SENSORIMOTOR FUNCTIONING IN DEVELOPMENTAL COORDINATION DISORDER:
A KINEMATIC AND PSYCHOMETRIC ANALYSIS

by

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ABSTRACT

The purpose of the present research was twofold: 1) to investigate whether deficits in sensorimotor mechanisms in DCD could be characterized using kinematic and psychometric analyses, and 2) to determine whether subtypes of sensory and/or motor deficits could be identified within a group of children identified with DCD. Participants included 40 children between the ages of 7-9 and 10-12 years, 20 who were clinic referred and met the diagnostic criteria for DCD and 20 age-matched controls without motor difficulties. Participants performed a manual aiming task with and without visual feedback of the moving hand to targets of varying complexity. Kinematic analyses of aiming movements revealed that the effects of sensory feedback on movements in DCD are dependent on several factors including age, feedback availability, and task complexity. With increases in task complexity, children with DCD demonstrated difficulty processing visual and non-visual feedback leading to an increased reliance on feedback control and/or decreased spatial accuracy and a higher frequency of kinematic abnormalities. Children with DCD were also found to perform significantly below average on standardized measures of sensory and motor functioning. Individual analyses of kinematic profiles within the DCD group revealed that both age groups of children with DCD demonstrated a large degree of variation in kinematic performance patterns in the absence of visual feedback. These patterns of performance were not related to any of the standardized measures indicating that distinct subtypes of sensory or motor deficits in the DCD population are unlikely. The results suggest, rather, that there are subgroups of children with DCD who demonstrate different control strategies to cope with more generalized deficits in sensorimotor functioning. The neural substrates implicated in these findings are discussed along with approaches to intervention and directions for future research.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank Dr. Eric Roy, my supervisor, for sharing his insights and expertise over the many years we have worked together. His passion for research was never-ending and I am grateful for having had the opportunity to work with him. I also thank my committee members, Dr. Helene Polatajko and Dr. Richard Steffy who were generous in sharing their time and expertise. Helene's extensive experience with the DCD population was instrumental in planning and implementing this research and Dick offered many helpful insights during the interpretation and writing stages of this dissertation.

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1. INTRODUCTION

Children with Developmental Coordination Disorder (DCD) do not have the motor competence to cope easily with motor activities of daily living and can be found in 5-6% of the population of school-aged children (APA, 1994). These children present a dramatic contrast to the fluent, coordinated movements produced by most children their age, and are referred to as "clumsy" or "physically awkward" by parents and teachers and in the literature. A diagnosis of Developmental Coordination Disorder (DCD) is established when a child lacks the motor coordination necessary to perform tasks that are considered to be appropriate for his or her age, given normal intellectual ability and the absence of other neurologic disorders. The problem may be manifested by marked delays in achieving motor milestones (e.g., crawling, walking), difficulties in self-care tasks (e.g., dressing, using utensils), poor handwriting and drawing abilities, and/or poor performance during leisure activities (e.g., sports) (APA, 1994, see Appendix A).

In considering the underlying causes of DCD, previous studies have investigated the perceptual-motor skills of these children, and deficits in visual perception (Lord & Hulme, 1987a; 1987b; 1988), kinesthesis/proprioception (Bairstow & Laszlow, 1981; Laszlow & Bairstow, 1985; Smyth & Mason, 1998), as well as motor programming (Rösblad & von Hofsten, 1994; Smyth, 1991; van der Meulen, van der Gon, Gielen, Gooskens & Willemse, 1991) have been proposed as contributing to the motor difficulties observed in children with DCD. Unfortunately, the lack of explicit criteria and agreed upon methods to identify the children has led to studies of DCD culminating in mixed results from which it is difficult to draw conclusions. For example, many studies investigating DCD have drawn the children from a variety of populations including those referred because of substantiated motor problems (Hoare, 1994; Hulme, Biggerstaff, Moran & McKinlay, 1982; Lord & Hulme, 1987a; 1987b; 1988), nominations by school teachers (Dewey, 1991; Henderson & Hall, 1982; Henderson, Rose & Henderson, 1992; Wright & Sugden, 1996), or from screening of a population of school children based on a test of motor performance (Smyth & Mason, 1998; van der Meulen et al., 1991). To further confound the issue, heterogeneity of DCD has been suggested in recent years, and investigations to explore the existence of subtypes have been recommended (e.g., Hoare, 1994; Pryde & Roy, 1999; Wright & Sugden, 1996). Given these methodological issues, there has been little consensus in the literature on the nature and cause of the motor skill problems in DCD.

Other than the common delay in the acquisition of normative motor skills, the only characteristic that has been demonstrated consistently in empirical studies of DCD is that these children have slower movement times, regardless of the type of task or how it is measured (Henderson, Rose & Henderson, 1992; Missiuna, 1994; Rösblad & von Hofsten, 1994). The reason for slower movement times appears to be related to a heavy reliance on visual information for the control of movement. A number of research studies manipulating the amount of visual information provided during movement have demonstrated the deficient performance of children with DCD relative to their peers without DCD (Rösblad

& von Hofsten, 1994; Smyth, 1991; van der Meulen, et al., 1991). Unfortunately, these studies did not perform detailed analyses of the movement trajectories[1] to specify the reason for the deficient performance, and some failed to examine the accuracy of the movements. The lack of these types of analyses and measures is problematic because the potential reason for slower movement in DCD is obscured.

The present research study is designed to achieve a better understanding of the perceptual, execution, and sensorimotor integration processes in DCD by examining the kinematic characteristics of goal-directed movement components as well as standardized measures that tap into these various processes. The performance of children who fully meet the DSM-IV criteria for developmental coordination disorder (e.g., referred due to significant motor problems, motor skills significantly below average) will be contrasted with that of their chronological peers (age-matched controls). The research methodology is designed to permit systematic manipulation of visual feedback for movement control and to permit detailed analyses of the planning and control aspects of movement. The goal of this research is to characterize the movement planning and control strategies of children with DCD and to provide further insight into the underlying cause(s) of their motor difficulties.

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[1] Although van der Meulen et al. (1991) analysed the movement trajectory, they purposely excluded corrective sub-movements (i.e., secondary movements) in their analysis. This is problematic because it eliminates information that is vital to determining subjects' use of sensory information in the control of their movements.

2. REVIEW OF RELATED LITERATURE

The review of the literature will be used to provide a background against which the purpose and the type of task described in this study may be fully understood. The first section provides a review of the studies that have investigated DCD in an attempt to identify the causal mechanisms of the disorder. The second section presents selected literature on the planning and control of goal-directed movements that pertains directly to the methodology and interpretation of the present study. The final section is concerned with the integration and consideration of these two bodies of literature as they apply to the approach taken.

Studies of Children with DCD: The Search for Causal Mechanisms

Experimental research attempting to identify causal mechanisms of DCD can be categorized into three areas of study. The first series of studies proposes that an underlying perceptual deficit of either vision or kinesthesis could explain the motor difficulties of children with DCD. Tasks which require visual, kinesthetic, or cross-modal perception are given to children with DCD and control groups in order to examine group differences. The second series of studies focuses on the characteristic slow and inconsistent motor performance of children with DCD using a variety of methodologies. The common feature of these studies is the manipulation of experimental tasks in order to measure group differences in speed of processing and execution during performance on a motor task. Finally, a third series of studies has emerged recently to examine subtypes of developmental coordination disorder. This line of research suggests that subtypes with distinguishable profiles of motor functioning exist within a population of children with DCD-like characteristics.

Studies of perceptual abilities

A series of studies conducted by Hulme and his colleagues compared the performance of groups of clumsy children (referred[2]) with a control group on a variety of tests measuring visual perception, kinesthesis, and visual-kinesthetic integration. The studies showed that clumsy children were less accurate than controls in their visual, kinesthetic, and cross-modal judgments of line length (Hulme, Biggerstaff, Moran & McKinlay, 1982), were significantly delayed in the development of visual perceptual and motor skills (Hulme, Smart, Moran & McKinlay, 1984), and were significantly worse than controls on measures of visual discrimination, tracing, drawing, and handwriting (Lord & Hulme, 1987, 1988). On the basis of correlations between the children's scores on the perceptual tests and their composite scores on everyday motor tasks, Hulme et al. have argued that the visual deficit is the cause of the clumsiness observed in these children.

Although the results of Hulme and his colleagues suggest a possible link between a visual perceptual deficit and poor motor skills, their results have been criticized on a number of factors. Sugden and Keogh (1990) have argued that the small number and poor description of the children render the results inconclusive.

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[2] Although the clumsy children recruited for these studies were referred because of significant motor problems, many of the children also had other neurological problems such as epilepsy and meningitis.

Furthermore, Henderson (1993) has criticized the findings due to the causal conclusions that were derived on the basis of statistically unreliable correlations as well as the fact that the results of the later series of studies contradict those of the earlier ones.

More recently, Mon-Williams, Pascal and Wann (1994) have examined opthalmic factors such as visual acuity, strabismus, orthophoria, stereopsis and ocular motility that might contribute to motor difficulties of children with DCD. Twenty-nine children nominated by their teachers and identified as DCD by the Movement Assessment Battery for Children (M-ABC; Henderson & Sugden, 1992) and twenty-nine control children were randomly selected to participate in the study. The results showed that there were no difficulties in any of the opthalmic tests that could be associated with the movement disorder. The researchers concluded that visual impairments were not a causal factor in DCD.

Laszlow and Bairstow have also conducted a series of studies that led them to argue strongly for kinesthetic dysfunction as the underlying cause of the motor difficulties seen in children with coordination problems. Their Kinesthetic Sensitivity Test (KST) (Laszlow & Bairstow, 1985) was designed to measure kinesthetic acuity, perception and memory. As Hulme and his colleagues did for visual perception, Bairstow and Laszlow (1981) investigated the relationship between their kinesthetic test and measures of motor skill and reported significant correlations between these measures. However, several researchers have presented data that are inconsistent with these findings (Elliot, Connolly & Doyle, 1988; Hoare & Larkin, 1991). Hoare and Larkin (1991), for example, measured the performance of a large sample of clumsy (referred) and control children. Children with coordination problems were found to be slightly deficient on only three of the seven kinesthetic tests and there was little correlation among any of the kinesthetic and motor skill measures. The authors concluded that kinesthesis is a complex, multi-modal system that is likely dependent on the task and the strategies adopted by the mover; therefore, relationships between kinesthetic deficiencies and motor ability are tenuous.

A more recent study by Smyth and Mason (1998) investigating the relationship between performance on simple tests of proprioception and more complex tests of perceptual-motor skill in DCD children (school-screened) and age-matched controls supports Hoare & Larkin's (1991) conclusion. Their results showed that simple non-visual movements do predict performance in more complex perceptual-motor tasks; however, the relationship between these tasks is weak and is affected by many task features rather than simply the reliance on proprioception (e.g., regulation of posture; target specification; effector system used). Thus, the authors concluded that any account of performance on non-visual tasks in terms of a unitary proprioceptive ability is incorrect.

Studies of motor planning and control

The second group of studies that has attempted to identify causal mechanisms of DCD has used theories of motor organization and control to manipulate various aspects of motor tasks. Specifically, these studies have focused on reaction time, movement time, movement accuracy, and movement variability to examine how children with DCD plan, organize, and execute motor responses.

Studies of goal-directed arm movements have examined clumsy children's ability to use visual and kinesthetic feedback for movement control. Smyth (1991) examined the RT and MT of clumsy (school-screened) and control children for simple and complex pointing movements with vision either available or precluded. Simple pointing movements involved a vertical movement of 22 cm, while complex movements involved a vertical movement of 22 cm followed by a horizontal movement of 25 cm to the right and a horizontal movement of 50 cm to the left. The RT of clumsy children was found to be significantly longer overall than that of the control group (i.e., main effect of RT), while the MT for the complex response only was found to be significantly longer for clumsy children (i.e., interaction between group and complexity). Interestingly, the results showed that the removal of vision increased MT by similar amounts for both groups indicating that clumsy and control children were equally able to use visual and kinesthetic feedback to facilitate movement. Smyth (1991) concluded that clumsy children experience difficulty with the programming of longer, more complex movements which results in a greater than normal dependence on feedback for movement control.

