condition interaction ($F_{(3,87)}=15.99$, $P<0.01$; see Fig. 3.4) revealed that compared to the older children, the younger children showed much higher temporal variability in the discontinuous circling but not in the other three conditions. The 5-year-olds decreased their temporal variability dramatically by 15 from the discontinuous to the continuous circle drawing while the 10-year-olds showed the similar temporal variability between these two conditions. Interestingly, contradictory to the ‘explicit timing’ hypothesis, we found that there were no age-related differences between the continuous and discontinuous line drawing in children. No difference was found between continuous circle drawing and line drawing either (*P*=0.81).

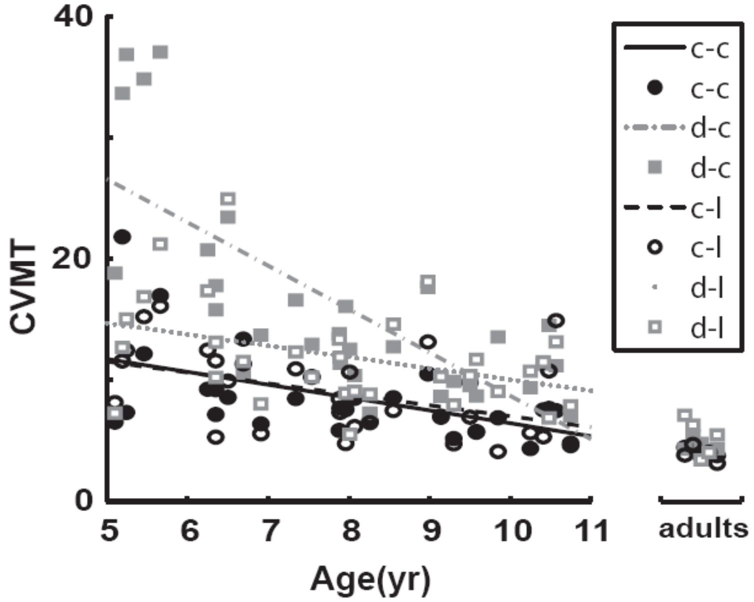

Figure 3.4 Age regression for coefficient of variation of movement time (CVMT). For explanation of legends see Figure 3.2.

The spatial variability was measured in two ways: the RMSE represents the variability between the real trajectory and the ideal movement (template); the CVTD represents the variability among real repetitive cycles. A mixed model regression analysis revealed the significant main effects of age ($F_{(1, 29)}$=5.99, $P<0.05$) and condition ($F_{(3, 87)}$=27.43, $P<0.01$) in RMSE (Fig. 3.5). All age children improved their spatial variability in all four types of movements. However, the circle drawings, both continuous and discontinuous, stayed more variable than the line drawing in all children, as measured by RMSE. The statistical results in CVTD were very similar to those in CVMT. Significant age by condition interaction ($F_{(3,87)}$=13.20, $P<0.01$; see Fig. 3.6) revealed that the younger children had much higher spatial variability than the older children in the discontinuous circling but not in the others. The older age children could maintain their spatial variability among four types of movements while the 5-year-olds could decrease their spatial variability by either moving continuous circles (15 units better) or drawing lines (7 units better). No significant difference was found between continuous circle and line drawing (*P*=0.50).

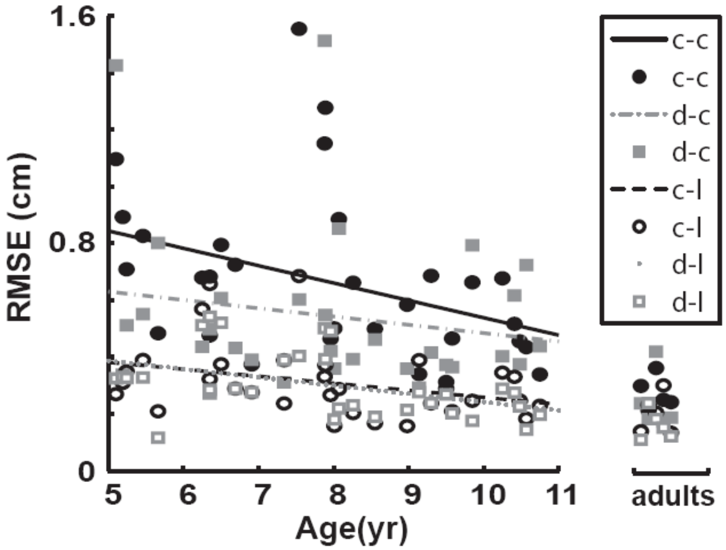

Figure 3.5 Age regression for RMSE. For explanation of legends see Figure 3.2.

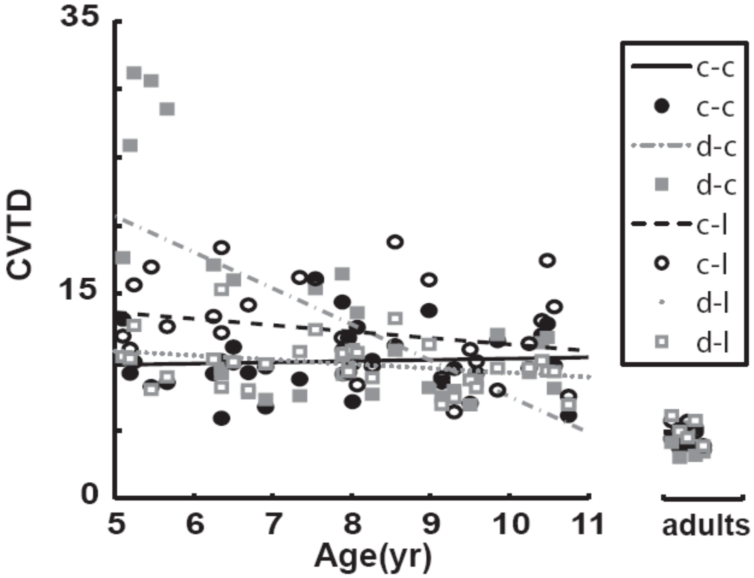

Figure 3.6 Age regression for coefficient of variation of movement distance (CVTD). For explanation of legends see Figure 3.2.

Discussion

The present study investigated whether there were different developmental trends in children’s discontinuous versus continuous drawing movements. Based on the ‘explicit timing’ hypothesis, we should expect that the young children showed high temporal and spatial variability in two types of discontinuous drawing, regardless circles or lines. Our results revealed that higher variability existed only in the discontinuous circling but not in the other conditions. The “explicit timing” process seems not to be able to explain our findings in children since the event timing should exist in both the discontinuous circle and line drawing. In a recent study (Bo et al., 2005), we examined whether we could improve cerebellar performance (i.e. both temporal and spatial variability) during discontinuous and continuous circling movements by supplying external timing information. Cerebellar subjects and controls performed continuous and discontinuous circling in fast speed with constant visual pacing (i.e. external timing). During “constant visual pacing”, subjects could see a dot moving around the circle at the desired pace for the entire time. Based on the ‘explicit timing’, we should expect that patients could improve their temporal variability since they wouldn’t need to rely on their event timing. Results showed that the opposite happened, the patients’ temporal variability actually increased. Further analysis showed that most of the control subjects could precisely predict when to start and stop a circle at appropriate time while the patients showed large variability in predicting when to initiate a movement. Thus, the cerebellar patients could not make appropriate movement planning based on the external sensory information. We argued that it was the less-tuned internal representation of sensory-motor relationship that related to their highly variable performance.

A number of developmental studies suggested that the internal sensory-motor representation is not fully developed (finely-tuned) in early childhood (Contreras-Vidal et al., 2005; Ferrel, Bard, & Fleury, 2001; Jansen-Osmann et al., 2002). Large variability in movement planning was found in younger age children during a computer-manipulated kinematic adaptation task (Contreras-Vidal, Bo, Boudreau, & Clark, 2005). Initial direction of movement, computed at 80ms after movement onset, showed a progressive tuning of movement direction with increasing age during baseline condition. On introduction of the screen cursor rotation, the 4-year-olds were less affected than older age children by the distortion during the early exposure period. Only the 8-year-olds showed significant aftereffect indicating that young children had less developed (i.e. broader) internal sensory-motor representation for hand movement. Less-tuned limb dynamics were also reported in force adaptation study (Jansen-Osmann et al., 2002). Younger age children had prolonged re-adaptation back to a null-force condition after they showed aftereffects suggesting that neural representation of limb dynamics in children lacked precision. Developing (sharpening) internal representations for limb dynamics and kinematics could both contribute to the high variability in children's movements. In the handwriting literature, it has been argued that the high neuromuscular noise level relates to the poor handwriting products (Smits-Engelsman & van Galen, 1997; van Galen, Portier, Smits-Engelsman, & Schomaker, 1993). Combining these findings, we can argue that the less-tuned internal representation of limb dynamics and kinematics is playing a very important role in controlling the drawing and writing movements in children.

In the current study, we simplified the complexity of the limb dynamics in the line drawing than that in the circle drawing by controlling the number of joint involvements. If the limb dynamics was playing an important role in the discontinuous and continuous drawing, we should expect different age-related trends in the line drawing vs. the circle drawing. In fact, the results pointed in this direction: both the temporal and spatial variability were very similar between the discontinuous and continuous line drawing, and were much lower than those in the discontinuous circle drawing. Decreasing the complexity of the limb dynamics could improve children's performance dramatically suggesting that children could keep similar temporal consistency in the dynamically simpler movements regardless of 'explicit timing' or 'implicit timing'. Kawato and colleagues have proposed that the cerebellum is very critical in adjusting the complex dynamics (interaction torques) during multijointed movements (Schweighofer, Arbib, & Kawato, 1998a; Schweighofer, Spoelstra, Arbib, & Kawato, 1998b). The cerebellar patients can make almost normal single-jointed reaching movements by fixing the shoulder, but have problems in the multiple-jointed reaching movements (Bastian et al., 2000). Our current results were consistent with the role of dynamic control in the cerebellum. Children had more difficulties in drawing the discontinuous circles, supposedly because their internal representation of limb dynamics and kinematics are not finely tuned and the dynamic control of the discontinuous circling is more challenging. Similar to the findings in the studies with cerebellar patients, when the control of limb dynamics was not that difficult (e.g. moving continuously, or drawing lines with single joint), the young children showed a much more consistent performance.

In summary, the children’s performance in continuous versus discontinuous drawing was not consistent with the predictions based on the ‘explicit timing’ hypothesis. Instead, the notion of limb dynamics control mediated by the cerebellum fits better to our current results. Decreasing the complexity of limb dynamics improved the temporal variability in young children, indicating that developing limb dynamics control may play an important role in the development of drawing skills in children. Our current behavioral findings, together with other evidence in animal (Gramsbergen, 2003) and human studies (Giedd et al., 1996), support the involvement of the developing cerebellum in the development of drawing and writing skills. However, it is important to note there is no simple linkage between brain structure and observed behavior. The current behavioral study is just a first step to examine the hypothesis that the function of the developing cerebellum might play an important role in the motor development in children. It is very possible that other mechanisms may also play important role in the development of drawing and writing skills.

CHAPTER IV

EXPERIMENT II

TEMPORAL CONSISTENCY IN CHILDREN WITH DEVELOPMENTAL COORDINATION DISORDER DURING CONTINUOUS AND DISCONTINUOUS DRAWING

Abstract

Patients with cerebellar lesions were reported to have restricted timing deficits in the discontinuous but not in the continuous circle drawing tasks (Spencer et al., 2003). This is thought to reflect the ‘explicit timing’ processes that require the integrity of the cerebellum for control of discontinuous movements. Similarly, children with Developmental Coordination Disorder (DCD) were reported to have high temporal variability in tasks that require precise timing. The current study examined the temporal consistency in the children with DCD performing the continuous and discontinuous drawing. Would children with DCD show the timing deficits similar to that of patients with cerebellar lesion? Could they improve their timing variability by decreasing the complexity of limb dynamics? Ten children with DCD and thirty-two children who were typically developing between the ages of five and eleven years (ten of these thirty-two were gender- and age-matched controls to the children with DCD) performed the continuous, discontinuous circle- and line-drawing tasks in random order. They were asked to move as consistently as possible for 20 seconds after synchronizing their movements with the metronome for 15 beats. The target speed was 550 ms for completion of one circle or one back-forth line. Group (DCD vs. control) and condition

main effects were found suggesting that both children with DCD and their controls had higher temporal variability in the discontinuous than that in the continuous drawings. Both groups of children improved their temporal consistency at similar level in the line drawing tasks. Individual comparisons between each child with DCD and the performance of children who were typically developing revealed interesting findings. Five out of ten children with DCD showed limited timing deficits in the discontinuous line drawing with two also having timing problems in the discontinuous circle drawing. The possibility of a compromised cerebellar function may only exist in subgroup of children with DCD supporting the heterogeneous nature of this population.

Introduction

One of the most salient features of coordinated movements is the temporal consistency across repetitions. Children with Developmental Coordination Disorder (DCD, also previously labeled as ‘clumsy’ or ‘uncoordinated’[3]) showed much higher temporal variability than age-matched controls in tasks that require precise timing (Geuze & Kalverboer, 1987; Lundy-Ekman, Ivry, Keele, & Woollacott, 1991; Williams, Woollacott, & Ivry, 1992). While up to 6% of American school children are thought to have this disorder (APA, 1994), its underlying mechanism and etiology are still not well understood except that it is not due to general medical conditions such as cerebral palsy or muscular dystrophy.