In a more recent study, Rösblad and von Hofsten (1994) also examined the control of goal-directed arm movements with and without visual feedback. In this study, however, the subjects included children who had been identified as DCD (referred) and of average intelligence. Children with and without DCD were required to pick up beads one at a time from a cup and place them into another cup. The apparatus used in the study allowed the researchers to preclude visual feedback of the targets and the moving limb. The results showed that children with DCD were consistently slower and much more variable than their peers. Similar to the findings of Smyth (1991), Rösblad and von Hofsten found that the withdrawal of visual information affected both groups of children in similar ways. The authors' conclusion concurs with that of Smyth (1991) as they suggest that children with DCD have an impaired capacity to program their movements and, as a result, consistently move more slowly and variably due to their reliance on feedback control.

Interestingly, both of the studies reported here concluded that the motor difficulties of clumsy children are due to an impaired capacity in movement programming. It is also interesting to note, however, that both of these conclusions were based on the findings that visual and kinesthetic feedback could be used equally well by both clumsy and control children, yet neither study measured the end-point accuracy of the children's movements. It is possible that children with motor difficulties may have moved in the same time as their peers in the absence of vision, yet they may have been significantly less accurate. If children with DCD were less accurate in the absence of vision, this finding would suggest that they have difficulty controlling their movements based on kinesthetic feedback.

A study conducted by van der Meulen et al. (1991) also examined the motor performance of clumsy children (school-screened) and controls for goal-directed arm movements with and without visual feedback and analyzed not only end-point accuracy but also implementation of the movement via the movement trajectory. A group of clumsy children were obtained based on ratings by school-teachers and a test of motor impairment and were matched with a group of their peers on age and gender. Children were required to make horizontal aiming movements as quickly as possible to lighted targets positioned up to 24 cm away from the starting position. The authors reported that clumsy children differ from their peers in that they have longer overall MTs particularly in the presence of visual feedback and larger variability in the distance moved during the acceleration (pre-programmed) phase of the movement. They also report no significant differences between the groups for end-point accuracy regardless of visual feedback. On the basis of these results, van der Meulen et al. concluded that clumsiness is linked to an inaccuracy in the pre-programmed phase of the movement.

The results of van der Meulen et al. (1991) within the context of visually-guided aiming are problematic. The researchers analyzed the implementation of movements by examining the movement trajectories of both groups of children, yet in their data analysis they clearly state that "corrective sub-movements (i.e., secondary movements) in the terminal phase of the movement were excluded from the analysis" (p. 44). All of the movements that were analyzed, then, consisted of one acceleration and one deceleration phase without prominent re-accelerations or re-decelerations in the trajectory. This method of analysis is problematic because it precludes important information about the way in which subjects are using sensory information to control their movements. This preclusion is especially troublesome in a study investigating the relationship between motor problems and sensory feedback since the use of feedback information is largely ignored. Studies of children and adults with various motor deficits have shown that the trajectories of visually-guided aiming movements are often characterized by several acceleration and deceleration phases (Flowers, 1975; 1976; Forsstrom & von Hofsten, 1982; Schellekens, Scholten & Kalverboer, 1983). These findings suggest that van der Meulen et al. (1991) ignored an important aspect of the movement trajectory in clumsy children and renders the findings of their study inconclusive.

Geuze and Kalverboer (1988) used a continuous tapping task between two targets at a distance of 24cm and examined the spatial and temporal parameters of performance in clumsy (school-screened) and control children. The results showed that both the preprogrammed phase and the feedback controlled correction phase contributed to the greater inaccuracy of clumsy children. The longer movement times and shorter, more variable acceleration phases indicate that clumsy children spend more time using feedback to correct the inaccuracy of the preprogrammed phase of their movements. Because visual feedback was not manipulated in this study, the origin of the programming problems of clumsy children (e.g., visual vs. non-visual) could not be determined.

Studies of subtyping

Given the heterogeneity of DCD, some investigations exploring the existence of subtypes within the population have been conducted. Hoare (1994) identified five distinct patterns of perceptual-motor dysfunctions among 80 children with DCD from six to nine years of age (referred). Using a series of both fine and gross perceptual-motor tests, five subtypes were produced from cluster analysis. Subtype 1 was characterized only by high scores in static balance and slow running times, suggesting that the notion of a subtype of DCD children with an overall gross motor deficit is too general. Subtype 2 was characterized by above average visual skills relative to the remainder of the DCD sample, providing evidence against the notion of a generalized visual perception deficit in children with DCD. Subtype 3 was below average on all visual and kinesthetic tasks, suggesting a generalized perceptual dysfunction. Subtype 4 was marked by high scores in kinesthetic acuity and low scores in the visual domains. Hoare emphasized that this difference may reflect a visual contribution to motor dysfunction in some children. Finally, subtype 5 was comprised of a small number of children who demonstrated below average scores on motor-loaded tasks, indicating problems in execution. Hoare's (1994) findings clearly demonstrate that among a group of children who are all identified as having DCD, there are examples of perceptual deficits that generalize across modalities as well as examples that are highly specific to a certain group of children.

In a similar study, Wright and Sugden (1996) investigated the existence of subtypes within a sample of 69 children with DCD aged six to nine years (school-screened). Using five clusters of variables from the M-ABC checklist and the M-ABC test, the researchers conducted a factor analysis that yielded four subgroups of DCD. Subgroup 1 showed an even profile across tasks, with no deviations from the average scores of the DCD group, indicating that they represented a mildly impaired group. Subgroup 2 demonstrated below average performance on tasks requiring catching, which the authors suggest may indicate a dysfunction separate from other manipulative tasks requiring visual-motor integration. Subgroup 3 showed the most difficulty on tasks in which the environment was changing, while subgroup 4 had the lowest scores on speeded manual dexterity tasks as well as tasks of dynamic balance.

In a recent study by Pryde and Roy (1999), two children with DCD-like characteristics (teacher-nominated) were examined on a manual aiming task relative to a group of their same-aged peers without motor difficulties. The aiming task was performed with and without visual feedback of the moving hand. The results revealed that the nature of the children's performance patterns were not only different from those of their peers, but also from those of each other. Specifically, one child's movement problems did not dramatically affect his ability to produce aiming movements. The only difficulty exhibited by this particular child was with respect to movement accuracy in the absence of vision, suggesting that his problems may lie at the perceptual stage of processing affecting his spatial localization abilities. In contrast, the findings for the other child indicated that his motor problems dramatically affected his ability to produce aiming movements. The nature of this child's difficulties suggested that his problems may lie more in the response programming and/or execution stages of processing affecting his ability to adjust the force parameters of movement.

Although these three studies provide some insight into the heterogeneity of DCD, they do not provide consistent subtypes of children. The data suggest, mainly, that any sample of DCD will likely be comprised of children demonstrating varying types and degrees of underlying deficits.

Summary of research on children with DCD

In summary, it is clear that children with DCD are a heterogeneous group. Studies of visuomotor control indicate that these children do tend to rely more heavily on feedback to control their movements relative to other children (Rösblad & von Hofsten, 1994; Smyth, 1991; van der Meulen et al., 1991a); however, it is unclear as to whether or not these children are able to use visual and kinesthetic feedback in the same way as their peers for the control of movement. There is evidence to suggest that most children with DCD do not have a difficulty with the use of visual information for movement control (Missiuna, 1995; Mon-Williams et al., 1994); however, detailed analyses of the processes underlying goal-directed movements have not been conducted to confirm this. Research on kinesthetic functioning has been inconsistent, yet there is evidence to suggest that children with DCD may have difficulty using kinesthetic information for movement control (Smyth & Glencross, 1988; Smyth & Mason, 1998).

Some evidence has been presented to suggest that one of the mechanisms underlying DCD is the impaired ability to accurately plan and organize a motor response (Geuze & Kalverboer, 1988; Rösblad & von Hofsten, 1994; Smyth, 1991; van der Meulen et al., 1991). Although many researchers have concluded that the motor difficulties of children with DCD are due to an impaired capacity in motor programming, many of these conclusions have been based on less than complete analyses. Furthermore, many of these studies recruited children who did not fully met the DSM-IV criteria for DCD (i.e., criterion B). Research is needed that will investigate the performance of manual aiming movements, with and without visual feedback, in a more "genuine" population of children with DCD. Detailed analyses of the movement trajectory as well as the accuracy of the movement components is necessary to specify the reasons underlying the motor difficulties observed in children with DCD. In addition, given the heterogeneity of the DCD population, it is necessary to perform within-group analyses to examine individual patterns of performance amongst children with DCD.

The Planning and Control of Goal-Directed Movements

Literature concerning the planning and control of goal-directed movement will be presented in order to understand the mechanism(s) in the information processing system which have been purported to underlie the motor problems of children with DCD.

How the CNS integrates information to produce goal-directed movement

This section is concerned with outlining the steps involved in integrating sensory representations of the environment and the motor system and transforming these into the appropriate coordinate systems for the production of goal-directed movement. A general model has been developed based on several models of motor control (Jeannerod, 1988; Kalaska, 1991; Schmidt; 1991; Smith et al., 1991) and provides a framework for understanding the perceptual, central, and execution mechanisms involved in goal-directed movement (see Fig. 2.1).

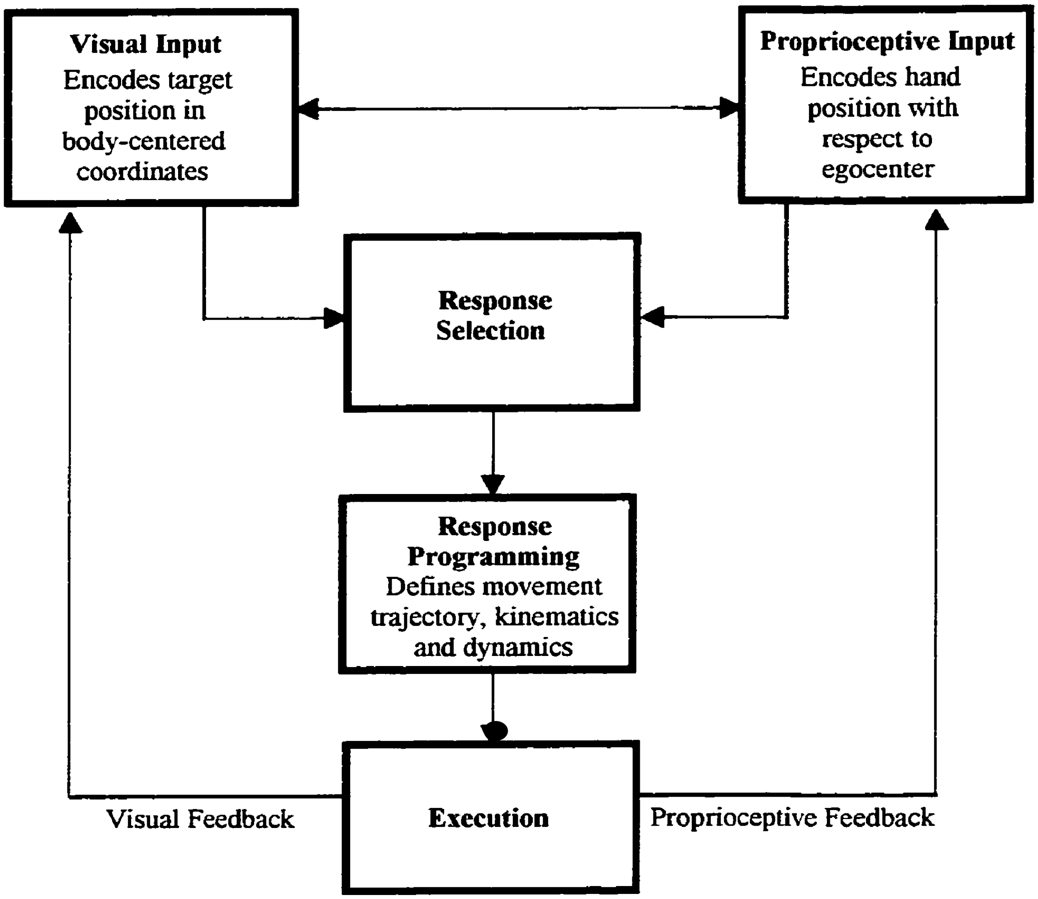

Figure 2.1. A general model of sensorimotor integration outlining the planning and control stages involved in the production of goal-directed movement. Adapted from Jeannerod (1988), Kalaska (1991), Schmidt (1991) and Smith et al. (1991).

The first part of the model involves two convergent streams of sensory processes. Beginning with the retina, one pathway generates an egocentric map of extrapersonal space indicating the target's position with respect to the head and then relative to the body. The other pathway concurrently analyzes afferent input from proprioceptors to synthesize an intrinsic-space map of the posture of the hand and arm relative to other parts of the body. Information from the intrinsic (proprioceptive) and extrinsic (visual) maps are merged to define the location of the target relative to the position of the hand, arm and body. This integration provides the basic information needed to plan the trajectory of the hand-arm movement through space to the target.

Once the plan for the desired trajectory is determined, the CNS can determine the kinematics (direction, velocity) and dynamics (forces)[3] necessary to produce the trajectory as well as the expected sensory feedback signals that will be generated from the motor plan or program. From the motor program, the appropriate pattern of muscle activation is in some way computed (Jeannerod, 1988; Kalaska, 1991; Smith et al., 1991). Once execution of the movement begins, the motor plan or program can be updated in several ways by means of feedforward, reflex, and/or feedback mechanisms.

The general processes involved in the transformation from the movement plan to the appropriate patterns of muscle activation have been the subject of particularly intense inquiry (Smith et al., 1991). Unfortunately the inverse kinematics/ dynamics problem and the proposed neurophysiological solutions are beyond the scope of this review. Of particular interest for this research are the characteristics of the movement trajectory and the control mechanisms necessary for successful implementation of goal-directed movement.

Woodworth (1899) was the first to describe goal-directed aiming as being two-phased: an initial motion followed by a controlled adjustment. The initial

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[3] "Velocity" refers to the rate of change in muscle length for a movement and "forces" refer to the level of muscle contraction for a movement.

phase transports the limb quickly towards the target location and the control phase subsequently corrects any errors made along the way using sensory feedback to reach the target accurately. Since that time, this notion has been reported consistently and extended in the literature (c.f. MacKenzie & Iberall, 1994). In terms of the kinematic components of simple aiming movements, the initial and control phases are manifested as a bell-shaped velocity profile (see Fig. 2.2). This profile consists of two components that differ in their reliance on sensory information. In simple aiming movements, the initial ballistic component transports the limb to the vicinity of the target. This initial component has been separated into an acceleration phase and a deceleration phase. The acceleration phase is less dependent on sensory feedback and is more reflective of preprogramming (MacKenzie, Marteniuk, Dugas, Liske & Eickmeier, 1987). The secondary component involves corrective movements to hit the target endpoint. This latter component is considered closed-loop because programming occurs on-line and the movements are slow and sensory dependent. The dichotomy between open- and closed-loop components of aiming is not absolute because the initial component can sometimes be modified by changes in visual information during the movement (Goodale, Pelisson & Prablanc, 1986; Prablanc, Pelisson & Goodale, 1986), although the limits of this effect have not been specified (Haaland, Harrington & Grice, 1993).

Researchers have shown that the symmetric or asymmetric nature of the bell-shaped profile is dependent upon the intrinsic properties of the target (e.g., size and fragility). MacKenzie et al. (1987) replicated the conditions from Fitts'

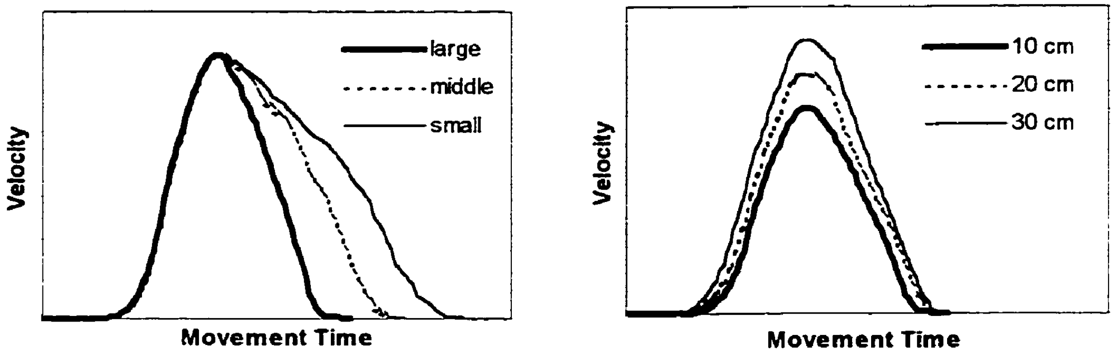

Figure 2.2. Velocity profiles scaled to target size (left) and amplitude (right).

study (1954) and found systematic effects of target size on the degree of asymmetry in the velocity profiles. Subjects were asked to point with a stylus as quickly and as accurately as possible to a target of varying size and at varying amplitudes (e.g., distances from the starting point). The question of interest was whether there was a reliable kinematic measure of the precision requirements of the task.

MacKenzie et al. (1987) measured the movement time (MT) of the tip of the stylus, the time to peak velocity (e.g., the maximum speed of the movement) and the percentage of MT after peak velocity. The results showed that there was a differential effect of target size and amplitude on these movement parameters. Specifically, peak velocity was primarily a function of target amplitude with no effect of target size (see Fig. 2.2). In contrast, the percentage of time spent in the deceleration phase of the movement increased as target size decreased with no effect of amplitude (see Fig. 2.2). Thus, the value of peak velocity was scaled to the amplitude of movement, but the relative timing of acceleration and deceleration components remained invariant for a given target size. The authors concluded that amplitude and target size effects are disassociable as the shape of the velocity profile is a function of target size (accuracy) and the peak speed along the trajectories is scaled according to movement amplitude (MacKenzie & Iberall, 1994).

Of particular interest here is what happens to the control of goal-directed movements when visual feedback is not available. Studies which have selectively excluded visual feedback during part of a movement or throughout an entire movement have shown that movements completed with visual feedback are more accurate than those completed without vision (Keele & Posner, 1968; Pryde & Roy, 1997; Vince, 1948; Woodworth, 1899; Zelaznik, Hawkins & Kisselburgh, 1983). It has been further shown that vision of the moving hand and arm is most critical prior to movement initiation (Prablanc, Echallier, Komilis & Jeannerod, 1979) as well as during the final part of the hand trajectory (Carlton, 1981; Conti & Beaubaton, 1976).

Vision of the hand and arm prior to movement initiation is critical for calibrating proprioceptive information about the position of the hand in space. Without calibration from vision, the proprioceptive map is insufficient to encode hand position and to efficiently drive the hand toward the target (Jeannerod, 1988; Prablanc et al., 1979). Vision of the hand during the latter part of the movement is also critical for achieving end-point accuracy as the hand approaches the target. Since the initial component of the movement is responsible for transporting the hand into the general area of the target, the secondary or corrective component is responsible for using sensory information (e.g., vision) to direct the hand toward the target end-point.

It should be noted here that secondary or corrective movements are not dependent upon visual feedback. Corrective movements have been observed in both the presence and absence of visual feedback although the absence of vision results in a higher overall error rate (Jeannerod, Michel & Prablanc, 1984; Meyer, Smith, Kornblum, Abrams & Wright, 1990). This finding indicates that proprioceptive information is at least in part necessary for making corrective movements of the hand toward the target end-point during goal-directed movement (Jeannerod, 1988).

Understanding the control of disordered movement

Kinematic analyses such as the one employed by MacKenzie et al. (1987) provide valuable information about the processes underlying the control of movement and are therefore useful for providing insight into the underlying nature of movement deficits. These analyses are particularly useful for determining the neuromotor mechanisms responsible for the slowness and variability that often accompany disordered movement.

As discussed in the previous section, bell-shaped velocity profiles are generally recognized as the invariant feature of efficiently programmed and controlled movements. In contrast, studies of patients with various neurological deficits have frequently observed manual aiming movements characterized by irregular, multi-peaked velocity profiles. For example, Jeannerod, Michel and Prablanc (1984) reported a study of goal-directed hand movements in a patient who suffered sensory loss in her right hand and forearm following a parietal lesion. Movements executed with her right hand (e.g., contralateral to the lesion) were affected by the presence or absence of visual feedback of the moving hand. In the 'visual feedback' condition the transportation component of prehension appeared to last longer than that of the normal hand due to the occurrence of corrective movements (i.e. secondary velocity peaks) during the deceleration phase. In the 'no visual feedback' condition, only the initial part of the transportation component was normal; following the first velocity peak, the hand wandered above the object location without reaching the object.

The kinematic analysis used in this case provides valuable information about the control of goal-directed movement in the presence of a sensory deficit. Specifically, the analysis showed that when kinesthetic control is lacking, vision plays a major substitutive role in motor control. The consequences of this alternate control of movement are longer movement times due to the greater portion of time spent in the secondary component making a greater number of on-line corrections. When visual feedback of the moving hand is prevented, movements become significantly longer and less accurate.

In contrast, studies of individuals with Parkinson's disease (PD) demonstrate movement deficits due to difficulties in motor programming/execution (Flash, Inzelberg, Schectman & Korczyn, 1992; Flowers, 1975, 1976; Isenberg & Conrad, 1994). A series of classic studies conducted by Flowers (1975, 1976) examined aiming movements to target stimuli at varying amplitudes in individuals with PD and control subjects. The findings revealed that individuals with PD experience difficulty with the initial pre-planned phase of their aiming movements and as a result spend more time using feedback to control their movements. Kinematic analyses of the movement components revealed that the initial, ballistic component was significantly longer and slower than that of the control group. Furthermore, the accuracy of this component with respect to driving the hand into the general area of the target was worse for the PD group particularly for movements at the largest amplitude (12.5 cm). As a result of this inaccurate initial movement, individuals with PD spend more time in the corrective phase of the movement as they rely more heavily on feedback to correct the hand trajectory.

Flowers (1975, 1976) concluded that individuals with PD have difficulty generating large-scale ballistic movements which forces them to perform slowly and with constant on-line monitoring of movements as they are executed. With small amplitude jumps this method is adequate since the errors of accuracy and slowness of execution are not marked. However, with movement amplitude where a ballistic response improves performance, individuals with PD are at a disadvantage. Their performance remains slow, irregular, and characterized by more corrections. These irregular movement patterns have also been described in more recent research on PD (Flash, Inzelberg, Schectman & Korczyn, 1992; Isenberg & Conrad, 1994).

In studies of children, Schellekens, Scholten and Kalverboer (1983) investigated the inter-response intervals as well as the duration and number of ballistic components in visually-directed aiming movements in a small group of institutionalized children with minimal brain dysfunction. Schellekens et al. found that these children demonstrated significantly longer total movement times than the control group, shorter times in the initial pre-planned phase of the movement, more corrective movements, and more irregularities or sub-peaks in the velocity profile. The authors concluded that children with a non-optimal neurological status experience difficulty with the programming of movements relative to control children and consequently spend more time using sensory feedback to control their movements.

It is important to note here, that irregular kinematic profiles (e.g., movements with multiple peaks) have also been found in developmental studies of neurologically normal individuals under certain task constraints. For example, several studies have shown that when children are required to make manual aiming movements in the absence of visual feedback of the hand, 6-7-year-old children demonstrate a higher percentage of irregular, multi-peaked movement patterns relative to their older counterparts (Hay, 1979, 1984; Pryde & Roy, 1998). These multi-peak movement patterns have been described as "step" movements in the literature and have been interpreted as abnormal responses from less than mature sensorimotor systems at this age.