One idea that certain developmental disorders can be linked to specific neurological abnormalities has recently taken firm hold in the neuroscience community

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[3] I use Developmental Coordination Disorder in current study based on American Psychiatric Association’s Diagnostic and Statistical Manual of Mental Disorders IV or the DSM IV (1994)

(Ivry, 2003; Nicolson, Fawcett, & Dean, 2001). A few studies indicate that children who were then classified as ‘clumsy’ had difficulties in fine motor tasks requiring precise timing (Geuze et al., 1987; Lundy-Ekman et al., 1991; Williams et al., 1992) similar to that observed in adult patients with cerebellar lesion. Clumsy children were significantly more variable than normal children in maintaining a set rate of tapping and in accurately judging time intervals (Williams et al., 1992). Some children with DCD were also reported to have higher timing variability in repetitive hand tapping, foot tapping, and jumping in place (Parker, Larkin, & Wade, 1997). Therefore, one hypothesis that has emerged is that the poor timing in some children with DCD may be attributed to cerebellar dysfunction although the underlying neural bases of clumsiness may be heterogeneous (Ivry, 2003).

The cerebellum plays a critical role in the precise representation of temporal information. Recently, it has been proposed that there are separate timing mechanisms controlling the temporal consistency in the different types of movements (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002). Timing can be event-related. Making discontinuous circle drawing or repetitive finger tapping requires an explicit representation of the temporal goal (i.e. when to start and stop) or explicit timing process. In contract, timing can be an emergent property in other actions reflecting temporal consistencies that arise through the control of other movement parameters (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). One example is continuous circle drawing, a task in which temporal consistency can be achieved by maintaining a constant angular velocity or minimizing higher-order derivatives. Support evidence for this claim can be found in the behavioral studies of patients with cerebellar lesions (Spencer, Zelaznik, Ivry, & Diedrichsen, 2002; Spencer et al., 2003). Patients with cerebellar damage show no increase in temporal variability during continuous circle drawing. The timing deficits are restricted to the discontinuous circle movements, which require initiation and termination for each circle during circle drawing. Based on their finding, Spencer et al. (2003) have proposed that timing emerged from the continuous drawing trajectory and is thus an “implicit timing” process. Discontinuous drawing, on the other hand, requires an “explicit timing” process that times the occurrence of specific events. This latter process involves the cerebellum.

Therefore, as a first step to examine the hypothesis that cerebellar dysfunction might be a major contributor for the timing deficit in some children with DCD, we used the continuous versus discontinuous circle drawing paradigm (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003), which required either “implicit timing” or “explicit timing” processes in controlling temporal consistency. Would children with DCD show the timing deficits in the discontinuous drawing similar to that of patients with cerebellar lesion? The first purpose for the current study was to examine the temporal consistency in the continuous versus discontinuous circle drawing in children with and without DCD. If a group of children with DCD had cerebellar ‘explicit timing deficit’, we could predict that children with DCD had much higher temporal and spatial variability in the discontinuous circle drawing than their age matched controls.

An alternative to the ‘explicit timing’ hypothesis, the temporal differences between the continuous and discontinuous drawing could be also explained by the dynamics of the discontinuous movement, which may be more difficult to control in the discontinuous drawing. The predictive control of complex dynamics (interaction torques) during multijointed movements has also been proposed as one of major cerebellar functions (Schweighofer, Arbib, & Kawato, 1998a; Schweighofer, Spoelstra, Arbib, & Kawato, 1998b). Patients with cerebellar lesion can make almost normal single-jointed movements, but have problems in the multiple-jointed movements (Bastian, Zackowski, & Thach, 2000). Volman and Geuze (1998) have reported that variable bimanual coordination in children with DCD is due to the deficit in dynamic movement control, as expressed by a less stable coordination stability. Will the 'dynamics' play a role in continuous and discontinuous drawing? This alternative hypothesis, which is also proposed as a major function in cerebellum, may help us understand whether the timing difficulty in the circle drawing task can be improved by decreasing the complexity of limb dynamics. Therefore, the second purpose for this study was to test the temporal consistency between the continuous and discontinuous line movements in children with and without DCD. Experimentally, we controlled the number of joints so that only the elbow was involved in the line drawing.

As noted by many researchers, the DCD population is comprised of heterogeneous subgroups. This raises the possibility that cerebellar dysfunction might be present in on subgroup of children with DCD and absent in other subgroups. Previous studies have addressed this issue by grouping participants using different criteria. Lundy-Ekman (1991) divided the clumsy children based on the soft neurological signs. Parker (1997) subgrouped children according to their performance on fine and gross motor tasks. With diverse ways of categorization, it is still not clear what are the appropriate grouping criteria. Thus, instead of subgrouping children, we evaluated the children with DCD individually based on the overall performance in children who were typically developing. We expected that some of the children with DCD would demonstrate higher temporal and spatial variability than the children who were typically developing while others not. The confidence intervals were calculated to define the range of normal performance using regression analysis on children who were typically developing.

In summary, the current study examined the temporal consistency in children with DCD performing the continuous and discontinuous drawing. Specifically, we observed 1) whether children with DCD showed the restricted timing deficits in discontinuous movement that patients with cerebellar lesion were reported to have problems with; and 2) whether they could improve their timing variability by decreasing the complexity of limb dynamics. We approached these questions in two ways. First, a comparison between the children with DCD and matched controls represented the overall group performance. Then, a comparison between individual children with DCD and the confidence limits (normal performance) defined by typically developing children could help identify those children who had difficulty in these tasks.

Methods

Subjects

Ten children (2 females, 8 males) diagnosed with Developmental Coordination Disorder DCD (DCD group, mean age 9.03 ± 1.40), and thirty-two children at the similar age level (range from 5 to 11 years of age, mean age 9.14 ± 1.27) who were typically developing from the area surrounding a suburban university community were recruited as subjects. Ten out of these thirty-two children were gender- and age-matched controls (control group, within ± 3 month) to ten children with DCD. All children were screened in the Movement Assessment Battery for Children (MABC, Henderson and Sugden, 1992) test and the Beery–Buktenica Developmental Test of Visual-Motor Integration (VMI, 4th edition, Beery, 1997). The Woodcock-Johnson Revised Cognitive Ability Early Development Scale (Woodcock & Johnson, 1990), and a pediatrics evaluation were added to screen the children with DCD. The inclusion criteria for children with DCD were 1) the MABC score at or below the 5th percentile (Henderson & Sugden, 1992); 2) normal cognitive ability as assessed by the Woodcock-Johnson Revised Cognitive Ability Early Development Scale (Woodcock et al., 1990); and 3) a DCD diagnosis from a pediatrician specializing in movement disorders. The exclusion criteria for children who are typically developing were 1) the standardized VMI score lower than 1½ standard deviations below the mean; and 2) the MABC score lower than 30th percentile. Children's parents or legal guardians were fully informed of the task purpose, and signed the consent forms prior to the child's participation in the study. The handedness was determined using MABC criteria. All procedures were approved by the Institutional Review Board of the University of Maryland-College Park. Upon completion of the experiment, participants received a modest remuneration as well as a toy.

Apparatus

Participants were seated in front of a table with a digitizing pen taped on their dominant hand's extended index finger (the hand used for handwriting). The height of the chair was adjusted so that the participants' hand could move freely at the horizontal plane, and the lower end of their sternum touched the tabletop throughout the experiment. A digitizing tablet (WACOM InTuos™, Vancouver) was placed on the table and centered at the participant's midline in front of the chest so that participants could directly look at their hand and a template during the whole experiment. The tablet was used to collect data on the pen position in the X-Y coordinates at 200 Hz sampling rate using custom software written in OASIS™ (Kikosoft, Nijmegen). The real-time visual feedback of the pen movements on the digitizing tablet was only available for the experimenter during the experiment. The participants' movement trajectories were recorded and stored on a computer for off-line processing. A paper template, either a circle or a 45-degree slanted thin ellipse, was placed at the center of the tablet. The diameter for the circle template was 5 cm. The size for the ellipse template was 5√2 cm in long-axis and 0.2 cm in short-axis. At the beginning of each trial for all conditions, a metronome (Quikwatz) was turned on to initiate the movement rhythm. The target cycle duration (the time to complete one circle or one thin ellipse) was fixed at 550 ms. After approximately 10-15 beats when the participant got the rhythm, the metronome was turned off. The participants were asked to move as consistently as possible for 20 seconds till that trial ends. We instructed participants to use the template as a guide rather than try to strictly trace the circle or ellipse.

Procedures

Before any tests started, the purposes and procedures were fully explained to both parents and participants with appropriate language. All participants were assessed through the screening tests before the drawing tests. For children with DCD, the participants were scheduled multiple visits for screening tests. Only the children who meet the inclusion criteria as DCD were scheduled for the drawing tests.

Screening tests

All screening tests took place in a quiet testing area. The Movement Assessment Battery for Children (Henderson et al., 1992) test was administered first to identify the overall motor performance. The Beery–Buktenica Developmental Test of Visual-Motor Integration (Beery, 1997) was tested afterward to evaluate the fine motor skill level. A 5-minute break was taken between the two screen tests. If the child was not disqualified to be a typically developing participant, he/she was excluded for the drawing tests. For children with DCD, the VMI was administered before the drawing tests because all other screenings had already been tested in prior visits.

Drawing experiment

The participants performed the continuous, discontinuous circle and line drawing movements on a template using their index finger in random order. The participants had one trial to get familiar with the task before each condition started. A formal trial began when the experimenter announced ‘ready, go’ and initiate the metronome. The participants synchronized the movements with the metronome for 15 beats and were asked to move as consistently as possible for 20 seconds without metronome afterwards. The instruction emphasized the temporal consistency instead of spatial accuracy throughout the tests. There were five trials in each condition. The randomization was among four conditions not among trials.

For continuous circle drawing (condition 1), the participants were asked to start each trial with the pen tip on the top of the circle template. They then made continuous counter-clockwise movements around the circle and tried to coincide each of their circling with the metronome beats at the top of the template. For discontinuous circle drawing (condition 2), the participants were asked to start each trial with the pen tip on the top of the circle template. They then made counterclockwise circle movement between two beats (one interval - 550ms), waited for the next beat (i.e. paused for one interval) before drawing the next circle. During these two circle drawing conditions, participants' wrist and fingers were not constrained, and the movements could be achieved by multiple-joints motions including elbow and shoulder.

During the continuous line drawing (condition 3), The participants started a trial at the upper end of the ellipse template and tried to pass the finger at the upper end of the ellipse coinciding with the beat of the metronome (550ms per up-and-down motion) while moving back-and-forth between two ends continuously. During the discontinuous line drawing (condition 4), the participants were asked to draw a back-and-forth line on the thin ellipse template for each interval formed by two beats, then waited for the next beat (i.e. paused for one interval) before the next back-and-forth movement. They attempted to initiate and stop one movement cycle, i.e. discontinuous line drawing, at the upper end of template coincident with the beat of the metronome. Due to the thin short axis of the ellipse, the movement is basically a line drawing motion. The duration for drawing one back-and-forth line and that for pausing were one beat interval – 550ms. In order to control the number of joints involvement in these two conditions, the participants wore a splint to keep the wrist and fingers rigid. The position of the elbow was supported so that the back-and-forth movements were controlled by the elbow motion.

The entire experiment lasted approximately 90 minutes including the screening tests. Children were allowed to take breaks between trials and conditions.

Measures & Analyses

The time series representing the *x/y* position of the pen movement were filtered through an eighth-order dual-pass Butterworth filter (cut-off frequency: 10 Hz). The position data were detrended before any analysis. A custom MATLAB program was used to mark each movement segments i.e. one cycle or one back-forth line, based on the following criteria. For the continuous circle drawing, the starting and the ending of each movement segment were marked when the position in the y-axis was positive and the position in the x-axis passed the zero (equivalent to the top of the circle template). For the continuous line drawing, the starting and the ending of each segment were marked when the position in both x- and y-axis was positive and closed to the top end of the ellipse. For the discontinuous circle and line drawings, the tangential pen velocity was first numerically obtained from the position data, and the maximum peak velocity was found. Then, the program searched the velocity time series, marked the starting points for each movement segment when the velocity raised higher than 5% of the maximum peak velocity and marked the ending points for each segment when the velocity dropped lower than 5% of the peak velocity. On the basis of these criteria, the experimenter visually inspected the data to verify that the identified starting and ending points for each segment were appropriate. In a few cases in which the algorithm failed to mark the starting or ending points, the experimenter manually adjusted the marks. Once all the segments were verified, the dependent variables were calculated. Movement time (MT, sec) was defined as the time taken for completion of one segment (i.e. one circle or one back-and-forth line). Movement Time Coefficient of Variation (CVMT, unit free) was calculated using the standard deviation of the MT divided by mean of MT, then times 100 to measure the temporal variability of the movements. Movement total distance (TD, mm) was the total movement length traveled by the pen for each individual segment, i.e. one circle or one back-and-forth line. Total Distance Coefficient of Variation (CVTD, unit free) was calculated using the standard deviation of TD divided by mean of TD, then times 100 to measure the spatial variability of the movements. Root mean squared error (RMSE, in mm) was calculated to assess the average deviation of the spatially re-sampled (to achieve equally-distant data samples) movement trajectory from the ideal traveling trajectory in each movement segment,

$$RMSE\ (in\ mm) = \sqrt{\frac{\sum_{i=1}^{N}\left[(x_a - x_i)^2 + (y_a - y_i)^2\right]}{N}} \qquad (1)$$

where (x_a, y_a) and (x_i, y_i) were corresponding points of the re-sampled trajectory and the mean trajectory, respectively, and N is the number of points in the path.

Statistic Analysis

The statistical analyses were conducted in two different ways; one was for group comparisons between children with DCD and age-matched controls. The other was for individual comparisons between each child with DCD and the confidence limits in children who were typically developing.

Mixed model repeated-measures ANOVA with group (DCD and control) as between-subjects factor, and condition (continuous, discontinuous circles and lines) as within subjects factors were performed on the dependent measures to compare the group differences between children with and without DCD. Age was considered as co-variant since it was not of interest for this analysis but might share some of the variance in the model. LSD post-hoc procedures were employed for any significant effects.