This section has considered several movement disorders that are characterized by slow, irregular movements and a heavy reliance on sensory feedback. The kinematic components of these disordered movements differ in two ways and as such provide grounds for what the kinematic characteristics of DCD movements might resemble given a kinesthetic versus a motor planning deficit. Specifically these differences are found in the initial ballistic component of the movement. In the case of a kinesthetic deficit (e.g., Jeannerod et al., 1984), the pre-programmed phase of the movement remains normal and more time is spent making corrections based on visual feedback. When visual feedback is prevented and kinesthesis is the only sensory modality for motor control, the pre-programmed phase of the movement remains normal, but the corrective phase becomes even longer and accuracy is largely affected.

In contrast, when motor programming is the underlying deficit of a movement disorder as in the case of Parkinson's disease or minimal brain dysfunction, the deceleration phase is also significantly longer with many corrective movements. However, the key feature of the kinematics that accounts for the longer deceleration phase is found in the initial pre-programmed phase of the movement. In these instances, the initial component is marked by abnormality as reflected in slower movement, more sub-peaks, and greater inaccuracy. Furthermore, motor programming deficits often result in more irregularities or sub-peaks in the overall velocity profile.

Summary of DCD and Goal-Directed Movement

The research on children with DCD has shown that a characteristic feature of the disorder is slowness and irregularity in motor performance, a characteristic which is not uncommon to many movement disorders. The question that remains is "What is the reason for the slowness and irregularity in the movements of children with DCD?" Slow, irregular movements may be caused by a difficulty in motor planning or by an impaired ability in using sensory feedback for movement control. A valuable approach to identify the mechanisms underlying slowness and irregularity in disordered movement rests on an analysis of the implementation of the movement by way of the movement kinematics. This approach allows for the examination of the planning and control phases of goal-directed movements.

Some evidence exists to suggest that the mechanism underlying DCD is the impaired ability to accurately plan and organize a motor response. This notion has derived from several studies revealing longer total movement times and shorter inaccurate preprogrammed movements in children with motor difficulties characteristic of DCD (Geuze & Kalverboer, 1988; Rösblad & von Hofsten, 1994; Smyth, 1991; van der Meulen et al., 1991). There is other evidence, however, to suggest that a difficulty in using sensory feedback for motor control may underlie the problems in DCD (Laszlow et al., 1988; Missiuna, 1994; Rösblad & von Hofsten, 1994; Smyth & Glencross, 1988; Smyth & Mason, 1998). Although several researchers have concluded that the motor difficulties of children with DCD are due to an impaired capacity in motor programming, detailed analyses have not been conducted to specify the reasons. Furthermore, given the heterogeneity of DCD, few studies have performed within-group analyses to identify possible differences in individual patterns of performance. Of particular interest, then, is to perform a detailed analysis of the movement trajectories to determine how DCD will affect the components of goal-directed movement under different visual feedback conditions relative to chronological peers. It is also of interest to use standardized neuropsychometric measures that tap into the various processes of sensorimotor control for goal-directed movement to determine how DCD affects these processes. In summary, the primary goal of this study is to characterize the movement planning and control strategies of children with DCD and to provide further insight into the mechanisms underlying their movement difficulties. A secondary aim of this study is to perform within-group analyses of children with DCD to provide further insight into individual patterns of performance within this population. Because of the exploratory nature of this research, specific hypotheses have not been formulated. Instead, specific research questions have been outlined.

3. RESEARCH OBJECTIVES

The goal of this research is to characterize the movement planning and control strategies of children with DCD relative to their chronological peers under different sensory feedback conditions. Moreover, this research aims to provide further insight into the mechanisms underlying the movement difficulties of children with DCD by investigating the relationship between kinematic patterns of performance and psychometric measures as well as the nature of individual patterns of performance.

The specific questions that guide this research are:

1. How will the availability of visual feedback affect the performance of children with DCD relative to their chronological peers without motor difficulties?
2. Will children with DCD be differentially affected by task requirements such as movement amplitude and target size relative to their peers?
3. Will DCD differentially affect the preprogrammed and/or feedback controlled components of goal-directed movement?
4. What is the relationship between movement kinematics and spatial accuracy in children with DCD relative to their peers? Is this relationship different within a group of children with DCD?
5. What is the relationship between kinematic/accuracy patterns of performance and neuropsychological measures in children with DCD?

Questions 1 to 3 are concerned with characterizing the kinematic components of goal-directed movement in children with DCD relative to their peers under different task constraints. Questions 4 and 5 are concerned with investigating and characterizing differences in individual patterns of performance within a group of children with DCD.

1. ***How will the availability of visual feedback affect the performance of children with DCD relative to their chronological peers?***

   Studies of children with DCD have shown that these children rely more heavily on visual feedback in order to control and correct their aiming movements. It is anticipated that if this reliance on vision is due to a proprioceptive or visual-proprioceptive deficit, then the removal of visual feedback will have a differential effect on movement kinematics and end-point accuracy. The effect on the kinematics will be dependent on the strategies that children with DCD use to implement their movements, therefore, specific predictions have not been made. It is expected, however, that end-point accuracy would be significantly lower in the absence of visual feedback if children with DCD are experiencing difficulties in proprioception or visual-proprioceptive integration.

2. ***Will children with DCD be differentially affected by task requirements such as movement amplitude and target size relative to their peers?***

   The effects of movement amplitude and target size on the kinematic components of goal-directed movement have been well documented (e.g., MacKenzie et al., 1987; MacKenzie & Iberall, 1994). In children without

DCD, it is expected that peak velocity will be scaled to movement amplitude and that the time spent in deceleration will be a function of target size. Because these effects are dependent on the ability to effectively plan and control a movement and because the effect of DCD on these processes is not fully understood, specific predictions about the kinematic characteristics of children with DCD under different task constraints have not been made. One general prediction that will be made is based on the tendency of children with DCD to rely heavily on visual feedback for movement control. It is expected that when visual feedback is available children with DCD will demonstrate differentially longer movement times when the accuracy requirements increase (e.g., target size decreases). In the absence of visual feedback, however, the effect of target size will be dependent on the ability to use proprioceptive information for movement control, thus, the size and direction of this effect is unclear.

3. Will DCD differentially affect the preprogrammed and/or feedback controlled components of goal-directed movement?

Studies of children with movement difficulties characteristic of DCD have shown that the preprogrammed component (i.e., time to peak velocity, peak velocity) of aiming movements are shorter, slower and less accurate. The effect of feedback availability on the accuracy and duration of the feedback-controlled components of their movement is, however, unknown. It is expected that the initial movement component of children without DCD will generally be marked by a bell-shaped profile with smooth acceleration and deceleration, occasionally followed by a secondary component of minor corrective adjustments. For children identified with DCD, difficulties due to a motor planning deficit should be characterized by abnormal preprogramming, regardless of the visual feedback available. Such movements are typically characterized by multi-peaked velocity profiles (e.g., 'step' movements in Pryde & Roy, 1999). Alternatively, if DCD is a problem of using sensory feedback, movements should be characterized by a normal pre-programmed phase and longer times spent in deceleration.

4. ***What is the relationship between movement kinematics and spatial accuracy in children with DCD?***

Kinematic abnormalities (i.e., irregular, multi-peaked velocity profiles) have been interpreted as indicators of deficient motor programming. For the aiming task, deficient programming could be the result of a motor programming/execution, sensory, or sensorimotor deficit. Each of these difficulties has been postulated as deficits in DCD. Thus, if DCD is the result of a programming deficit, kinematics should be abnormal for both visual and no visual feedback conditions, but accuracy should generally be normal (e.g., similar to that of controls). If DCD is the result of a sensory (proprioceptive) or sensorimotor (visual-proprioceptive) deficit, however, then kinematics should generally be normal, particularly in the visual feedback condition, but accuracy should be normal in the visual feedback condition and abnormal in the no visual feedback condition.

	Programming		**Sensory or Sensorimotor**	
	Vision	**No Vision**	**Vision**	**No Vision**
Kinematics	-	-	+	+
Accuracy	+	+	+	-

It is possible, however, that children will compensate for a given deficit by using different strategies; thus, kinematic/accuracy patterns will be characterized and examined on a within-subject basis.

5. ***What is the relationship between kinematic/accuracy patterns of performance and neuropsychological measures in children with DCD?***

This question of interest stems from the work of Pryde & Roy (1999) and relates to testing various aspects of the aiming task using a series of construct validation tests. After categorizing children into the various kinematic/accuracy patterns, tests tapping the processes that could account for these patterns of performance will be examined. For example, children who demonstrate a + kinematics, - accuracy pattern in the no visual feedback condition may have proprioceptive deficits; thus, DCD children with this pattern might be expected to perform less well on the proprioceptive measure. Conversely, a – kinematics, + accuracy pattern in either the visual or no visual feedback condition may be attributable to programming/execution problems; thus, DCD children demonstrating this pattern would be expected to do less well on measures of complex motor functioning (c.f. Hoare, 1994).

4. METHOD

1. Participants

The study included 20 children identified as having the characteristics of developmental coordination disorder as defined by DSM-IV (see Appendix A) and 20 children without motor problems. The DCD sample was selected from children referred due to significant functional motor problems to an occupational therapy treatment program at the University of Western Ontario. Referrals typically came from teachers, physicians, and parents. The control sample was recruited from the local communities of London and Waterloo, Ontario, Canada. Each sample was comprised of 17 males and 3 females within two age groups: 7-9 years and 10-12 years. Participants were matched for gender and age (± 6 months).

The presence/absence of DCD was based on the children's performance on the Movement Assessment Battery for Children Test (M-ABC) (Henderson & Sugden, 1992) (see Appendix B for a description of this measure). Children were identified as having the characteristics of DCD if their overall score on the M-ABC Test was below the 15th percentile; whereas, children without motor problems were identified based on an overall score above the 25th percentile. All children were also tested on the Kaufman Brief Intelligence Test (K-BIT) (Kaufman & Kaufman, 1990) to ensure normal intelligence (e.g., IQ within one standard deviation of the normative mean) (see Appendix B for a description of this measure). The selection of the DCD sample, then, was based on multiple criteria: referral due to significant functional motor problems, score significantly below average on a test of motor performance, and normal intelligence.

None of the children recruited for participation in this study were known to have physical impairments or uncorrected vision or hearing problems. Hand preference was established by children's responses to the following questions: With which hand do you write, throw a ball, comb your hair, and eat with a spoon? The descriptive information characterizing the participants in this study is presented in Table 4.1.1.

Table 4.1.1
Characteristics of the Participants

	DCD		**CONTROL**	
	7-9 Years	**10-12 Years**	**7-9 Years**	**10-12 Years**
Age (years)				
X	8.31	10.91	8.39	11.01
s.d.	0.75	1.03	0.91	0.81
M-ABC				
X	20.05	21.55	3.75	4.25
s.d.	5.70	5.70	2.47	2.62
IQ				
X	110.75	109.60	116.31	118.88
s.d.	10.36	12.61	12.25	13.97
Hand Preference				
R	17	20	20	19
L	3	0	0	1

2. Apparatus and Testing Materials

Apparatus

The apparatus used to present the manual aiming task is similar to that used previously by Pryde and Roy (1997, 1998, 1999) and is illustrated in Figure 4.2.1. The apparatus consisted of a box (55 cm w x 60 cm d x 120 cm h) resting on a table, divided horizontally into two compartments by a reflecting mirror. A computer monitor was placed face down through the top of the box such that the computer screen's image was reflected in the mirror. In this way, a cursor and various targets were presented on the mirror along the participants' sagittal axis. Participants were seated in front of the box looking at the mirror in the upper compartment and controlling a mouse on a digitizing tablet in the lower compartment. A black curtain hung down from the mirror in front of the digitizing tablet so that view of the participant's hand was occluded at all times.

Movements made with the mouse were detected by a computer sampling the SummaSketch III digitizing tablet (MM III 1201, Summagraphics) at 121.7 Hz. The tablet was used for recording the child's movements to the various targets presented on the mirror. A one-to-one correspondence existed between the child's movement of the mouse and the movement position of the cursor on the mirror. In other words, movements of the cursor on the mirror were analogous to movements of the hand and mouse under the mirror.

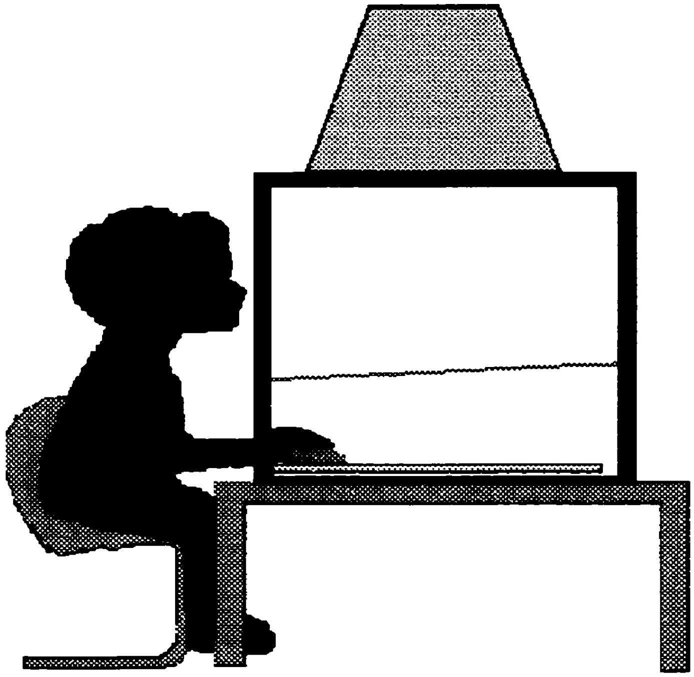

Figure 4.2.1. Experimental apparatus showing the computer monitor on the upper surface of the box, the mirror within the box, and the digitizing tablet and mouse in the lower compartment.

Standardized Tests

Several standardized measures were administered to tap into the various processes involved in the aiming task. These assessments are widely available and are described briefly below.

Motor-Free Visual Perception Test (Colarusso & Hammill, 1995)

The Motor-Free Visual Perception Test (MFVPT) provides an estimate of visual perceptual ability in children with no requirements for graphomotor responses from the child. The test uses a target-stimulus matching approach to measure five visual perceptual skills including spatial relationships, visual discrimination, figure-ground, visual closure, and visual memory. An overall perceptual quotient is yielded. This test was selected for use in this research to rule out the possibility that sensorimotor difficulties in children with DCD are a function of visual perceptual deficits.

Imitating Hand Positions subtest of the NEPSY (Korkman, 1998)

The Imitating Hand Positions (IHP) task is a subtest within the Sensorimotor Functions domain of the NEPSY. The IHP assesses kinesthetic praxis – the ability to imitate a hand position from a model. The examiner models a series of hand positions, one at a time, ranging from simple to complex and the child attempts to reproduce each within 20 seconds. A low score on the IHP is indicative of difficulty with the fine-motor coordination required to reproduce the positions, which is often based on inefficient processing of kinesthetic information, or difficulty reproducing the spatial relationships presented by the model (Korkman, 1998).

Although this test is not a "pure" measure of kinesthesis, it was chosen as a measure of kinesthetic functioning for this study because it does tap into the kinesthetic processing required to perform the experimental aiming task. More specifically, as in the IHP task, the aiming task requires children to integrate visual information about various target characteristics and spatial relationships in order to generate a movement response to quickly and accurately adapt to those characteristics.

Developmental Test of Visual-Motor Integration - Revised (Beery, 1997)

The Developmental Test of Visual-Motor Integration (VMI) is a perceptual-motor ability test consisting of 24 geometric forms arranged in order of increasing complexity. Children are required to copy the forms, one at a time, until three consecutive failures are made. A low score on the VMI could be indicative of difficulty in the coordination or integration of visual perceptual and motor coordination abilities. It may also be indicative of deficient visual and/or motor abilities (Beery, 1997). This test was chosen as a measure of the extent to which children could integrate visual and motor abilities, as is required on the aiming task.

Grooved Pegboard Test (Trites, 1989)

The Grooved Pegboard Test (GPT) is a complex test of manual dexterity consisting of a small board containing a 5 x 5 set of holes randomly oriented in different directions. Each peg has a ridge along one side requiring participants to rotate it into position for insertion into the holes. Total time to completion is scored; thus, participants are required to complete the task as quickly as possible. The GPT is considered to be a neuropsychologically sensitive test of the hemispheric components of motor functioning and motor dexterity (Lezak, 1983). This test was selected as a measure of complex motor functioning, similar to the nature of the manual performance required to perform the aiming task.

3. Procedure

Each child was tested individually in sound-attenuated testing rooms. The principal investigator conducted testing on the aiming task, while standardized testing was conducted by the principal investigator, a research colleague/ occupational therapist, and two research assistants with psychometric training.

The total testing time was approximately 120 minutes. Children were given short breaks throughout the session.

Aiming Task

At the beginning of a trial, the starting position and the cursor (a rocketship) indicating the participant's hand position were presented on the mirror at the bottom centre of the screen. An analogous starting position was outlined on the digitizing tablet so that the mouse was aligned with the cursor at the beginning of every trial. Once the participant had the mouse in position under the mirror, a key press made by the experimenter initiated the trial. At the beginning of each trial an auditory tone was presented and after a variable delay of 1-3 seconds, one of two target sizes (1.25 cm or 2.25 cm in diameter) in the shape of planet earth was displayed directly above the starting position at an amplitude (e.g., distance) of either 50 mm, 100 mm, or 150 mm. When the planet/target was displayed the participant moved the rocketship to the planet as quickly and as accurately as possible. Once the rocket was moved into the planet the child pressed a mouse button to end the trial. The rocketship/cursor measured 0.75 cm in width and 1 cm in height.

On visual trials, feedback of the cursor position was available throughout the trial. On non-visual trials, view of the cursor position was removed 10 ms after target onset and remained undetectable for the duration of the movement. Once the child pressed the mouse button to mark the end of the movement, visual feedback of the terminal position of the cursor was provided.

Before starting the test trials, children were given a minimum of three practice trials with visual feedback to ensure they were familiar with the nature of the aiming task. Each participant then performed five trials in each of the 12 conditions (3 amplitudes x 2 sizes x 2 feedback). The trials were blocked for feedback availability and randomized for movement amplitude and target size. The order in which participants performed the feedback conditions was also randomized. Each child completed a total of 60 experimental trials.

Because the present experiment involved children, reinforcement was provided after every six trials in order to increase the children's motivation to perform the task. One of three pictures appeared indicating how accurate the last 6 movements had been. The most accurate picture that could be attained was a green picture of the rocketship inside the planet. The second most accurate picture was purple in colour and depicted the rocketship a few centimetres outside of the plant. The least accurate picture that could be attained was red and depicted the rocket several inches outside of the planet. In each of the feedback conditions the participants were encouraged to attain as many green pictures as possible. This knowledge of results has been found to be very successful in increasing children's motivation to perform the task (Pryde, 1997).

4. Data Analysis

The raw displacement data were filtered with a second-order dual-pass Butterworth filter (Winter, 1990) using a low-pass cutoff frequency of 5 Hz. Velocity was subsequently determined by differentiating displacement data. The movement onset and end-point were determined from the velocity profiles as the time points where the signals departed from or, respectively, returned to their baseline. Modifications to the primary movement impulse, i.e., movement corrections or subpeaks, were defined as secondary movement impulses with velocity values equivalent to at least 5% of the primary movement velocity peak.

Several kinematic variables were determined to characterize the movements on the aiming task: reaction time, total movement time, peak velocity, time to peak velocity, time after peak velocity, number of subpeaks, and initial and final accuracy. RT was defined as the interval between the onset of the target stimulus and the beginning of the hand movement. The different components of the movement included: the acceleration phase of the initial component, the deceleration phase of the initial component, and if present, the corrective movement(s). The acceleration phase began at the end of the RT interval and ended when peak velocity was reached. The deceleration phase began at the end of the acceleration phase and terminated at the movement end-point or when velocity decreased at least 50% and increased again to enter a second acceleration phase (e.g., secondary movement impulse). The corrective movement was defined as the time interval between the end of the deceleration phase and the movement end-point.

Accuracy was defined as the difference between the desired and actual movement amplitude on both the x- and y-axes (e.g., radial accuracy). Accuracy was measured at the end of the initial uncorrected movement (initial accuracy) and at end of the corrected movement (end-point accuracy).

5. RESULTS

Analysis of results will proceed in four steps according the questions of interest for this research: (i) the kinematic parameters will be statistically compared between the groups (DCD and control); (ii) the normal and abnormal kinematic profiles will be described and statistically compared between the groups (DCD and control); (iii) the relationship between kinematic profiles and movement accuracy will then be described and statistically compared between the groups; and (iv) the relationship between kinematic/accuracy patterns and standardized measures will be investigated within the DCD group. Analyses conducted for step one (i.e., on the kinematic parameters) utilized the mean values of the five trials; all subsequent analyses examined data on a trial-by-trial basis for each participant.

Consistent with previous developmental research (Hay, 1984; Pryde & Roy, 1998), preliminary analyses of key measures of performance on the aiming task (i.e., movement time and accuracy) revealed different patterns of performance across age groups. Specifically, a 2 (age) x 2 (group) x 2 (feedback condition) analysis of variance revealed a significant three-way interaction for the accuracy measure, $F(3, 35) = 3.78, p < 0.05$. Further analyses of this interaction, separately for each group, showed that children in the 7-9-year-old control group demonstrated significantly poorer accuracy in the no visual feedback condition of the aiming task relative to their older counterparts, $F(1, 18) = 5.70, p < 0.05$. This interaction suggested the need to examine the two age groups separately; thus, all statistical comparisons are made separately for the 7-9- and 10-12-year-old age groups.

1. Comparison of Kinematic Parameters between Groups

The results were analyzed in a 2 (group) x 2 (feedback condition) x 2 (target size) x 3 (target amplitude) repeated measures analysis of variance, with group as the between-subjects factor and feedback condition, target size, and target amplitude as the within-subjects factors. This test was run separately for each age group and for each of the kinematic parameters (i.e., reaction time, movement time, velocity measures, and accuracy). Significance was tested at the .05 level. In a few cases where the analysis indicated no significant effects or trends towards significant effects, whereas visual inspection of and patterns of performance in the data suggested otherwise, the effects are reported. It is felt that this practice is justified given the exploratory nature of this study, although it is also accepted that this practice increases the chances of making Type I errors, *i.e.*, rejecting the null hypothesis when it should be accepted.

Because of the abnormal kinematic profiles exhibited by children in both DCD and control groups (see section 2: **Description of Kinematic Profiles**), several kinematic parameters such as peak velocity, time to and after peak velocity, and initial accuracy could only be analysed for the normal movement patterns. However, measures of reaction time, movement time, number of subpeaks, and final accuracy could be analysed for both normal and abnormal movement patterns. Separate analyses of the normal and abnormal kinematic profiles revealed similar patterns of results; therefore, only the results for the normal movements are reported since all kinematic parameters could be considered.

Seven- to nine-year old children

Reaction Time (RT)

The time between the onset of the target stimulus and the beginning of the hand movement (RT) was affected by the level of visual feedback provided, F(1, 18) = 70.89, $p < 0.0001$. Post hoc analyses of the Feedback effect using Duncan's Multiple Range test (alpha = 0.05), revealed that RT was significantly longer when visual feedback of the moving hand was removed (374 ms with vision vs. 629 ms without vision). There was no significant effect of Group on RT, F(1, 18) = 0.08, $p = 0.78$, nor did the effect of Feedback differ between the DCD and control groups, F(1, 18) = 0.31, $p < 0.58$.

Movement Time (MT)

MT was significantly longer for the DCD than the control group, F(1, 18) = 5.51, $p = 0.03$, for increases in target size, F(1, 18) = 27.47, $p < 0.0001$, and for increases in target amplitude, F(2, 36) = 72.91, $p < 0.0001$. Significant interactions between Group, Feedback, and Size, F(2, 17) = 3.98, $p = 0.04$, and Group, Feedback, and Amplitude, F(4, 35) = 2.55, $p = 0.05$, indicated that the differences in MT of the two groups were influenced by the visual feedback condition and the target features (see Figs. 5.1.1 and 5.1.2). Further analysis of the interaction between Group, Feedback, and Size looking at the effects of Group and Size for each feedback condition revealed significant differences between the

DCD and control groups, F(1, 18) = 10.59, $p = 0.004$, and between the small and large target sizes, F(1, 18) = 40.42, $p < 0.0001$, when visual feedback was available. In the absence of visual feedback, the differences between Group and Size were no longer significant.