In order to assess the individual performance in children with DCD compared with typically developing children, we performed a mixed model linear regression analysis with age being treated as a continuous variable in each condition. The 95% upper and lower confidence limits (UCL and LCL) on the individual predicted values were calculated to represent the 95% confidence intervals around the typically developing children's mean performance. Individual data higher than the UCL would suggest that the variability was higher than the normal range at a 0.05 significance level.

Results

The mean movement time for each subject was faster than 1.1s, which verified that both children with and without DCD were moving inhe 'cerebellar' timing range (Handy, Gazzaniga, & Ivry, 2003; Ivry & Richardson, 2002). Repeated measure ANOVA revealed significant main effect of group ($F_{(1,18)}$=7.86, $P<0.05$) and condition ($F_{(3,54)}$=10.36, $P<0.01$) for MT. Post hoc analysis showed that the mean MT for the discontinuous circling was about 0.2s longer than that for the continuous circling ($F_{(1,54)}$=4.22, $P<0.05$). The mean difference for MT decreased approximately 0.1s ($F_{(1,54)}$=20.27, $P<0.01$) from the discontinuous line drawing to the continuous line drawing (Fig. 4.1A). Group main effect revealed that the children with DCD moved 0.1s slower than the age-matched controls on average. The mean movement time for controls was 0.54s, which was very close to the target timing – 550ms.

The temporal variability, as measured by CVMT, showed significant age ($F_{(1,18)}$=11.74, $P<0.01$) and condition main effects ($F_{(3,54)}$=15.08, $P<0.01$). Both groups showed higher temporal variability in the discontinuous circling than that in the continuous circling ($F_{(1,54)}$=27.01, P<0.01). Higher temporal variability was also found in the discontinuous line than that in the continuous line drawing ($F_{(1,54)}$=12.62, P<0.01). Furthermore, the improved temporal variability was found from discontinuous circle to line drawing ($F_{(1,54)}$=6.25, P<0.05). The children with DCD moved more variably than the controls temporally in all conditions (Fig. 4.1B). No interaction was found suggesting that the high temporal variability was not restricted to the discontinuous drawing in these children with DCD.

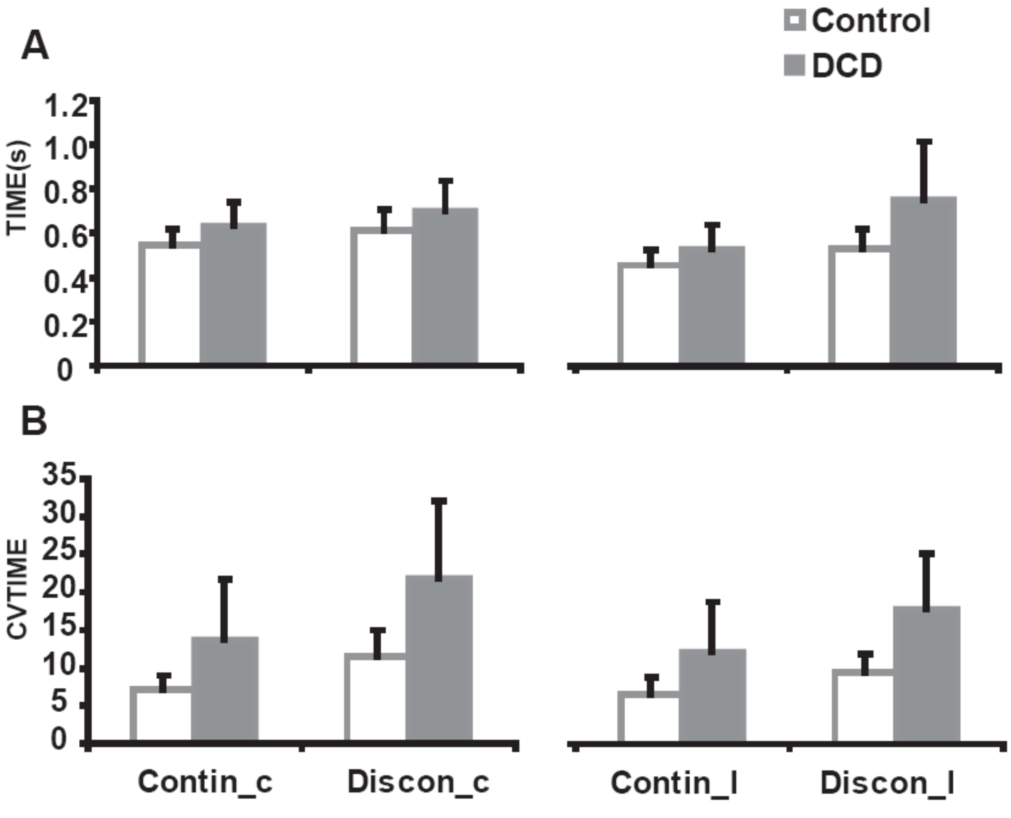

Figure 4.1 Mean and standard deviation of MT (**A**) and CVMT (**B**) between ten children with DCD and ten age- and gender-matched controls for four conditions (continuous circle, discontinuous circle, continuous line and discontinuous line drawing).

Condition main effect on TD ($F_{(3,54)}=20.18$, $P<0.01$) revealed that the children moved longer in the continuous circle drawing than others (all $P<0.01$, see Fig. 4.2). The spatial variability between the children's movement trajectory and template also varied significantly across conditions as RMSE (Fig. 4.3A) scores were higher for the continuous circling (M=0.79), the discontinuous circling (M=0.57) compared to the continuous line (M=0.32) and discontinuous line drawing (M=0.30). The spatial variability in the discontinuous circling was also significantly higher than that in the continuous circling ($P<0.01$). No statistical significant group differences were found for TD or RMSE. However, the spatial variability measure across repetitions, as measured by CVTD, showed significant main effect of group ($F_{(1,18)}=6.13$, $P<0.05$) and condition ($F_{(3,54)}=3.12$, $P<0.05$). Similar to the temporal variability measure, the children with DCD moved significantly more variable than the controls spatially (Fig. 4.3B). Condition main effect was due to the higher spatial variability in the discontinuous circling than that in the discontinuous line ($F_{(1,54)}=6.67$, $P<0.05$).

In order to observe the individual differences among the children with DCD, the confidence intervals were first calculated based on the children who were typically developing to define the normal performance range. The age regression on CVMT, shown in Figure 4.4, illustrates the individual temporal variability in each of the drawing conditions. In the continuous circling, two out of ten children with DCD

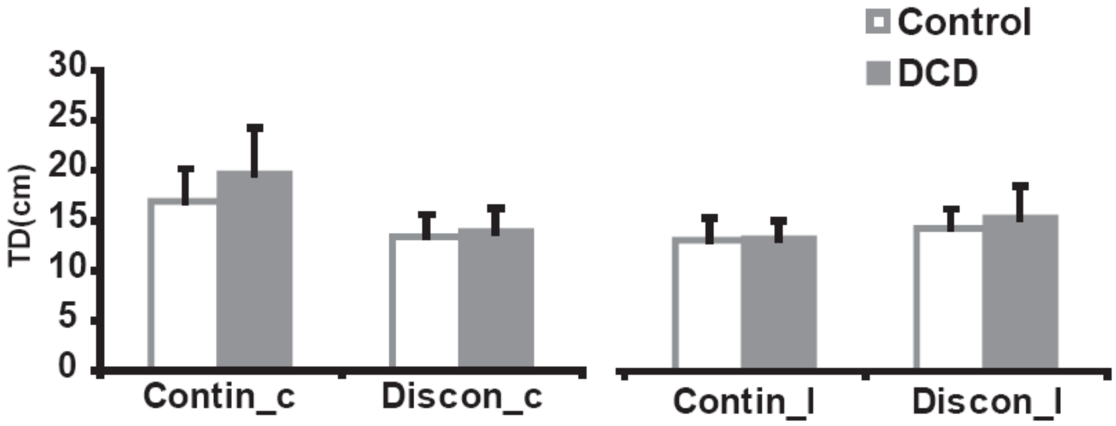

Figure 4.2 Mean and standard deviation of TD between ten children with DCD and ten age- and gender-matched controls for four conditions.

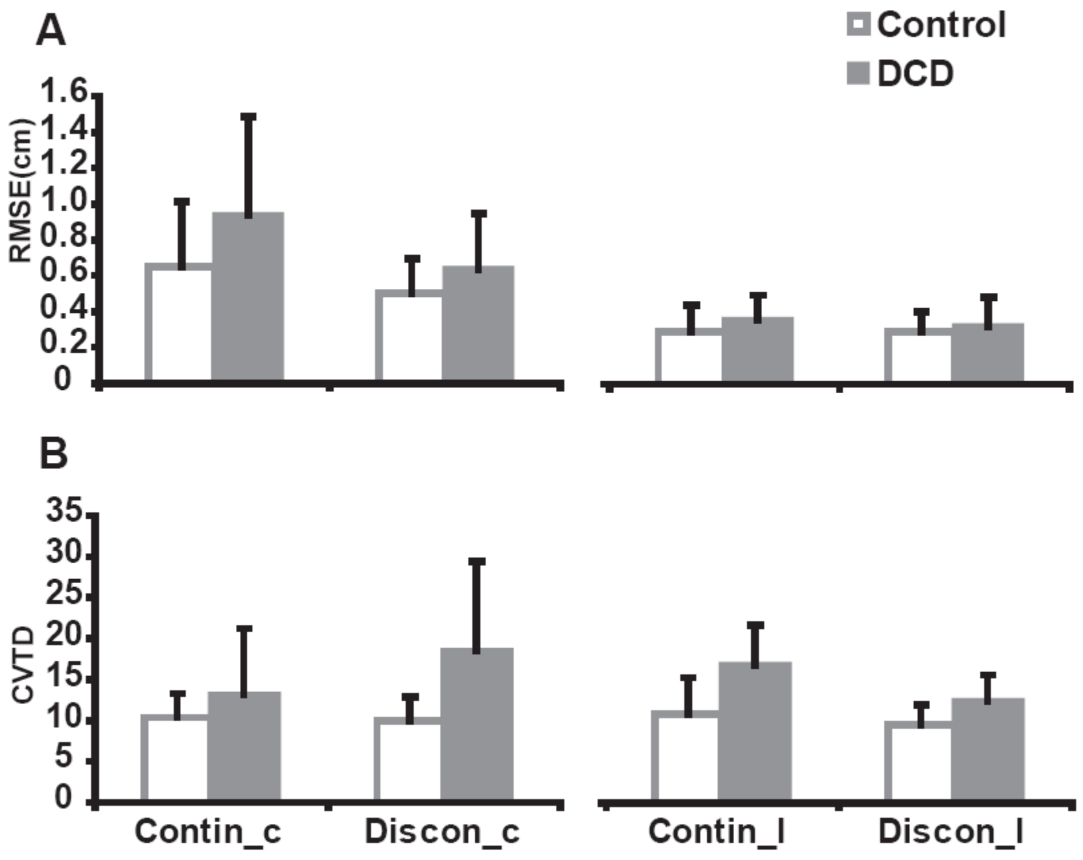

Figure 4.3 Mean and standard deviation of RMSE (**A**) and CVTD (**B**) between ten children with DCD and ten age- and gender-matched controls for four conditions.

showed higher temporal variability than the upper confidence limit (UCL). Five children had higher temporal variability than the normal range in the discontinuous circling. In the line drawing conditions, the CVMT scores were markedly higher with three children in the continuous and eight in the discontinuous drawing. Figure 4.5 is

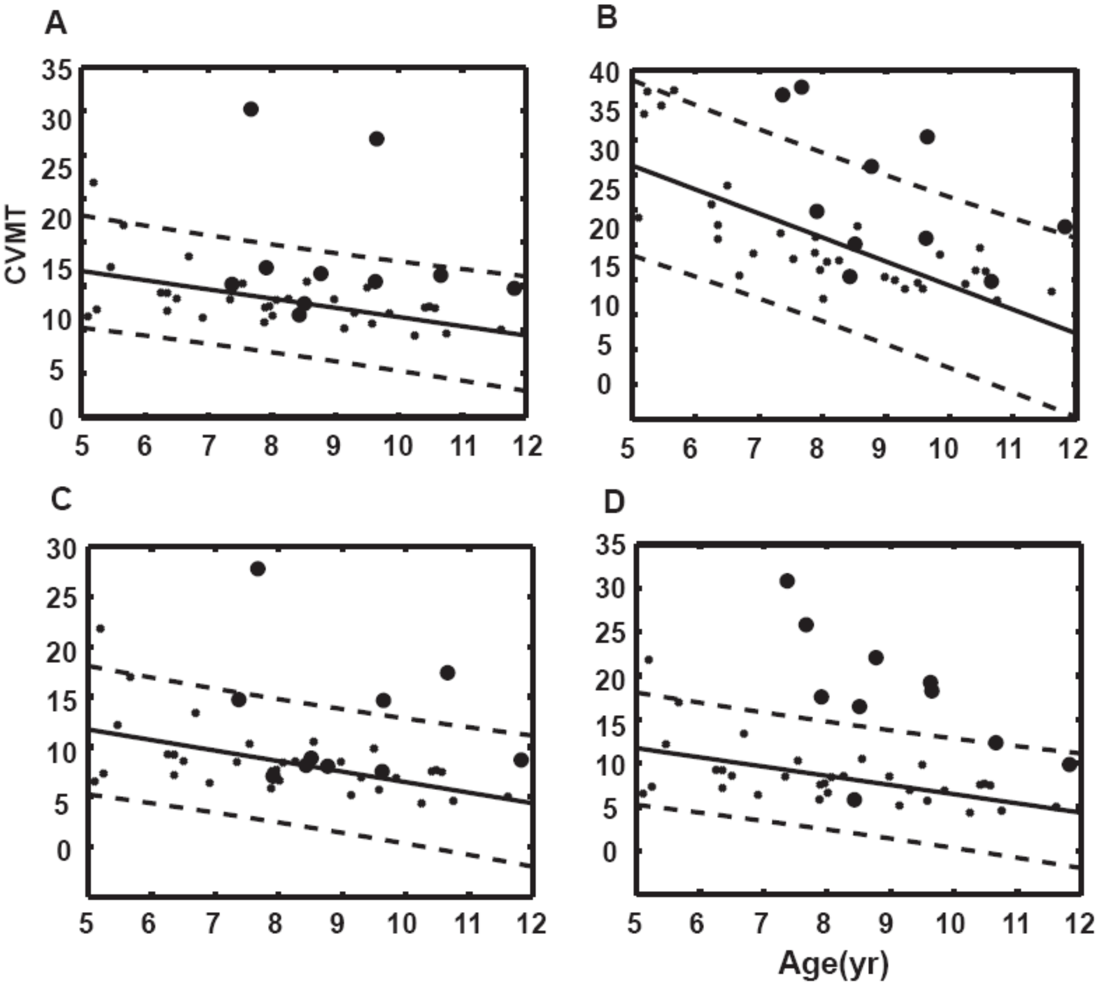

Figure 4.4 CVMT for Individual child with DCD (large solid dots) and thirty-two children who are typically developing (small solid dots) in four conditions: **A**) continuous circle, **B**) discontinuous circle, **C**) continuous line, and **D**) discontinuous line drawing. The solid line represents the age regression and two dash lines represent the upper confident limit (UCL) and lower confident limit (LCL) based on the children who are typically developing.