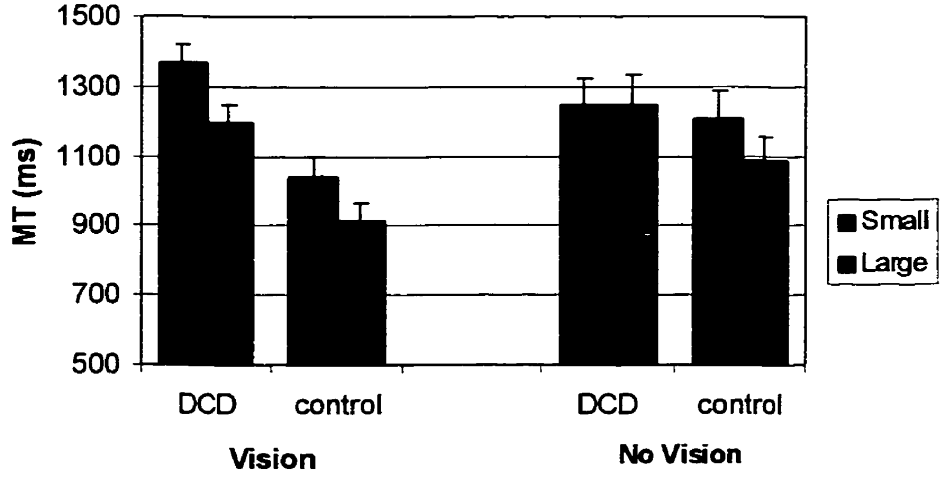

Figure 5.1.1. Interaction between Group, Feedback, and Size for movement time in the 7-9-year-olds.[4]

Further analysis of the interaction between Group, Feedback, and Amplitude, looking at the effects of Group and Amplitude effects for each feedback condition, also revealed significant differences only when visual feedback was available. As may be noted in Fig. 5.1.2, in this condition, MT of children with DCD was significantly longer overall compared to the controls, F(1, 18) = 10.07, $p = 0.005$, and MT increased significantly with increases in target amplitude, F(1, 18) = 43.51, $p < 0.0001$.

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[4] All graphs depict cell means and standard errors.

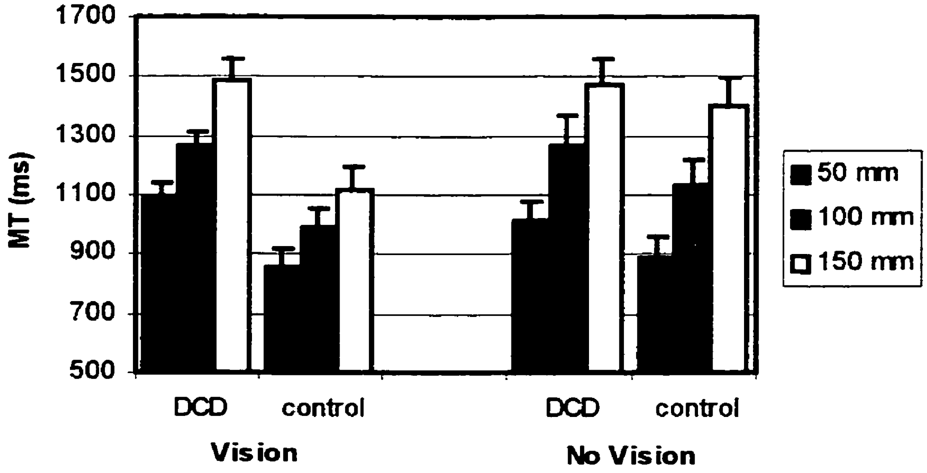


Figure 5.1.2. Interaction between Group, Feedback, and Amplitude for movement time in the 7-9-year-olds.

The three-way interactions for MT are important findings with respect to the research questions of interest. The findings are consistent with previous research (Rösblad & von Hofsten, 1994; Smyth, 1991; van der Meulen et al., 1991) indicating that the presence of visual feedback has a differential effect on the movement times of children with DCD. Specifically, the DCD group demonstrated longer movement times overall, and particularly with increases in target complexity (i.e., changes in size and amplitude).

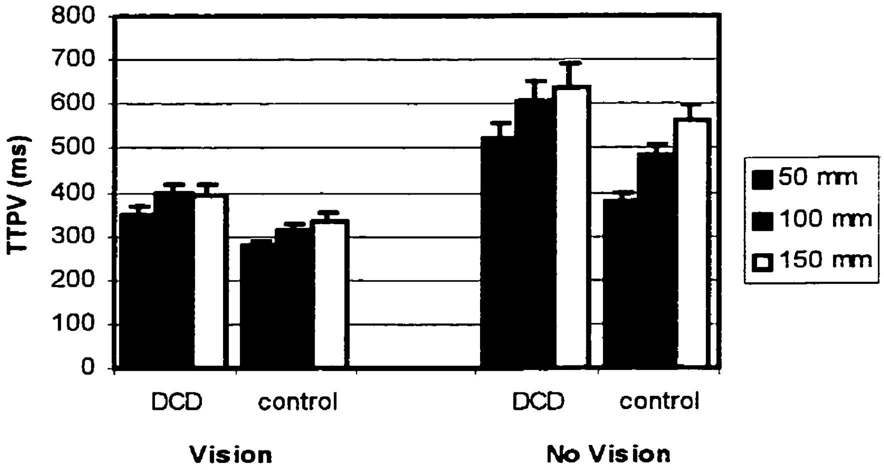
Velocity Parameters

Peak Velocity (PV) (i.e., the maximum speed of a movement) was significantly affected by Feedback, F(1, 18) = 7.22, $p < 0.01$, Size, F(1, 18) =

5.90, $p = 0.03$, and Amplitude, F(2, 36) = 214.8, $p < 0.0001$. The effect of Feedback revealed that PV was significantly higher when visual feedback was available (NV=187 vs. V=234 ms). The effects of Size and Amplitude indicated that PV increased significantly with incremental increases in target size (S=203 vs. L=217 ms) and amplitude (N=143 vs. M=221 vs. F=267 ms). Although the effect of target size on PV is inconsistent with general findings in the motor control literature, the effect of amplitude implies that for both the DCD and control groups, PV related to amplitude in the way predicted by previous studies (e.g., Fitts, 1954; MacKenzie et al., 1987).

Time to Peak Velocity (TTPV) was significantly longer for children with DCD, F(1, 18) = 6.33, $p = 0.02$, in the absence of visual feedback, F(1, 18) = 35.83, $p < 0.0001$, and for increases in target amplitude, F(2, 36) = 22.87, $p < 0.0001$. A significant interaction between Group, Feedback, and Amplitude was also found, F(4, 34) = 3.15, $p = 0.03$. Further analysis of this three-way interaction, looking at the Group and Amplitude effects separately for each feedback condition, indicated that in the absence of visual feedback, children with DCD had longer TTPV overall, F(1, 18) = 4.50, $p = 0.048$; however, only the control group exhibited increases in TTPV with increases in target amplitude, F(2, 36) = 5.90, $p = 0.03$ (see Fig. 5.1.3). When visual feedback was available, there were no significant differences between the DCD and control groups or between the three target amplitudes.

Time after Peak Velocity (TAPV) was significantly longer when visual feedback was available, F(1, 18) = 4.78, $p = 0.04$, for decreases in target size, F(1, 18) = 23.93, $p < 0.0001$, and increases in target amplitude, F(2, 36) = 49.78, $p < 0.0001$. The results also revealed a strong trend towards a two-way interaction



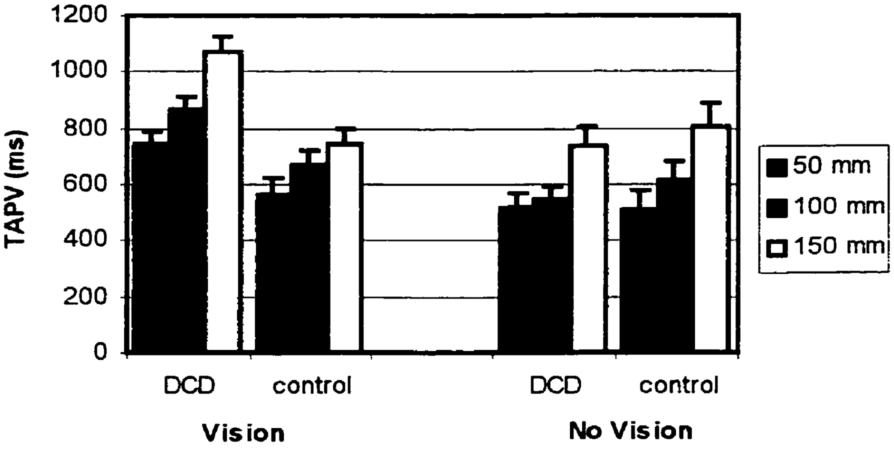


Figure 5.1.3. Interaction between Group, Feedback, and Amplitude for time to peak velocity (upper) and time after peak velocity (lower) in the 7-9-year-olds.

between Group and Feedback, F(1, 18) = 3.67, $p = 0.07$. Further analysis of this interaction, looking at the effects of Group separately for each feedback condition, indicated that children with DCD spent significantly longer amounts of time in the deceleration phase of the movement only when visual feedback was available, F(1, 18) = 9.24, $p = 0.007$.

An additional trend towards a three-way interaction between Group, Feedback, and Size, F(1, 17) = 3.13, $p = 0.069$, revealed that the effect of visual feedback on TAPV for the DCD group was dependent on target size. Further analysis of this three-way interaction, looking at the Group and Feedback effects separately for each target size, indicated that TAPV was longer for the DCD group when they moved to the small target in the presence of visual feedback, F(1, 18) = 3.72, $p = 0.06$ (see Fig. 5.1.4).

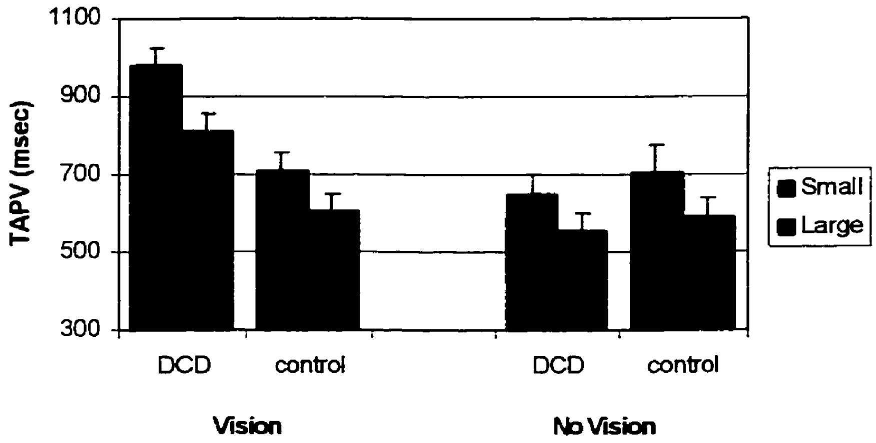


Figure 5.1.4. Interaction between Group, Feedback, and Size for time after peak velocity in the 7-9-year-olds.

Surprisingly, there was no interaction between Group, Feedback, and Amplitude, F(4, 36) = 1.44, $p = 0.20$. Given that children with DCD exhibited longer MTs to the 150 mm amplitude target when visual feedback was available, yet did not show any differences with respect to PV or TTPV in this condition (i.e., the 150 amplitude target with vision), it stood to reason that longer times in deceleration (i.e., TAPV) must have been accounting for their longer MTs. In fact, analysis of the effects of Group and Amplitude, separately for each feedback condition, revealed that relative to controls, children with DCD demonstrated significantly longer TAPVs overall when visual feedback was available, F(1, 18) = 8.81, $p = 0.008$, and particularly when moving to the 150 mm amplitude target, F(2, 36) = 5.92, $p = 0.026$ (see Fig. 5.1.3, p. 46).

In response to the third question of interest for this research, the results of the velocity parameters indicate that the DCD children in this age range generally program their movements in the same way as their age-matched peers, as reflected in similar patterns of PV and TTPV. The differences between the groups occur mainly in the feedback-controlled parameters of movement (i.e., TAPV), and are dependent on feedback availability and the nature of the target constraints. Relative to the control group, children with DCD spend longer amounts of time in the deceleration phase of the movement when visual feedback is available to them and when the task constraints become more complex (e.g., decreased size, increased amplitude). These findings would suggest that the greater use of visual feedback in the DCD group is not related to a difficulty in motor programming, but rather a difficulty in using or processing sensory feedback.

Number of Subpeaks

A significantly greater number of subpeaks (e.g., corrective movements) was exhibited by children with DCD relative to the controls, F(1, 18) = 9.04, p = 0.008, and for movements made to the small versus the large target, F(1, 18) = 5.30, p = 0.034. A significant interaction between Group, Feedback, and Size, F(2, 17) = 3.75, p = 0.045, indicated that the differences in the number of subpeaks of the two groups were influenced by the visual feedback condition and the size of the target (see Fig. 5.1.5). Further analysis of this interaction, looking at the Group and Size effects for each feedback condition, revealed significant differences between the DCD and control groups, F(1, 18) = 14.06, p = 0.002, and

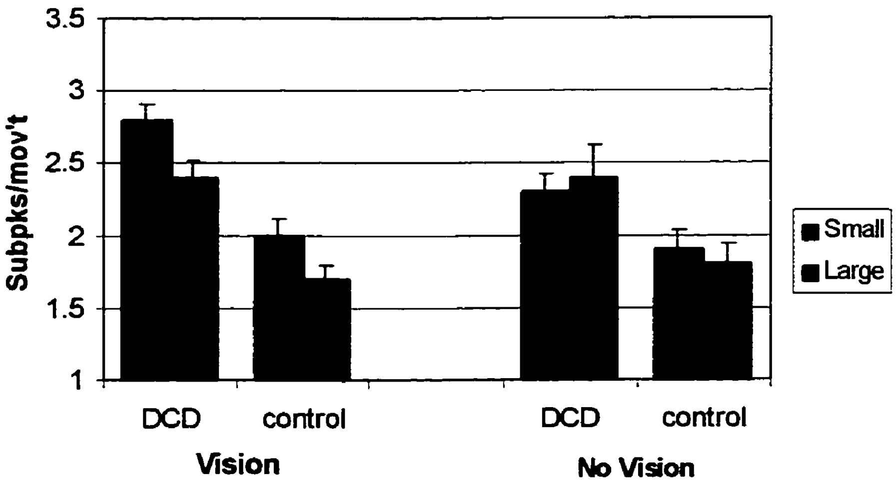


Figure 5.1.5. Interaction between Group, Feedback, and Size for the mean number of subpeaks per movement in the 7-9-year-olds.

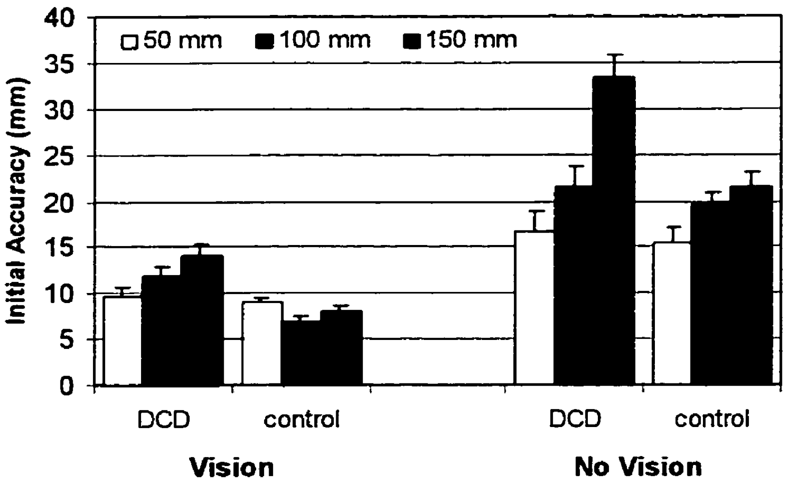
between the small and large target sizes when visual feedback was available, F(1, 18) = 21.23, $p = 0.0002$. In the absence of visual feedback, the differences between Group and Size were no longer significant. This finding is consistent with those of the velocity and MT parameters in that children with DCD in this age range tend to spend more time using feedback to control and correct their movements when visual information about those movements is available.

Accuracy

Initial accuracy (i.e., accuracy of the initial, uncorrected movement) was significantly poorer for children with DCD, F(1, 18) = 10.92, $p = 0.004$, in the absence of visual feedback, F(1, 18) = 79.61, $p < 0.0001$, and for increases in target amplitude, F(2, 36) = 17.51, $p < 0.0001$. Figure 5.1.6 on the following page depicts the interaction between Group, Feedback, and Amplitude, F(4, 34) = 8.74, $p < 0.0001$, and reveals that the differences between the DCD and control groups were dependent on feedback availability and target amplitude. Further analysis of this interaction, looking at the Group and Amplitude effects separately for each feedback condition, showed that the initial, uncorrected movements made by children with DCD were significantly less accurate for the 150 mm amplitude (e.g., far) target in the absence of visual feedback, F(2, 34) = 7.43, $p < 0.0001$.

Final accuracy (i.e., accuracy of the movement end-point) was also significantly poorer in the absence of visual feedback, F(1, 18) = 296.61, $p < 0.0001$, and for increases in target amplitude, F(2, 36) = 24.97, $p < 0.0001$. Although a main effect of Group was not found as in the findings for initial accuracy, a three-way interaction between Group, Feedback, and Amplitude, F(4,

34) = 12.75, $p < 0.0001$, again revealed that the movement end-points of children with DCD were significantly less accurate for the 150 mm amplitude (e.g., far) target in the absence of visual feedback, F(2, 34) = 8.92, $p < 0.0001$ (see Fig. 5.1.6).



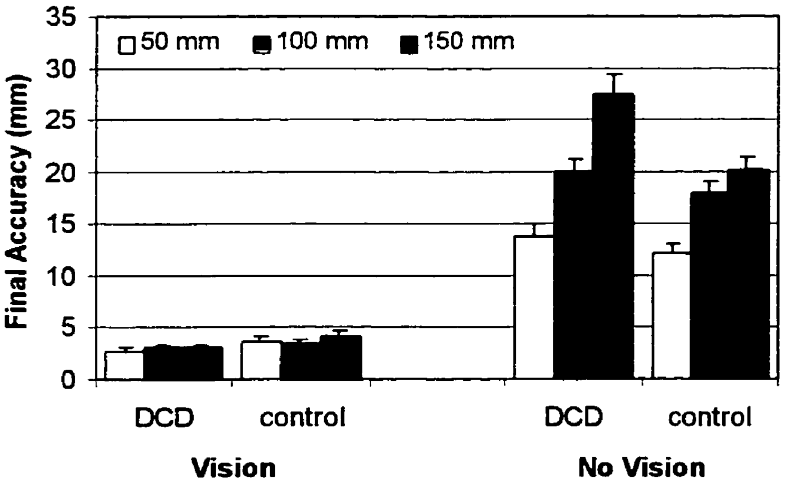


Figure 5.1.6. Interaction between Group, Feedback, and Amplitude for initial accuracy (upper) and final accuracy (lower) in the 7-9-year-olds.

The three-way interactions for the accuracy measures are important findings. Although the results for the timing parameters (i.e., MT, PV, TAPV) suggest that there are no differences between the DCD and control groups in the no visual feedback condition, the findings for initial and final accuracy indicate that this is not the case. In the absence of vision, children with DCD demonstrate significant difficulty generating spatially accurate movements to complex targets (i.e., far amplitudes). In response to the first question of interest for this research, these findings suggest that DCD may involve a difficulty in integrating complex visual information about the target with proprioceptive feedback of the moving hand.

Ten- to twelve-year old children

Reaction Time (RT)

A main effect of Feedback, F(1, 18) = 60.77, $p < 0.0001$, revealed that the time between target onset and movement initiation (RT) was longer in the absence of visual feedback (331 ms with vision vs. 519 ms without vision). An interaction between Group, Feedback, and Size, F(2, 18) = 3.60, $p = 0.046$, indicated that the differences between the visual and no visual feedback conditions were significantly affected by group membership and target size. Further analysis of this three-way interaction, looking at Group and Size effects for each visual feedback condition, revealed that for the large target, the DCD group took significantly less time than controls to initiate their movements in the absence of visual feedback, F(1, 17) = 7.14, $p = 0.016$ (see Fig. 5.1.7).

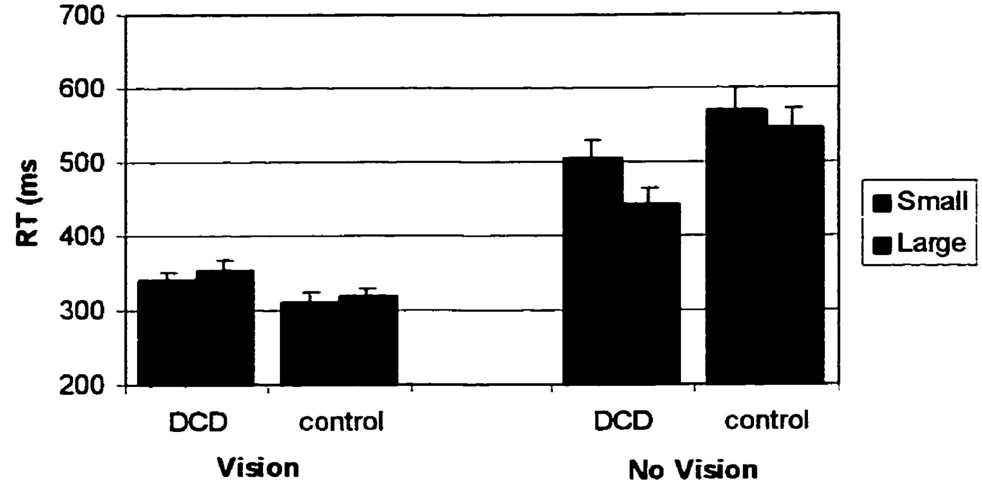


Figure 5.1.7. Interaction between Group, Feedback, and Size for reaction time in 10-12-year-olds.

Movement Time (MT)

Movement times (MT) were significantly longer in the absence of visual feedback, F(1, 18) = 4.66, $p = 0.045$, for decreases in target size, F(1, 18) = 17.38, $p = 0.0006$, and for increases in target amplitude, F(2, 36) = 103.51, $p < 0.0001$. A trend towards a three-way interaction between Group, Feedback, and Amplitude, F(4, 35) = 2.33, $p = 0.07$, indicated that the differences between the feedback conditions and target amplitudes were dependent on group membership. Further analysis of this three-way interaction, looking at Feedback and Amplitude separately for each of the DCD and control groups, revealed that control children were able to move in less time overall when visual feedback was available F(1, 9) = 9.11, $p = 0.015$, and in particular, when moving to the 150 mm (e.g., far) amplitude target F(2, 18) = 3.06, $p < 0.07$ (see Fig. 5.1.8, p. 55).

As may be noted in Figure 5.1.8, the DCD group did not demonstrate differentially longer MTs relative to the controls in the visual feedback condition. This result is in contrast to the findings of the younger DCD group whose MTs were significantly longer than those of their same-age peers when visual feedback was available. Thus, the older children with DCD seem to show an improved ability to process visual feedback. However, that DCD children in this age group did not show any MT differences between the feedback conditions suggests that they still do not benefit from visual feedback to the same extent as their peers in the control group, particularly when generating more complex movements. Children in the control group were able to move in shorter times when visual feedback was available, especially to the further amplitude targets. Children with DCD, in contrast, did not show any differences between the visual feedback conditions for any of the target amplitudes.