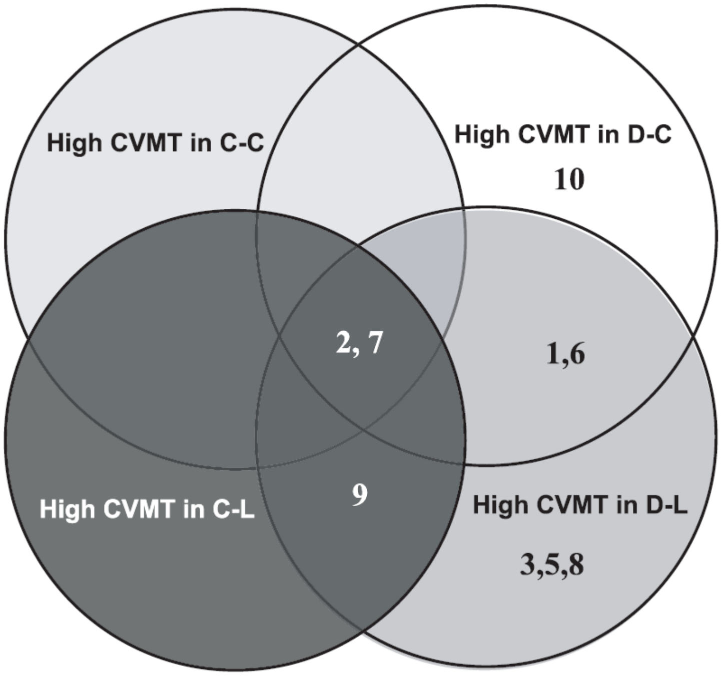

Figure 4.5 Venn diagram for individual child with DCD who had higher CVMT scores compared to UCL in four conditions.

the Venn diagram illustrating the high temporal variability in each child with DCD in four conditions. Two children with DCD (#2 and #7) showed higher temporal variability and one (#4) revealed normal performance in all four conditions. One child (#10) revealed poor temporal consistency only in the discontinuous circling. Two children (#1 and #6) showed higher temporal variability in both types of the discontinuous drawing. In addition, there are three children (#3, #5 and #8) showed impaired timing in only the discontinuous line drawing conditions. None of the children with DCD had higher temporal variability only in the continuous drawing tasks.

Figure 4.6 illustrates the individual spatial variability, as measured by RMSE, in each of the drawing conditions. Children with DCD performed similarly to the typically developing children in two line drawing conditions. Interestingly, another spatial measure, CVTD, had a different pattern (Fig. 4.7). More children with DCD showed higher variability than the upper confidence limit (UCL) in the line drawings than those in the circle drawings. Five out of ten children had higher variability than the normal range in the continuous line drawing. And three of those ten children showed high spatial variability in the discontinuous line drawing. In general, children who had higher spatial variability also had higher temporal variability in most of the conditions.

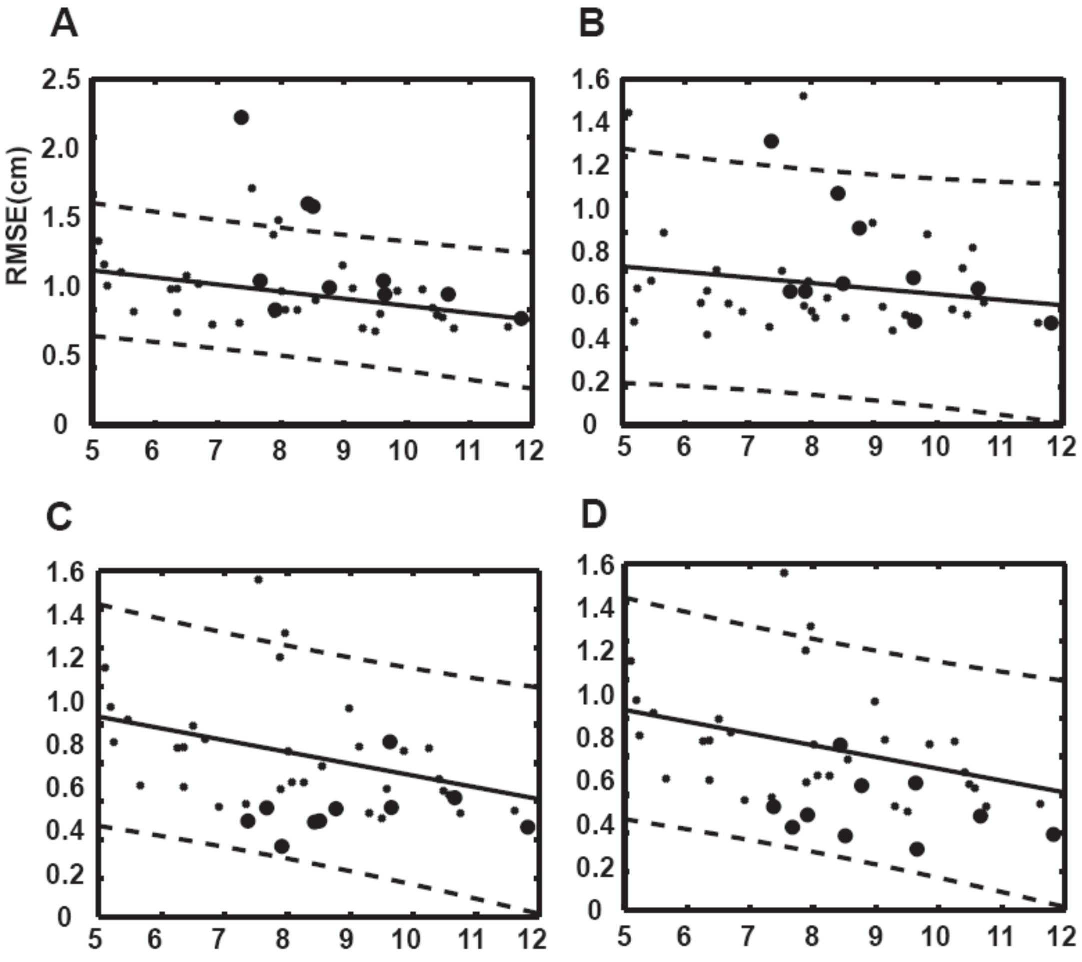

Figure 4.6 RMSE for Individual child with DCD (large solid dots) and thirty-two children who are typically developing (small solid dots) in four conditions: **A**) continuous circle, **B**) discontinuous circle, **C**) continuous line, and **D**) discontinuous line drawing. The solid line represents the age regression and two dash lines represent the upper confident limit (UCL) and lower confident limit (LCL) based on the children who are typically developing.

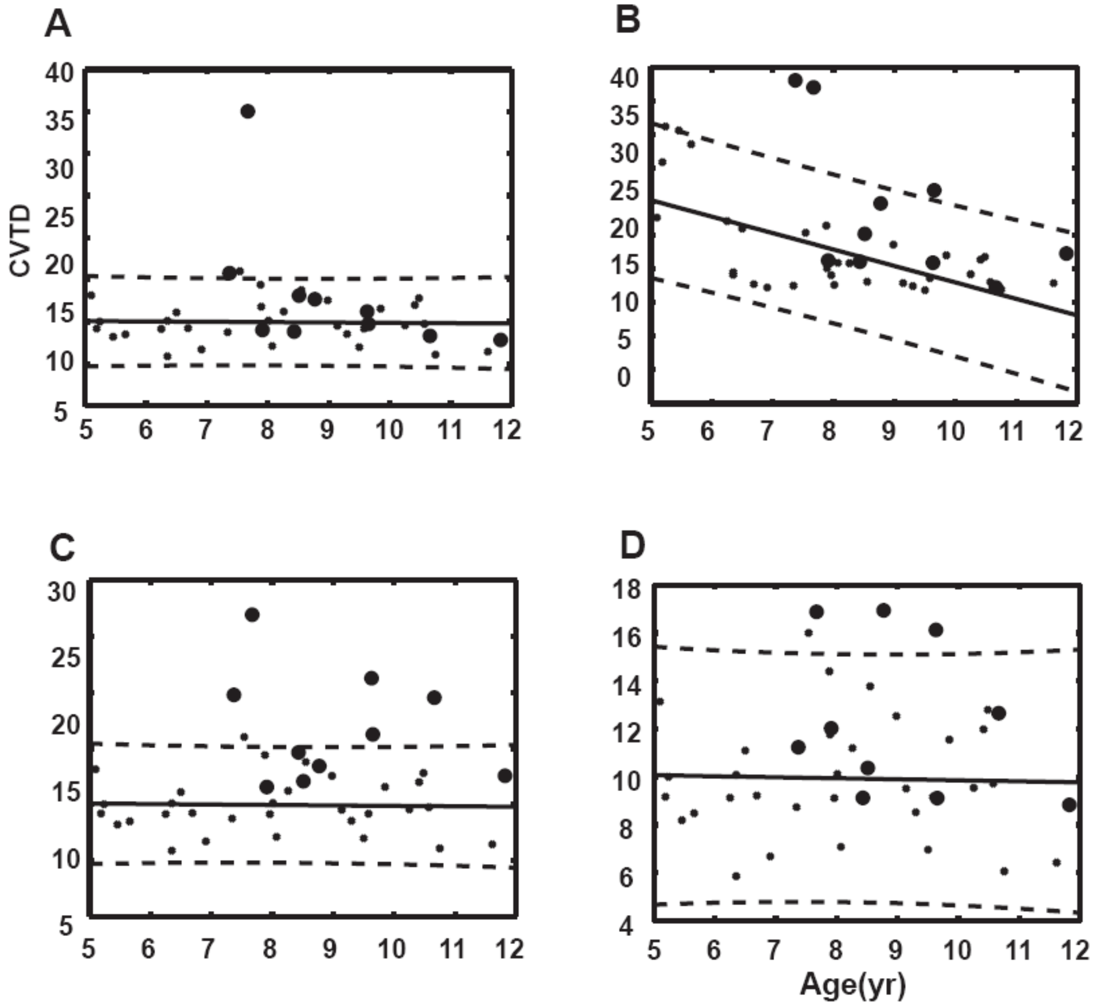

Figure 4.7 CVTD for Individual child with DCD (large solid dots) and thirty-two children who are typically developing (small solid dots) in four conditions: **A**) continuous circle, **B**) discontinuous circle, **C**) continuous line, and **D**) discontinuous line drawing. The solid line represents the age regression and two dash lines represent the upper confident limit (UCL) and lower confident limit (LCL) based on the children who are typically developing.

Discussion

The present study investigated the temporal consistency in continuous and discontinuous drawing in children with DCD. We tested the hypothesis that the cerebellar dysfunction might be a major contributor for the timing deficit in some children with DCD, based on a recent finding that patients with cerebellar lesion had timing deficits limited to discontinuous but not in the continuous circling (Spencer et al., 2003). Three questions were asked: 1) whether children with DCD showed the restricted timing deficits similar to patients with cerebellar lesion; 2) whether they could improve their timing variability by decreasing the complexity of limb dynamics; and 3) whether we could identify the heterogeneity of children with DCD based on their behavioral performance?

The main finding from the group comparison was not consistent with the 'explicit timing' prediction. Both children with DCD and age-matched controls had higher temporal variability in the discontinuous than the continuous circling. No group by condition interaction suggested that the 'timing deficit' was not restricted to the discontinuous drawing, which is different from the previous reports on patients with cerebellar lesion (Spencer et al., 2003). One possibility to explain this finding was due to the fact that the children who were typically developing also showed the higher temporal variability in the discontinuous than the continuous circling (Experiment I). We argued that the 'explicit timing' was not the only mechanism to explain the difference between continuous and discontinuous drawing. In a recent study (Bo, Block, Clark, & Bastian, 2005) in patients with cerebellar lesion, we replicated the circle drawing tasks and examined whether we could improve cerebellar performance (i.e. both temporal and spatial variability) by supplying external timing information. The results were also different from those reported in Spencer et al., (2003). Both the cerebellar patients and controls had higher temporal variability in the discontinuous than the continuous circling. When the external timing was provided by 'constant pacing', the patients did not improve their temporal variability, which was contradicted to the ‘explicit timing’ hypothesis. Further analysis showed that most of the control subjects could precisely predict when to start and stop a circle at the appropriate time while the patients showed large variability in predicting when to initiate a movement. This analysis revealed that the ‘explicit timing’ might not explain the different mechanisms between continuous and discontinuous movements. We argued that it was the less-tuned internal representation of sensory-motor relationship (including forward prediction, inverse kinematic and dynamic controls) that related to the higher variability in the discontinuous drawing in the cerebellar patients.

Combining the results from our cerebellar patients (Bo et al., 2005) and the children who were typically developing (Experiment I), we proposed that the temporal difference between the continuous and the discontinuous drawing could be explained by the complexity of the limb dynamics, which was more difficult in the discontinuous drawing. The patients with cerebellar lesion could make almost normal single-jointed movements, but showed large variability in the multiple-jointed movements (Bastian, Zackowski, & Thach, 2000) suggesting that the cerebellum was very critical in adjusting the complex dynamics (interaction torques) during multijointed movements (Schweighofer et al., 1998a; Schweighofer et al., 1998b). Because both children with DCD and their age-matched controls had less tuned dynamic control (Jansen-Osmann, Richter, Konczak, & Kalveram, 2002; Volman & Geuze, 1998), it was not surprising that the high variability was not restricted in the discontinuous circling in children with DCD.

Thus, could children with DCD improve their timing variability by decreasing the complexity of limb dynamics in the line drawing? The significant difference between the discontinuous line and circle drawing supported this claim. However, the age-matched controls had the same rate of improvement. Similar group differences were also found between discontinuous and continuous line drawing. It seems that the children with DCD, as an undifferentiated group, did not show more problems in controlling the drawing movements compared to the children who were typically developing. Therefore, in order to better understand the temporal control in children with DCD and its possible underlying mechanism, it is important to observe the individual performance in this heterogeneous population.

A number of previous studies reported the diverse group of children with DCD (Lundy-Ekman et al., 1991; Macnab, Miller, & Polatajko, 2001; Parker et al., 1997). Lundy-Ekman et al. (1991) used subgrouping based on the presence of ‘soft neurological sign’ of either basal ganglia or cerebellar dysfunction. The cerebellar signs corresponded to a deficit in timing control while basal ganglia signs to a deficit in force control. Volmen and Geuze (1998) used the same grouping methods but fail to report that children with DCD had timing deficit in rhythmic movements. Parker (1997) subgrouped children according to their performance on fine or gross motor tasks and reported that about 70% of children with DCD showed temporal difficulty in either task. Since it was still not clear what were the appropriate grouping criteria, we used different approach to identify the individuality of children with DCD. We compared each child with DCD to the confidence intervals defined by the performance in children who were typically developing. Five children with DCD showed higher temporal variability in the discontinuous line drawing with two also having timing problems in the discontinuous circle drawing. As argued before, the dynamic control in the circle drawing was more complex, and therefore more challenging, than that in the line drawing. Thus, the comparison between the discontinuous and continuous circling combined the problems in both the limb dynamic and timing controls. The less-tuned dynamic control in the typically developing children masked the timing deficit in some children with DCD. When the dynamic control became simpler in the line drawing tasks, the timing deficit in the discontinuous line drawing emerged in some children with DCD. In the current study, three out of ten children who did not show differences in the circle drawing appeared to have limited timing deficits in the discontinuous line drawing. This restricted timing problem implicates a cerebellar 'explicit timing' impairment, as suggested by studies indicating a link between compromised cerebellar function and the timing problems in both animal studies (e.g., Gramsbergen, 2003) and human experiments (for review see Ivry, 2003).

In summary, the performance of some children with DCD in our study supports the notion of a deficiency in "cerebellar timing", rendering restricted deficits in controlling the event timing during discontinuous line drawing. The finding that children were identified with such differences in the circle drawing task may relate to the multiple functions of the cerebellum. The complexity of the task may sometimes mask the functional deficits in children with DCD. Heterogeneous nature of DCD population is further confirmed in the current study. It is likely that some children have relatively restricted dysfunction e.g. cerebellum, while others have a multitude of neurological profiles. The individuality analysis using the developmental landscape (i.e. a representation of children's performance over a specific age range) seems to be a useful method to understand the underlying mechanisms of DCD.

CHAPTER V

GENERAL DISCUSSION AND FUTURE DIRECTION

Temporal consistency is a basic requirement for many repetitive movements, including drawing and writing. With the current experiments in this dissertation, we examined the age-related changes temporal consistency in continuous and discontinuous drawing movements. These studies on children who were typically developing provided a ‘developmental landscape’ to evaluate the performance of children with Developmental Coordination Disorder (DCD). This dissertation addressed three specific aims to determine: 1) whether there were age-related differences between the continuous and discontinuous circle drawing, 2) whether the children’s performance in the circle drawing tasks was the same as their performance in the dynamically simpler discontinuous and continuous line drawing tasks, and 3) whether the pattern of results found in Aim 1 and Aim 2 in children who were typically developing were the same as for age- and gender-matched children with DCD.

Development of Temporal Consistency in Drawing

In the first experiment (see chapter III), we focused on Aims 1 and 2. Based on the ‘explicit timing’ hypothesis, younger children should have more problems in controlling when to start and stop their movements with an explicit representation of the temporal goal or event-related timing in the two types of discontinuous drawing. As a consequence of this, they were expected to show high temporal and spatial variability regardless of whether they were drawing circles or lines. Our results were not consistent with this prediction. The higher temporal and spatial variability existed only in the discontinuous circling but not in the other conditions. This would suggest that the ‘explicit timing’ function is not what is rate-limiting children’s temporal consistency in drawing tasks, but rather it is the less finely-tuned ‘dynamic control’ in children that affects the development of temporal consistency in continuous and discontinuous drawing.

Dynamic control, e.g. interaction torques in multi-jointed movements, has been proposed as one of the major functions of the cerebellum (Schweighofer, Arbib, & Kawato, 1998a; Schweighofer, Spoelstra, Arbib, & Kawato, 1998b). Cerebellar patients exhibit large variability in the multi-joint movements although they have been shown to improve their temporal consistency in single-jointed movements (Bastian, Zackowski, & Thach, 2000). Our current results in children are consistent with this hypothesis: once the requirement for dynamic control decreased, either through drawing discontinuous lines or drawing continuous circles, children improved their temporal and spatial variability dramatically. Supporting evidence for less well developed dynamic control in children can be found in other developmental studies. For example, in a force adaptation study (Jansen-Osmann, Richter, Konczak, & Kalveram, 2002), children younger than 6 had prolonged re-adaptation back to a null-force condition after they showed aftereffects following adaptation, suggesting that the neural representation of limb dynamics in children lacked precision. Developing (and thus, sharpening) internal representations for limb dynamics might contribute to the high variability in children’s movements. In the handwriting literature, it was previously argued that the poor handwriting was due to the noisy neuromuscular control (Smits-Engelsman & van Galen, 1997; van Galen, Portier, Smits-Engelsman, & Schomaker, 1993). This neuromuscular noise level decreased with increasing age. Combining these findings, we could argue that it might be the less well tuned internal representation of limb dynamics, and not the ‘explicit timing’ process, that is playing the critical role in controlling children’s temporal consistency in drawing and writing movements.

Temporal consistency in children with DCD

In the second experiment (chapter IV), we focus on Aim 3 to test the hypothesis that a possible cerebellar dysfunction might be a major contributor to the poor temporal control observed in some children with DCD. The same continuous and discontinuous drawing paradigms were used to examine whether 1) some children with DCD showed the restricted timing problems in the discontinuous movements similar to that reported in the patients with cerebellar lesion, 2) they improve their timing variability when the complexity of limb dynamics are decreased.

Again, our results were not consistent with the ‘explicit timing’ hypothesis. Both children with DCD and their age- and gender-matched controls had higher temporal variability in the discontinuous circle drawing task compared to the continuous circling task. In the first experiment, children who were typically developing improved in their temporal control from discontinuous circle drawing to line drawing. In the second experiment, children with DCD showed a similar improvement. The results suggested that the children with DCD, as an undifferentiated group, did not show more temporal control problems compared to the children who were typically developing. Taken as a sample, it seems that there is no ‘timing deficit’ in the discontinuous movement in children with DCD which differs from the previous reports on patients with cerebellar lesions (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003).

However, when the individual children’s data were examined, we found that three of the ten children with DCD did not show a difference in the continuous versus discontinuous circle drawing but exhibited a ‘timing deficit’ in the discontinuous but not continuous line drawing. As argued in the first experiment, the dynamic control required in the circle drawing task was more complex than that required in line drawing owing to the multiple joint involved. Thus, the comparison between the discontinuous and continuous circling combined the problems in both the limb dynamic and timing controls. We argued that the less-tuned dynamic control in the typically developing children masked the timing deficit in some children with DCD. When the dynamic control of the drawing became simpler as in line drawing tasks, the timing deficit in the discontinuous line drawing emerged in children with DCD. The performance of some children with DCD in our study implied the cerebellar ‘explicit timing’ impairment, as suggested by studies indicating a link between compromised cerebellar function and the timing problems in other human experiments (for review see Ivry, 2003).

Further directions

In the current dissertation, the continuous versus discontinuous drawing paradigm is used to examine the hypothesis that the developing cerebellar function might play an important role in the development of temporal consistency in drawing skills in children. The results from the first experiment let us argue that it might be the less well tuned internal representation of limb dynamics, not the ‘explicit timing’ process, that is playing the critical role in controlling children’s temporal consistency. Therefore, how do other functions of a developing cerebellum affect the motor development in children? Further testing of this hypothesis can be directed in at least two different ways: one is to test multiple functions of the cerebellum behaviorally; and, the other approach would be to examine the cerebellar structure itself using brain image technologies such as fMRI.

Similar approaches can be used to test the hypothesis that the cerebellar dysfunction might be a major contributor for some children with DCD. The heterogeneous nature of DCD population suggests that it is likely that some children have relatively restricted dysfunction such as in the cerebellum, while others have dysfunctions in other areas (e.g., basal ganglia) or in a complex interaction across brain areas (Lundy-Ekman, Ivry, Keele, & Woollacott, 1991; Williams, Woollacott, & Ivry, 1992). Correlations among multiple tasks on the same group of children may give us stronger evidence to support the notion that cerebellum is playing an important role in some children with DCD. Other possible approaches to further test our hypotheses are 1) whether certain experience e.g. musical training, can change children's performance and 2) whether clinical assessment correlate with certain un-coordinated behavior.

Behavioral studies

Although the 'explicit timing' hypothesis was the focus, other timing tasks, e.g. finger tapping, or interval perceptual task, have also been used to examine the internal timing function in cerebellum. In fact, a few studies reported that children who were classified as 'clumsy' had difficulties on fine motor tasks requiring precise timing (Geuze & Kalverboer, 1987; Lundy-Ekman et al., 1991; Williams et al., 1992) similar to that observed in adult patients with cerebellar lesion. Thus, in order to understand the 'timing deficit' in these children with DCD, it is reasonable to examine whether those children who had ‘restricted timing deficit’ in the discontinuous movement also showed the timing problem in other related tasks, e.g. tapping, or interval perceptual task.

Although numerous findings have pointed to the contribution of cerebellar timing function to developmental problems, interestingly, few studies have evaluated the role of timing on motor skill development in typically developing children. The current dissertation is the first step to examine a possible relationship between cerebellar ‘explicit timing’ function and motor skill development. Further studies should include other timing tasks in order to understand the internal timing function in the developing cerebellum.

Recently, we examined whether we could improve cerebellar performance (i.e. both temporal and spatial variability) during discontinuous and continuous circling movements by supplying external timing information (Bo, Block, Clark, & Bastian, 2005). Cerebellar subjects and controls performed continuous and discontinuous circling in fast speed with constant visual pacing (i.e. external timing). During “constant visual pacing”, subjects could see a dot moving around the circle at the desired pace for the entire time. Based on the ‘explicit timing’ hypothesis, we should expect that patients could improve their temporal variability since they wouldn’t need to rely on their event timing. Contradictory to this prediction, the patients’ temporal variability actually increased. Further analysis showed that most of the control subjects could precisely predict when to start and stop a circle at appropriate time while the patients showed large variability in predicting when to initiate a movement. We argued that it was the less-tuned internal representation of sensory-motor relationship that related to their highly variable performance.

Indeed, prediction is a very fundamental function related to the cerebellum (Kawato & Wolpert, 1998; Wolpert, Miall, & Kawato, 1998). It is suggested that the cerebellum implements prediction by internal model: inverse models calculate the motor commands required to achieve a certain goal based on the desired state, forward models make predictions about the behavior of the motor system and its sensory consequences with the actual sensory feedback from movement and used to optimize motor control. A number of developmental studies suggested that the internal sensory-motor representation was not fully developed (finely-tuned) in early childhood (Contreras-Vidal, Bo, Boudreau, & Clark, 2005; Ferrel, Bard, & Fleury, 2001; Jansen-Osmann et al., 2002). Large variability in movement planning was found in younger age children (Contreras-Vidal et al., 2005) as well as in children with DCD (Kagerer, Bo, Contreras-Vidal, & Clark, 2004). In order to further explore the less-defined prediction, we can examine how children with and without DCD perform in the other prediction tasks e.g. ball catching (Lang & Bastian, 1999), that cerebellar lesion patients have problems with.

An alternative hypothesis for the current dissertation is the role of the cerebellum in dynamic control during coordinate movements. Kawato and colleagues have proposed that the cerebellum learns an internal model of body mechanics, allowing it to adjust for the complex dynamics (interaction torques) inherent in multi-jointed movement (Schweighofer et al., 1998a; Schweighofer et al., 1998b). Behavioral study (Bastian, Martin, Keating, & Thach, 1996) revealed that cerebellar patients were impaired in adjusting for interaction torques that occurred during fast reaching movements. Results for the current studies revealed that the dynamic control played a very important role in discontinuous circle drawing movements in both children with and without DCD. Failing to identify the timing problems in children with DCD in the circle drawing revealed that the less-developed dynamic control in the typically developing children masked the timing deficit in the children with DCD.

Besides timing, prediction and dynamic control, learning and fine-tuning of coordinated movements have also been proposed as one of the major functions in the cerebellum (Thach, 1998). A number of behavioral and brain imaging studies (Ghilardi et al., 2000; Imamizu et al., 2000) have shown that the cerebellum is heavily involved in sensorimotor tasks which require fine-tuning and online adjustment, such as required in gradual adaptation tasks. Robertson and Miall (1999) have reported that adaptation to gradual visual distortion is blocked by inactivation of the dentate nucleus, one of the cerebellum's deep nuclei. Tasks in which the adaptation is sudden, however, may employ different neural circuits. Contreras-Vidal and colleagues (2003) have argued that the basal ganglia are more involved in sudden adaptation tasks whereas the cerebellum plays a more central role in the fine-tuning as seen in gradual adaptation tasks. In healthy adults, it has been shown that gradually increasing perturbations of visual feedback allow for a more complete adaptation than a large, sudden distortion onset (Kagerer, Contreras-Vidal, & Stelmach, 1997). In previous studies (Bo, Kagerer, Contreras-Vidal, & Clark, 2004; Kagerer, Contreras-Vidal, Bo, & Clark, in revision), we examined the adaptation to sudden and gradual visuomotor distortions in children between the ages of 4 and 10 years of age in a point-to-point drawing task as well as in ten children with DCD. Results showed that the typically developing children were well able to successfully adapt to a 60° rotation of the visual feedback, independent of the distortion condition. Children with DCD, however, adapted more effectively during exposure to sudden than to gradual visuo-motor perturbation. Given the known role of the cerebellum in providing an error signal necessary for adaptation and learning, the results of the our studies added to the growing body of findings implicating compromised cerebellar function in DCD.

Following the same line of learning hypothesis in the cerebellum, we further tested how the children who were typically developing as well as children with DCD adapted to prism distortion in a throwing task (Dickey, Bo, Contreras-Vidal, Kagerer, & Clark, 2006). Patients with a damaged cerebellar cortex or inferior olive (the source of climbing fibers to the cerebellar cortex) were severely impaired or unable to adapt in this setting (Martin, Keating, Goodkin, Bastian, & Thach, 1996). Our preliminary results showed that both groups of children showed the ability to adapt (by hitting progressively closer to the target in the adaptation phase) and showed positive aftereffects (throwing to the right of the target during the first five throws of the post-prism phase). However, half of the children with DCD could not adapt to their age level. Combining with the results in the computer-manipulated tasks (Bo et al., 2004; Kagerer et al., in revision), it would be very interesting to know whether these children who showed the deficit in prism adaptation task also had problem in adapting to the gradual distortion task.

Brain imaging studies

It has been shown that the cerebellum develops slower and later than most other brain areas (Anderson, 2003). Longitudinal cerebral magnetic resonance imaging of 259 subjects from age 4 to 20 years revealed that the cerebellum volume matures later than other brain areas (Giedd et al., 1996). Cerebellar volume peaks at approximately age 19 compared to a peak in total cerebral volume at approximately age 16 years. However, little evidence can be found to evaluate the correlation between the behavioral performance in children who are typically developing and their brain structure e.g. cerebellar volume. Further studies on this topic can give strong evidence to support the importance of developing cerebellum on motor development in childhood.

When evaluating the relationship of the cerebellum to DCD, we found only little evidence linking other developmental disorders to this structure. Much of this work is based on neuroanatomic analyses with brain imaging technologies, e.g. magnetic resonance imaging (MRI). This technique allows for the in vivo analysis of brain structure with high spatial resolution. Courchesne and colleagues (1988) reported the pronounced cerebellar hypoplasia in children with autistics. Children with ADHD show approximately 10% reduction in total brain volume (including the cerebellum) compared to children who are typically developing (Giedd, Blumenthal, Molloy, & Castellanos, 2001). Cerebellar dysfunction has also been linked to developmental dyslexia (Zeffiro & Eden, 2001). Unfortunately, few studies have been done to explore the correlation between children with DCD and potential cerebellar abnormality. Future imaging studies, e.g. fMRI, or MEG, will add neuroanatomical evidence implicating compromised cerebellar function in DCD.

How experience shape the behavior in children

Numerous lesion, deficit and enrichment studies have suggested that experience can modify the brain by altering synaptic organization of the cortex (Knudsen, 1998; Neville & Bavelier, 2002; Taub, Ramey, DeLuca, & Echols, 2004). For example, increased cortical representation of the fingers of the left hand was found in string players (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995), hippocampal volume was correlated with the amount of time spent in taxi driver (Maguire et al., 2000). Therefore, it is possible that certain experience in the early childhood can influence the motor skill development. The correlation between temporal consistency in children with musical experience and increased cerebellar volume may further support the importance of developing cerebellum on motor development.

Connection to clinical evaluation

The presence of soft neurological signs in children is assumed to be an indication of minor neurological dysfunction (Touwen, 1979), and it was suggested that particular soft signs might related to a particular movement control deficit (Lundy-Ekman et al., 1991). In the present studies, all included children with DCD were screened in the Physical and Neurological Examination for Soft Signs (PANESS, Denckla, 1985), the Movement Assessment Battery for Children (MABC, Henderson and Sugden, 1992) test and the Beery–Buktenica Developmental Test of Visual-Motor Integration (VMI, 4th edition, Beery, 1997). In the study of Lundy-Ekman et al. (1991), it was found that cerebellar soft signs corresponded to a deficit in timing control. But in the study of Volman & Geuze (1998), such correlation was not found in the children with DCD. Our current studies included MABC, VMI tests and PANESS, a relative current version of clinical evaluation in pediatrics. Future studies exploring the correlation among multiple clinical evaluation tests and behavioral performance will be very helpful in understanding the underlying mechanism and developing therapeutic methods in children with DCD.

Summary

In summary, to test the hypotheses that the developing cerebellar function might play an important role in motor development in childhood and it is a major player in some children with DCD, we need to realize the diverse functions of cerebellum. The current dissertation focused one of many theories related to the cerebellum. It is logical to further test whether 1) children who are typically developing show the similar age-related changes in diverse cerebellar tasks, and 2) the same group of children with DCD who showed deficit in one of the cerebellar functions also showed the problem in other cerebellar tasks. Brain imaging studies may add structural evidence to support our current hypotheses. However, we need to always keep in mind that it is not only the cerebellum but also the whole brain structures are developing in the childhood. While testing the importance of the cerebellum in this dissertation, we cannot exclude the influence of other brain area. In children with DCD, the compromised function may not be restricted to cerebellum. It is possible that the damage spans relatively large area or afflicts multiple neural circuities. Moreover, some neural abnormalities can be subtle and/or relatively diffuse. It is even challenging to identify the brain dysfunction in children with multiple co-morbidities. Therefore, when we design an experiment or interpret results, it is important to consider all the possible factors. Sometime, the negative results may embed some positive findings.

Appendix 1: Permission Form A – for child participant

PERMISSION FORM

University of Maryland, Cognitive-Motor Behavior Laboratory

Identification of Project	Project Title: Development of Visuomotor Coordination and Adaptation
Statement of Age of Participant	I state that I am the parent or legal guardian of this child, that he/she is between 4 and 12 years of age, and that he/she wishes to participate in a research project being conducted by Dr. Jose L. Contreras-Vidal, Dr. Jane Clark, Dr. Florian Kagerer & Jin Bo at the Department of Kinesiology, University of Maryland, College Park.
Purpose	The purpose of this research is to investigate the way children who are normally developing and those with developmental coordination disorder control arm movements under changing movement conditions. The experiment is designed in a way that makes it possible to determine the influence of different task conditions, such as movement direction and distance, on movements.
Procedures	My child will sit comfortably in a chair with his/her hand resting on a table and perform point-to-point arm movement with the dominant hand using a special "computer pen". Movements between two points, in different directions, will be performed. A computer will store information about the position of their hand and arm during the movement task. This task will require approximately 60 minutes to complete; and will be followed by a 30 minute screening assessment for perceptual-motor ability. This screening assessment is designed to identify children's perceptual-motor abilities between the ages of 4 and 12, and involves such interactive tasks as drawing, leg and arm coordination tasks. Total time involved in completing the entire session (both assessments and the computer task) will be 90 minutes. During the whole experiment, my child will be video recorded for “coding” purposes.
Confidentiality	All information collected in the study is strictly confidential except as I specify on the signed permission form for video and image illustrations, and my child's name will not be identified at any time. The data my child provides will be grouped with data others provide for reporting and presentation. Data will be stored in a locked file cabinet in the Cognitive-Motor Behavior Laboratory. Only the principal investigator and his collaborators will have access to this locked file.
Risk	I understand that as a result of my child's participation in this study, he/she may experience a modest degree of fatigue from the

concentration required during the performance of the test but there are no other known risks and no long-term effects associated with participation in this study.

Benefits, Freedom to Withdraw and to ask questions

I understand that the experiment is not designed to help my child specifically, but it may have substantial impact on understanding how the brain controls visually-guided movement. I understand that I am free to ask questions or to withdraw permission for my child's participation at any time without penalty. I understand that I must have a signed copy of this permission form given to me and that the investigators will provide me with the results of this study. At the end of the experiment, my child will receive a small toy and completion certificate as awards for participation in the experiment.
I understand that the University of Maryland does not provide any medical or hospitalization insurance coverage for participants in the research study nor will the University of Maryland provide any compensation for any injury sustained as a result of participation in this study except as required by law.

Principal Investigator

Dr. Jose L. Contreras-Vidal (PI),
Dr. Jane Clark (Collaborator),
Dr. Florian Kagerer (Collaborator),
Jin Bo (graduate student)
Department of Kinesiology, 2363 HHP Bldg
University of Maryland, College Park, MD 20742
(301)-405-2495

Informed Consent Requirements

"I am voluntarily making a decision whether or not to permit the participation of my child in the research study described above. My signature indicates that I have read the information provided above, have had all of my questions answered, and have permitted my child to participate in this study. I further understand that my child has agreed to participate in this study. I will be given a copy of this consent form to keep."

Name of Participant: ______________________________

Participant's Birth date: ____

Signature of Participant's Parent/Guardian (if minor): ________________________

Today's Date: ____

IF YOU HAVE QUESTIONS ABOUT YOUR PARTICIPATION IN THIS STUDY OR YOUR RIGHTS AS A VOLUNTEER, YOU MAY CONTACT:
Chair, The Human Subjects Research Committee
Department of Kinesiology (301)405-2455

Appendix 2: Permission Form A-for adult participant

CONSENT FORM

University of Maryland, Cognitive-Motor Behavior Laboratory

Identification of Project	Project Title: Development of Visuomotor Coordination and Adaptation
Statement of Age of Participant	I state that I am an adult between the ages of 18 and 30, and am willing to participate in a research project being conducted by Dr. Jose L. Contreras-Vidal, Dr. Florian Kagerer, Dr. Jane Clark & Jin Bo at the Department of Kinesiology, University of Maryland, College Park.
Purpose	The purpose of current research is to investigate how a person controls arm movements in different environment. The experiment is designed in a way that makes it possible to determine the influence of different task conditions, such as movement direction and distance, on movements.
Procedures	I will sit comfortably in a chair with my hand resting on a table and perform point-to-point arm movement with the dominant hand. A computer will store information about the position of my hand and arm during the movement task. This task will require approximately 60 minutes to complete. During the whole experiment, I will be video recorded for “coding” purposes.
Confidentiality	All information collected in the study is strictly confidential except as I specify on the signed permission form for video and image illustrations, and my name will not be identified at any time. The data I provide will be grouped with data others provide for reporting and presentation. Data will be stored in a locked file cabinet in the Cognitive-Motor Behavior Laboratory. Only the principal-investigator and his collaborators will have access to this locked file.
Risk	I understand that as a result of my participation in this study, I may experience a modest degree of fatigue from the concentration required during the performance of the test but there are no other known risks and no long-term effects associated with participation in this study.
Benefits, Freedom to Withdraw and to ask questions	I understand that the experiment is not designed to help me specifically, but it may have substantial impact on understanding how the brain controls visually-guided movement. I understand that I am free to ask questions or to withdraw permission for my participation at any time without penalty. I understand that I must have a signed copy of this consent form given to me and that the investigators will

provide me with the results of this study.
I understand that the University of Maryland does not provide any medical or hospitalization insurance coverage for participants in the research study nor will the University of Maryland provide any compensation for any injury sustained as a result of participation in this study except as required by law.

Principal Investigator

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(301)-405-2495

Informed Consent Requirements

"I am voluntarily making a decision whether or not to participate in the research study described above. My signature indicates that I have read the information provided above, have had all of my questions answered, and have decide to participate in this study. I will be given a copy of this consent form to keep"

Name of Participant: ____
Participant's Birth date: _______________________________________
Today's Date: ____

IF YOU HAVE QUESTIONS ABOUT YOUR PARTICIPATION IN THIS STUDY OR YOUR RIGHTS AS A VOLUNTEER, YOU MAY CONTACT:
Chair, The Human Subjects Research Committee
Department of Kinesiology
(301)405-2455

Appendix 3: Raw data for each subject in four conditions (means)

grp	age	id	condi	time	sdtime	cvtime	rmse	dist	sddist	cvdist
1	5.1	131	1	0.63715	0.041784	6.5397	1.096	21.029	2.7655	13.135
1	5.1	131	2	0.61508	0.11194	18.841	1.4258	18.531	3.5125	17.649
1	5.1	131	3	0.57107	0.04686	8.1584	0.26953	12.398	1.4769	11.893
1	5.1	131	4	0.39299	0.028398	7.2685	0.32517	15.508	1.6133	10.4
1	5.19	120	1	0.75842	0.15573	21.824	0.89245	20.388	1.8946	9.1754
1	5.19	120	2	0.90703	0.29595	33.656	0.33785	12.33	2.9415	25.889
1	5.19	120	3	0.60008	0.073101	11.585	0.30918	12.961	1.3943	10.942
1	5.19	120	4	0.59544	0.075552	12.705	0.33017	14.116	1.4344	10.248
1	5.24	134	1	0.47171	0.034567	7.3316	0.70888	18.995	1.8891	10.007
1	5.24	134	2	0.50489	0.18061	36.873	0.51147	12.844	3.8153	31.2
1	5.24	134	3	0.38646	0.049133	12.459	0.35003	12.66	1.9504	15.649
1	5.24	134	4	0.4729	0.064746	13.059	0.37739	14.917	1.7182	11.463
1	5.46	116	1	0.70615	0.086042	12.182	0.82631	10.469	0.8478	8.1977
1	5.46	116	2	0.71689	0.2223	34.867	0.55087	10.497	2.4962	30.614
1	5.46	116	3	0.34862	0.052638	15.237	0.38979	12.779	2.1608	16.958
1	5.46	116	4	0.98327	0.16671	16.889	0.32845	17.704	1.4125	7.9847
1	5.66	132	1	0.71908	0.12335	16.977	0.48371	13.134	1.0973	8.4872
1	5.66	132	2	0.7341	0.26331	37.051	0.8008	7.9655	2.0711	28.547
1	5.66	132	3	0.43421	0.073024	16.109	0.20912	11.181	1.3952	12.603
1	5.66	132	4	0.88837	0.1853	21.22	0.1165	13.303	1.1809	8.9109
1	6.25	140	1	0.73624	0.069505	9.2491	0.67913	18.561	1.6961	9.133
1	6.25	140	2	0.66527	0.14359	20.742	0.43559	13.484	2.0418	17.123
1	6.25	140	3	0.55774	0.068626	12.486	0.56902	16.507	2.1531	13.338
1	6.25	140	4	0.47983	0.079009	17.379	0.51132	17.73	1.8328	10.203
1	6.35	121	1	1.0886	0.10073	9.2125	0.47598	18.148	1.0538	5.8703
1	6.35	121	2	0.83502	0.15014	17.807	0.27137	12.538	1.1524	9.1472
1	6.35	121	3	0.43026	0.049832	11.59	0.32232	12.809	2.2766	18.382
1	6.35	121	4	0.39978	0.04102	10.225	0.28491	14.513	1.1836	8.1478
1	6.35	138	1	0.53142	0.038127	7.1684	0.6827	18.088	1.8078	10.09
1	6.35	138	2	0.51355	0.081408	15.806	0.49848	12.319	1.1765	9.5315
1	6.35	138	3	0.47556	0.024768	5.2291	0.70342	18.41	2.2489	12.347
1	6.35	138	4	0.42123	0.055455	13.13	0.54226	16.609	2.5013	15.314
1	6.5	133	1	0.46388	0.039528	8.5733	0.79424	18.97	2.117	11.097
1	6.5	133	2	0.35663	0.084085	23.443	0.60713	15.277	2.4487	16.03
1	6.5	133	3	0.42038	0.041349	9.9316	0.37473	15.086	1.4889	9.9236
1	6.5	133	4	0.40858	0.10209	24.96	0.52061	16.199	1.6146	10.011
1	6.69	115	1	0.80951	0.11055	13.387	0.72441	18.769	1.7526	9.223
1	6.69	115	2	0.68941	0.073618	10.589	0.43222	13.975	1.0755	7.7495
1	6.69	115	3	0.62344	0.06196	11.344	0.28917	15.795	2.2091	14.184
1	6.69	115	4	0.86131	0.10134	11.554	0.28871	15.234	1.2025	7.9571
1	6.91	141	1	0.49891	0.031914	6.3932	0.37228	15.12	1.0086	6.6906
1	6.91	141	2	0.63368	0.08617	13.727	0.39046	13.381	0.96502	7.2545
1	6.91	141	3	0.50293	0.028124	5.5811	0.27571	11.583	1.1132	9.6279
1	6.91	141	4	0.55385	0.04483	8.0554	0.27725	13.565	1.3312	9.8643

1	7.34	137	1	0.48762	0.041218	8.488	0.38682	16.38	1.4274	8.7395
1	7.34	137	2	0.60883	0.10064	16.624	0.3107	12.567	0.94602	7.5193
1	7.34	137	3	0.37004	0.040292	10.93	0.23695	10.31	1.6459	16.196
1	7.34	137	4	0.34975	0.043386	12.334	0.38895	12.174	1.3066	10.755
1	7.54	156	1	0.51284	0.053301	10.298	1.5545	23.253	3.8682	15.999
1	7.54	156	2	0.68992	0.089946	12.956	0.60248	14.779	2.3181	15.384
1	7.54	156	3	0.37467	0.038702	10.232	0.68471	16.741	2.6834	16.109
1	7.54	156	4	0.44955	0.046413	10.247	0.40304	16.26	2.0287	12.372
1	7.88	114	1	0.6468	0.038026	5.8573	1.1511	21.669	3.1279	14.394
1	7.88	114	2	0.68142	0.080448	13.838	1.5128	20.232	3.3676	16.464
1	7.88	114	3	0.35326	0.029111	8.466	0.3309	14.356	1.6666	11.781
1	7.88	114	4	0.4618	0.061346	13.378	0.50142	17.047	1.7797	10.447
1	7.96	119	1	0.74351	0.054725	7.5575	0.46429	16.298	1.9097	11.763
1	7.96	119	2	0.80618	0.13447	16.078	0.42096	12.927	1.2992	10.105
1	7.96	119	3	0.48365	0.022958	4.7659	0.26651	15.248	1.4169	9.2284
1	7.96	119	4	0.65483	0.057672	8.9104	0.49158	14.751	1.3811	9.2997
1	7.89	149	1	0.62325	0.048109	7.705	1.2769	22.758	2.0712	9.1192
1	7.89	149	2	0.67971	0.077714	11.388	0.54878	15.428	1.4022	9.0774
1	7.89	149	3	0.54629	0.040127	7.337	0.37098	16.309	1.7613	10.884
1	7.89	149	4	0.53368	0.063715	11.901	0.39306	16.413	1.7267	10.63
1	8.07	135	1	0.55836	0.046684	8.5015	0.88518	18.698	2.3973	12.538
1	8.07	135	2	0.67387	0.071402	10.381	0.85202	18.08	2.4823	13.621
1	8.07	135	3	0.37949	0.023661	6.174	0.28744	13.768	1.1354	8.3165
1	8.07	135	4	0.49842	0.045344	9.0918	0.21921	15.637	1.7349	10.703
1	8.98	150	1	0.49514	0.052242	10.51	0.58362	16.125	2.2583	13.77
1	8.98	150	2	0.61209	0.1065	17.633	0.35886	12.321	0.98598	8.1145
1	8.98	150	3	0.55918	0.072823	13.154	0.15752	11.589	1.8584	16.022
1	8.98	150	4	0.78033	0.14406	18.14	0.2138	13.901	1.597	11.285
1	8.01	151	1	0.69146	0.058627	8.4202	0.50044	17.69	1.2331	7.0919
1	8.01	151	2	0.59149	0.073613	12.55	0.35904	11.772	1.2864	10.926
1	8.01	151	3	0.53042	0.056715	10.667	0.15781	11.505	1.1001	9.88
1	8.01	151	4	0.4631	0.02593	5.5323	0.18104	12.551	1.3817	10.86
1	8.26	154	1	0.53948	0.03565	6.63	0.66127	18.576	1.8844	10.123
1	8.26	154	2	0.57401	0.042269	7.2634	0.39303	13.567	1.0252	7.6264
1	8.26	154	3	0.39443	0.025643	6.483	0.20386	12.337	1.1981	9.6858
1	8.26	154	4	0.49184	0.043865	8.8573	0.23047	15.588	1.3802	8.8363
1	8.55	158	1	0.54036	0.046273	8.5572	0.49896	13.48	1.5081	11.201
1	8.55	158	2	0.63519	0.07778	12.752	0.46164	14.352	1.5729	10.861
1	8.55	158	3	0.53061	0.03978	7.4971	0.16697	9.3048	1.7493	18.799
1	8.55	158	4	0.62145	0.1055	14.609	0.18959	16.029	2.1234	13.187
1	9.3	153	1	0.5106	0.026334	5.1766	0.68596	19.195	1.8263	9.5142
1	9.3	153	2	0.52853	0.052629	9.9175	0.41609	13.845	1.1047	7.9077
1	9.3	153	3	0.47962	0.022926	4.7435	0.23729	14.648	0.92006	6.3363
1	9.3	153	4	0.59357	0.048796	7.9532	0.23814	16.038	1.1895	7.392
1	9.14	118	1	0.79563	0.054841	6.9357	0.33993	13.827	1.177	8.5291
1	9.14	118	2	0.81289	0.069514	8.6661	0.29213	11.857	0.88341	7.4501
1	9.14	118	3	0.49129	0.034944	7.0337	0.38941	11.809	1.0444	8.8427
1	9.14	118	4	0.72865	0.074879	10.285	0.27673	11.555	0.79748	6.886

1	9.5	130	1	0.58419	0.057469	9.8271	0.31254	16.019	1.1104	6.9686
1	9.5	130	2	0.661	0.062827	9.5519	0.37259	14.526	1.0111	6.86
1	9.5	130	3	0.50559	0.035628	6.9456	0.28884	12.949	1.4107	10.922
1	9.5	130	4	0.50912	0.052021	10.378	0.26856	11.357	0.97421	8.687
1	9.58	136	1	0.52521	0.029995	5.7112	0.46553	12.984	1.1849	9.1694
1	9.58	136	2	0.67283	0.05849	8.7011	0.3642	11.956	1.0297	8.6344
1	9.58	136	3	0.52407	0.029885	5.7602	0.20995	13.866	1.3851	10.026
1	9.58	136	4	0.64135	0.076018	11.717	0.20209	14.132	1.1475	8.1141
1	9.85	147	1	0.54581	0.037556	6.8925	0.66302	11.555	1.3182	11.554
1	9.85	147	2	0.55228	0.075711	13.568	0.79284	9.2167	1.09	12.028
1	9.85	147	3	0.5315	0.021798	4.1056	0.24627	12.864	1.012	7.9287
1	9.85	147	4	0.56437	0.051472	9.0696	0.17516	12.521	1.1896	9.5514
1	10.25	139	1	0.52663	0.022719	4.3566	0.6771	18.509	1.7878	9.5477
1	10.25	139	2	0.58463	0.054732	9.3769	0.40205	11.352	1.0454	9.2208
1	10.25	139	3	0.3994	0.023001	5.6489	0.3443	15.741	1.8227	11.344
1	10.25	139	4	0.50523	0.054753	10.745	0.2878	13.994	1.3284	9.5507
1	10.41	144	1	0.45612	0.03473	7.5416	0.51692	13.167	1.5747	11.983
1	10.41	144	2	0.35804	0.040604	11.317	0.61661	10.052	1.1441	11.396
1	10.41	144	3	0.48253	0.025777	5.3193	0.33021	13.355	1.7376	13.033
1	10.41	144	4	0.46675	0.054104	11.51	0.2749	12.737	1.2725	10.103
1	10.48	143	1	0.48409	0.037022	7.6678	0.45521	14.994	1.8997	12.794
1	10.48	143	2	0.54333	0.078803	14.524	0.3741	11.825	1.3775	11.8
1	10.48	143	3	0.53087	0.061816	10.759	0.24763	14.019	2.4237	17.444
1	10.48	143	4	0.45761	0.039854	8.6462	0.22307	9.8096	0.95235	9.7068
1	10.57	148	1	0.46643	0.034673	7.4825	0.43462	14.395	1.3979	9.7299
1	10.57	148	2	0.5165	0.061888	11.178	0.72345	12.329	0.94946	8.0723
1	10.57	148	3	0.50632	0.067568	13.162	0.18415	12.498	1.657	13.349
1	10.57	148	4	0.50305	0.065484	13.164	0.14413	12.751	1.1679	9.2874
1	10.75	146	1	0.51269	0.023544	4.592	0.3392	14.66	0.88872	6.0695
1	10.75	146	2	0.49344	0.034657	7.0412	0.43828	12.07	0.83852	6.9786
1	10.75	146	3	0.50096	0.024285	4.8025	0.2291	12.334	0.89558	7.4806
1	10.75	146	4	0.5509	0.043588	7.8713	0.1966	11.333	0.77813	6.8707
1	11.61	157	1	0.52084	0.026229	5.0304	0.35241	16.737	1.0723	6.4317
1	11.61	157	2	0.59303	0.05036	8.2915	0.33198	12.43	0.97706	7.8868
1	11.61	157	3	0.50231	0.027326	5.4546	0.37948	13.568	1.2468	9.179
1	11.61	157	4	0.49393	0.0312	6.3089	0.38437	12.864	0.71435	5.5466
1	adults	110	1	0.54663	0.022054	4.034	0.30772	14.102	0.63048	4.4733
1	adults	110	2	0.55853	0.033305	3.8685	0.24617	14.444	0.60697	4.2027
1	adults	110	3	0.5119	0.017374	3.3934	0.14831	14.392	0.82823	5.7827
1	adults	110	4	0.50884	0.034213	6.6667	0.11881	13.235	0.81103	6.1606
1	adults	111	1	0.64074	0.039324	4.2015	0.22177	14.573	0.55188	3.7952
1	adults	111	2	0.68914	0.048166	4.9281	0.19134	14.672	0.45281	3.0792
1	adults	111	3	0.54562	0.02334	4.2629	0.24083	17.659	0.91435	5.1713
1	adults	111	4	0.6588	0.040998	5.8634	0.24711	16.184	0.81702	5.0043
1	adults	113	1	0.70359	0.023126	3.2862	0.37045	17.706	0.7237	4.0827
1	adults	113	2	0.53136	0.022974	4.353	0.42819	15.25	0.81071	5.3551
1	adults	113	3	0.44859	0.015563	3.4744	0.21378	16.099	0.91939	5.746
1	adults	113	4	0.50048	0.015101	2.999	0.19115	18.099	0.82314	4.5395

1	adults	152	1	0.55508	0.020252	3.6403	0.25903	15.085	0.79587	5.272
1	adults	152	2	0.58326	0.022227	3.8152	0.18412	12.818	0.41678	3.2521
1	adults	152	3	0.53412	0.019328	3.6198	0.30986	15.57	0.77828	4.9737
1	adults	152	4	0.51641	0.018691	3.6091	0.16101	12.794	0.73953	5.8062
1	adults	155	1	0.53707	0.017897	3.3398	0.25038	14.824	0.54059	3.6481
1	adults	155	2	0.37666	0.015068	3.9233	0.19682	13.596	0.47314	3.4917
1	adults	155	3	0.54383	0.014696	2.7006	0.14339	14.329	0.56823	3.9696
1	adults	155	4	0.47583	0.023875	5.058	0.13059	14.077	0.55271	3.9425
2	7.37	290	1	0.73419	0.072838	10.205	2.1684	29.143	4.2576	15.77
2	7.37	290	2	0.72005	0.25971	36.397	1.277	16.272	5.9823	38.067
2	7.37	290	3	0.59212	0.085017	14.713	0.29888	11.769	2.3251	19.759
2	7.37	290	4	1.192	0.36345	30.837	0.33754	15.381	1.7368	11.238
2	9.63	291	1	0.4808	0.050639	10.519	0.75185	18.14	2.0419	11.195
2	9.63	291	2	0.62749	0.097821	15.902	0.56674	14.649	1.588	10.922
2	9.63	291	3	0.48091	0.036404	7.5332	0.71065	16.116	3.3963	21.248
2	9.63	291	4	0.62562	0.13218	19.231	0.46106	14.523	2.3266	16.122
2	8.43	292	1	0.57757	0.039379	6.6988	1.4197	24.083	2.1401	8.8233
2	8.43	292	2	0.58083	0.060644	10.432	1.0054	17.702	2.0793	11.094
2	8.43	292	3	0.52784	0.042688	8.1512	0.29299	13.204	1.9312	14.632
2	8.43	292	4	0.51533	0.030091	5.8384	0.6591	21.385	1.944	9.1257
2	7.67	293	1	0.82491	0.32251	30.226	0.75072	15.34	6.416	35.026
2	7.67	293	2	0.75673	0.28876	37.492	0.4955	9.9815	3.5938	37.009
2	7.67	293	3	0.75017	0.21296	27.799	0.36694	14.166	3.8238	26.923
2	7.67	293	4	1.1593	0.27963	25.832	0.23091	13.291	2.1951	16.876
2	8.51	294	1	0.61252	0.04931	7.991	1.3956	24.287	3.2029	13.089
2	8.51	294	2	0.83677	0.12563	15.083	0.53583	13.566	2.0634	15.227
2	8.51	294	3	0.47967	0.042528	8.8686	0.29933	12.646	1.524	12.059
2	8.51	294	4	0.81838	0.13283	16.481	0.18654	12.37	1.2708	10.375
2	10.66	295	1	0.67913	0.088633	11.238	0.6351	18.351	1.5459	8.2976
2	10.66	295	2	0.62442	0.059588	9.7369	0.50955	14.544	1.0546	7.2693
2	10.66	295	3	0.61659	0.10978	17.409	0.41931	15.482	2.9302	19.515
2	10.66	295	4	0.58985	0.072776	12.352	0.28901	15.243	1.9375	12.654
2	7.91	296	1	0.53861	0.065689	12.099	0.49932	15.52	1.3987	9.0091
2	7.91	296	2	0.54835	0.10596	19.762	0.49603	12.204	1.3612	11.271
2	7.91	296	3	0.36445	0.026065	7.0654	0.16634	10.621	1.2345	11.542
2	7.91	296	4	0.49211	0.09128	17.586	0.29498	13.701	1.6473	12.021
2	11.82	297	1	0.72069	0.069214	9.7366	0.42473	14.777	1.1539	7.8176
2	11.82	297	2	0.78551	0.13582	17.554	0.3306	12.16	1.4731	12.31
2	11.82	297	3	0.5078	0.042369	8.681	0.26677	11.587	1.4589	12.546
2	11.82	297	4	0.5016	0.049513	9.8647	0.19359	12.855	1.1529	8.8348
2	9.65	298	1	0.64112	0.1824	26.825	0.6329	18.494	1.87	9.7167
2	9.65	298	2	0.97671	0.29363	30.408	0.3404	12.439	2.3841	21.704
2	9.65	298	3	0.37764	0.057428	14.639	0.36849	12.744	2.0171	16.237
2	9.65	298	4	0.93794	0.17294	18.272	0.11707	13.304	1.207	9.1175
2	8.77	299	1	0.55212	0.065363	11.428	0.69276	17.762	2.238	12.662
2	8.77	299	2	0.58697	0.15925	26.167	0.82491	15.965	3.0472	19.754
2	8.77	299	3	0.57111	0.046624	8.0571	0.36256	14.205	1.876	13.414
2	8.77	299	4	0.70567	0.15642	22.079	0.44772	20.576	3.458	16.934

Appendix 4: Raw data for additional measures: circularity ratio and slant

Circularity ratio and slant were calculated to explore whether there is an age-related difference in drawing a circle or directing a line. Principle component analysis (PCA) was used to calculate these two measures. Here are raw data for each subject in four conditions (means)

grp	age	id	condi	slant1	ratio
1	5.1	131	1	1.408	0.5982
1	5.1	131	2	-36.517	0.4267
1	5.1	131	3	43.057	0.0053
1	5.1	131	4	45.771	0.0020
1	5.19	120	1	-17.689	0.6533
1	5.19	120	2	-44.886	0.5125
1	5.19	120	3	42.729	0.0044
1	5.19	120	4	40.931	0.0138
1	5.24	134	1	-2.387	0.6325
1	5.24	134	2	-7.264	0.6478
1	5.24	134	3	43.705	0.0034
1	5.24	134	4	44.845	0.0025
1	5.46	116	1	-27.853	0.5823
1	5.46	116	2	-39.591	0.5296
1	5.46	116	3	43.903	0.0199
1	5.46	116	4	46.543	0.0034
1	5.66	132	1	-5.340	0.7333
1	5.66	132	2	-17.593	0.6746
1	5.66	132	3	45.781	0.0018
1	5.66	132	4	44.893	0.0038
1	6.25	140	1	11.259	0.6163
1	6.25	140	2	0.343	0.7002
1	6.25	140	3	39.183	0.0091
1	6.25	140	4	40.522	0.0039
1	6.35	121	1	-39.343	0.7622
1	6.35	121	2	-54.928	0.6686
1	6.35	121	3	45.432	0.0014
1	6.35	121	4	45.959	0.0071
1	6.35	138	1	7.915	0.5728
1	6.35	138	2	-18.507	0.5689
1	6.35	138	3	49.619	0.0084
1	6.35	138	4	42.571	0.0100
1	6.5	133	1	49.883	0.5219
1	6.5	133	2	-0.528	0.5032
1	6.5	133	3	43.331	0.0060
1	6.5	133	4	42.376	0.0076
1	6.69	115	1	-41.408	0.7435
1	6.69	115	2	-48.023	0.8040
1	6.69	115	3	42.227	0.0027

1	6.69	115	4	44.532	0.0039
1	6.91	141	1	24.575	0.6196
1	6.91	141	2	-20.931	0.7328
1	6.91	141	3	42.948	0.0013
1	6.91	141	4	46.311	0.0016
1	7.34	137	1	60.415	0.7801
1	7.34	137	2	-35.223	0.6303
1	7.34	137	3	44.043	0.0023
1	7.34	137	4	44.143	0.0048
1	7.54	156	1	15.415	0.6644
1	7.54	156	2	39.725	0.5416
1	7.54	156	3	43.742	0.0103
1	7.54	156	4	45.203	0.0048
1	7.88	114	1	-22.063	0.6893
1	7.88	114	2	0.296	0.6315
1	7.88	114	3	40.794	0.0097
1	7.88	114	4	41.449	0.0032
1	7.96	119	1	31.808	0.5958
1	7.96	119	2	-22.275	0.6709
1	7.96	119	3	39.360	0.0016
1	7.96	119	4	40.398	0.0281
1	7.89	149	1	-19.342	0.6192
1	7.89	149	2	-8.195	0.6903
1	7.89	149	3	40.652	0.0071
1	7.89	149	4	40.632	0.0036
1	8.07	135	1	9.700	0.6002
1	8.07	135	2	-2.768	0.6910
1	8.07	135	3	40.069	0.0015
1	8.07	135	4	42.623	0.0010
1	8.98	150	1	18.830	0.6520
1	8.98	150	2	0.845	0.4909
1	8.98	150	3	42.036	0.0017
1	8.98	150	4	42.837	0.0013
1	8.01	151	1	19.286	0.7124
1	8.01	151	2	-32.735	0.4081
1	8.01	151	3	43.594	0.0016
1	8.01	151	4	43.145	0.0019
1	8.26	154	1	-18.159	0.7961
1	8.26	154	2	-16.008	0.7036
1	8.26	154	3	42.396	0.0049
1	8.26	154	4	43.316	0.0011
1	8.55	158	1	17.878	0.5797
1	8.55	158	2	-0.334	0.5427
1	8.55	158	3	42.595	0.0004
1	8.55	158	4	42.988	0.0017
1	9.3	153	1	0.140	0.6792
1	9.3	153	2	-14.978	0.7554
1	9.3	153	3	44.520	0.0010
1	9.3	153	4	42.449	0.0010
1	9.14	118	1	-7.714	0.8200

1	9.14	118	2	-44.814	0.6536
1	9.14	118	3	42.278	0.0180
1	9.14	118	4	42.176	0.0123
1	9.5	130	1	11.522	0.7046
1	9.5	130	2	11.522	0.7046
1	9.5	130	3	40.505	0.0028
1	9.5	130	4	41.177	0.0070
1	9.58	136	1	-18.607	0.8194
1	9.58	136	2	-58.754	0.6075
1	9.58	136	3	42.423	0.0032
1	9.58	136	4	43.886	0.0050
1	9.85	147	1	-4.992	0.6499
1	9.85	147	2	-0.215	0.4542
1	9.85	147	3	41.912	0.0013
1	9.85	147	4	42.893	0.0020
1	10.25	139	1	29.519	0.7602
1	10.25	139	2	5.063	0.6728
1	10.25	139	3	44.048	0.0016
1	10.25	139	4	42.653	0.0073
1	10.41	144	1	20.958	0.6321
1	10.41	144	2	-31.795	0.6981
1	10.41	144	3	44.388	0.0043
1	10.41	144	4	44.844	0.0023
1	10.48	143	1	15.411	0.6201
1	10.48	143	2	-37.593	0.5567
1	10.48	143	3	43.322	0.0057
1	10.48	143	4	43.784	0.0104
1	10.57	148	1	29.737	0.7111
1	10.57	148	2	19.842	0.5766
1	10.57	148	3	42.328	0.0010
1	10.57	148	4	43.012	0.0017
1	10.75	146	1	25.851	0.7612
1	10.75	146	2	-21.851	0.6856
1	10.75	146	3	43.308	0.0019
1	10.75	146	4	41.067	0.0019
1	11.61	157	1	-2.309	0.8440
1	11.61	157	2	-6.180	0.7819
1	11.61	157	3	44.210	0.0023
1	11.61	157	4	42.051	0.0029
1	adults	110	1	18.589	0.6663
1	adults	110	2	10.416	0.6999
1	adults	110	3	44.956	0.0012
1	adults	110	4	47.234	0.0008
1	adults	111	1	-20.262	0.7167
1	adults	111	2	11.092	0.7056
1	adults	111	3	43.154	0.0086
1	adults	111	4	41.966	0.0020
1	adults	113	1	30.266	0.7562
1	adults	113	2	-37.762	0.6635
1	adults	113	3	45.488	0.0050

1	adults	113	4	44.063	0.0004
1	adults	152	1	28.159	0.8357
1	adults	152	2	-37.497	0.7920
1	adults	152	3	43.304	0.0013
1	adults	152	4	44.169	0.0012
1	adults	155	1	1.802	0.6503
1	adults	155	2	-17.398	0.6706
1	adults	155	3	43.283	0.0008
1	adults	155	4	43.433	0.0004
2	7.37	290	1	-15.238	0.5828
2	7.37	290	2	-13.253	0.4792
2	7.37	290	3	45.012	0.0064
2	7.37	290	4	43.689	0.0054
2	9.63	291	1	-13.951	0.6663
2	9.63	291	2	-43.295	0.6166
2	9.63	291	3	40.120	0.0055
2	9.63	291	4	42.082	0.0042
2	8.43	292	1	16.687	0.6414
2	8.43	292	2	-56.440	0.7849
2	8.43	292	3	41.434	0.0011
2	8.43	292	4	41.980	0.0030
2	7.67	293	1	-77.636	0.4955
2	7.67	293	2	-9.838	0.3434
2	7.67	293	3	42.030	0.0084
2	7.67	293	4	42.026	0.0019
2	8.51	294	1	7.336	0.5555
2	8.51	294	2	-27.038	0.4288
2	8.51	294	3	41.443	0.0038
2	8.51	294	4	43.561	0.0042
2	10.66	295	1	10.593	0.7102
2	10.66	295	2	14.001	0.7023
2	10.66	295	3	42.785	0.0069
2	10.66	295	4	39.609	0.0045
2	7.91	296	1	12.977	0.5836
2	7.91	296	2	25.530	0.4684
2	7.91	296	3	44.075	0.0008
2	7.91	296	4	41.354	0.0015
2	11.82	297	1	-10.944	0.5813
2	11.82	297	2	-33.823	0.7540
2	11.82	297	3	43.645	0.0034
2	11.82	297	4	45.076	0.0010
2	9.65	298	1	-21.164	0.6346
2	9.65	298	2	-58.984	0.3822
2	9.65	298	3	43.626	0.0026
2	9.65	298	4	44.498	0.0029
2	8.77	299	1	14.521	0.6542
2	8.77	299	2	0.915	0.6333
2	8.77	299	3	46.576	0.0073
2	8.77	299	4	40.639	0.0050

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