Velocity Parameters

Peak velocity (PV) was significantly higher when visual feedback was available, F(1, 18) = 25.33, $p < 0.0001$, and with increases in target amplitude, F(2, 36) = 186.51, $p < 0.0001$. A trend towards an interaction between Group and Feedback, F(1, 18) = 4.03, $p = 0.06$, revealed that the difference between the feedback conditions was dependent on Group. Further analysis of the interaction revealed that when visual feedback was available the control group exhibited higher PVs than in the no visual feedback conditon, F(1, 9) = 31.15, $p = 0.0003$. Children with DCD did not show significant differences in PV between the feedback conditions. A significant three-way interaction between Group,

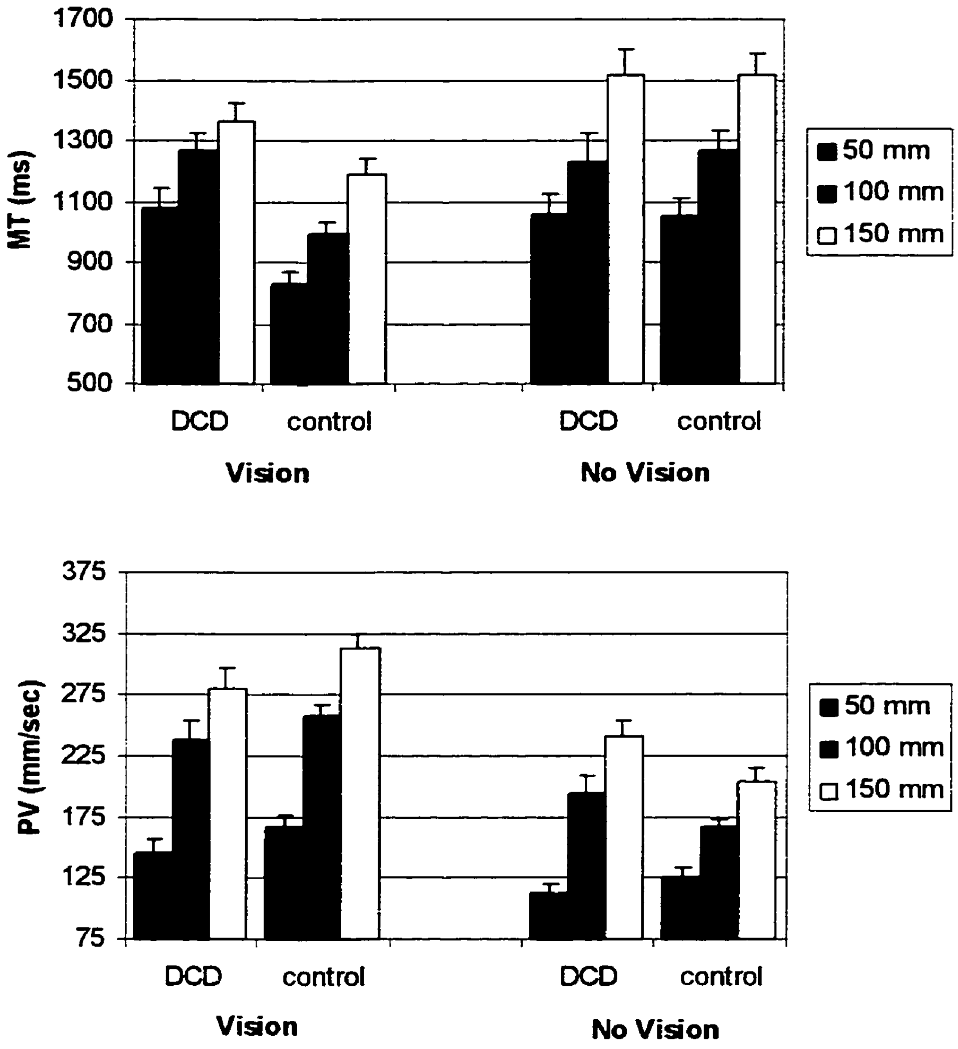


Figure 5.1.8. Interaction between Group, Feedback, and Amplitude for movement time (upper) and peak velocity (lower) in 10-12-year-olds.

Feedback, and Amplitude, F(4, 35) = 60.77, $p < 0.0001$, was also revealed. Further analysis of the simple interactions between Feedback and Amplitude separately for the DCD and control groups, showed that the higher PVs exhibited by the control children in the presence of visual feedback was dependent on target amplitude. Figure 5.1.8 shows more specifically that PVs of the controls were significantly higher more when visual feedback was available on movements to the 100 and 150 mm amplitude targets, F(2, 18) = 40.78, $p < 0.0001$.

As may be noted in Figure 5.1.8, the findings for PV coincide with those of MT. That is, control children are able to move more quickly (e.g., higher PVs) and in less time (e.g., shorter MTs) when visual feedback is available, particularly with increases in task complexity. That the DCD group does not demonstrate these differences across the feedback conditions indicates that they do not benefit from visual feedback in the same way as their age-matched peers.

Time to Peak Velocity (TTPV) was significantly longer in the absence of visual feedback, F(1, 18) = 50.96, $p < 0.0001$, and for increases in target amplitude, F(2, 36) = 7.27, $p = 0.002$ (332 vs. 588 ms and 419 vs. 455 vs. 505 ms, respectively for Feedback and Amplitude). TTPV did not differ between the DCD and control groups in this age range either overall or according to feedback availability.

Time after Peak Velocity (TAPV) was significantly longer with decreases in target size, F(1, 18) = 15.24, $p = 0.001$, and for increases in target amplitude, F(2, 36) = 81.33, $p < 0.0001$. Similar to the findings for TTPV, the effect of target amplitude did not interact with either the group or group and feedback conditions. These findings imply that for both the control and DCD groups, TTPV and TAPV did not relate to target amplitude in the way predicted by previous studies (e.g., Fitts, 1954; MacKenzie et al., 1987).

An interaction between Group, Feedback, and Size, F(1, 17) = 3.24, $p = 0.05$, revealed significant differences between the DCD and control groups, F(1,

18) = 7.21, $p = 0.015$, and between the small and large target sizes, F(1, 17) = 18.22, $p = 0.0005$, when visual feedback was available. In the absence of visual feedback, the differences between Group and Size were no longer significant (see Fig. 5.1.9). This finding is consistent with that of the 7-9-year-olds and with the notion that the feedback-controlled parameters of movements in DCD are differentially affected by the availability of visual feedback. Children with DCD spend more time using visual feedback to manage task complexities such as target size.

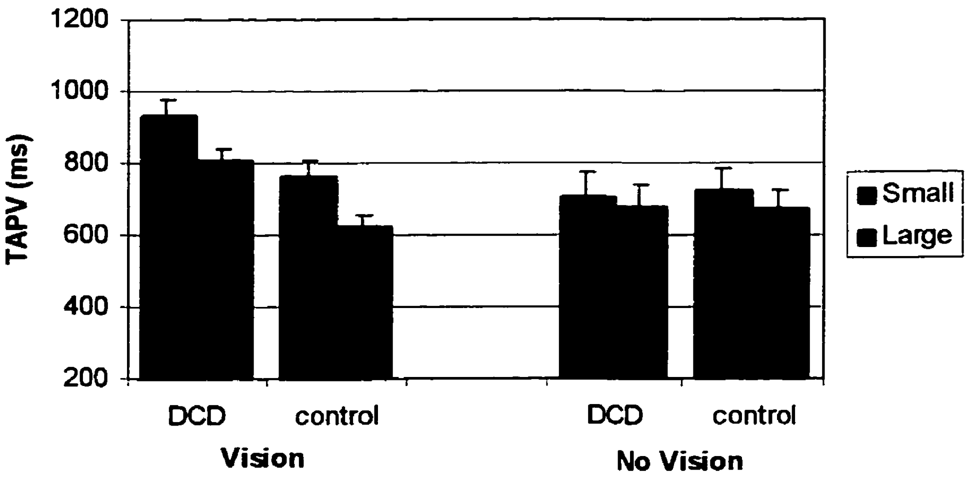


Figure 5.1.9. Interaction between Group, Feedback and Size for time spent in the deceleration phase of movement in 10-12-year-olds.

The results for the velocity parameters indicate that children with DCD in this age range are not as dependent on the visual feedback-controlled phases of movement as their younger counterparts; however, they are still not able to benefit from visual feedback in the same way as their peers. The 10-12-year-old control children were able to use visual feedback to move faster (e.g., higher PVs) than in the no visual feedback condition, particularly with increases in target complexity (e.g., amplitude). In contrast, the children with DCD in this age range did not show such an advantage – the PVs of their movements did not differ across feedback conditions or target amplitudes. Furthermore, the findings for TAPV did not differ between the 10-12-year-old DCD and control groups with respect to target amplitude as they did in the younger groups, suggesting that the older DCD children showed some improved ability to contend with visual feedback. However, that the 10-12-year-old DCD group spent more time than their peers in the deceleration phase of the movement to contend with changes in target size (e.g., longer TAPVs) indicates that they were experiencing some difficulty processing sensory feedback.

Number of Subpeaks

The number of subpeaks per movement (e.g., corrective movements) was significantly affected by Group, F(1, 18) = 7.44, $p = 0.014$, Size, F(1, 18) = 5.23, $p = 0.035$, and Amplitude, F(2, 36) = 5.55, $p = 0.008$. Post hoc analyses of these effects using Duncan's Multiple Range test (alpha = 0.05) showed that the number of subpeaks was significantly greater for the DCD than control group (2.8 for DCD vs. 1.9 for control), for decreases in target size (2.2 for large vs. 2.5 for small), and for increases in target amplitude (2.0 for 50 mm vs. 2.1 for 100 mm vs. 2.5 for 150 mm). The higher number of corrective movements exhibited by the DCD group is consistent with the notion that these children are not utilizing sensory feedback as efficiently as their peers (i.e., they spend more time in the feedback-controlled phases adjusting their movements).

Accuracy

Initial accuracy was significantly lower for children with DCD, F(1, 18) = 8.29, $p = 0.01$, when visual feedback was removed, F(1, 18) = 99.85, $p < 0.0001$, and for increases in target amplitude, F(2, 36) = 19.11, $p < 0.0001$. A significant interaction was found between Group, Feedback, and Size, F(2, 17) = 5.88, $p = 0.012$. Figure 5.1.10 on the following page shows that for the larger target, the initial, uncorrected movements of the DCD group were significantly less accurate than controls in the absence of visual feedback, F(1, 17) = 6.09, $p = 0.039$.

A significant interaction was also found between Group, Feedback, and Amplitude, F(4, 35) = 11.15, $p < 0.0001$. Further analysis of this interaction, looking at Group and Amplitude effects separately for each feedback condition, showed that the initial, uncorrected movements made by children with DCD were significantly less accurate for the 150 mm amplitude (e.g., far) target in the absence of visual feedback, F(2, 34) = 20.44, $p < 0.0001$ (see Fig. 5.1.11, p.61).

Final accuracy was significantly lower for the DCD group, F(1, 18) = 6.47, $p = 0.02$, when visual feedback was removed, F(1, 18) = 226.98, $p < 0.0001$, and for increases in target amplitude, F(2, 36) = 23.02, $p < 0.0001$. A Group by Feedback interaction, F(1, 18) = 6.38, $p < 0.022$, revealed that children with DCD were significantly less accurate than controls when visual feedback was removed (DCD: V=2.6 and NV=23.8 mm vs. Control: V=2.7 and NV=16.8 mm). Second-order interactions between Group, Feedback, and Size, F(2, 17) = 6.29, $p = 0.009$, and Group, Feedback, and Amplitude, F(4, 35) = 11.17, $p < 0.0001$, indicated that the differences between the DCD and control groups in the no visual feedback condition were dependent on target size and amplitude. Further analysis of the Group, Feedback, and Size interaction, looking at Group and Size effects separately for each feedback condition, showed that for the large target, the movement end-points of the DCD group were significantly less accurate than controls, F(1, 17) = 6.09, $p = 0.039$ (see Figure 5.1.10).

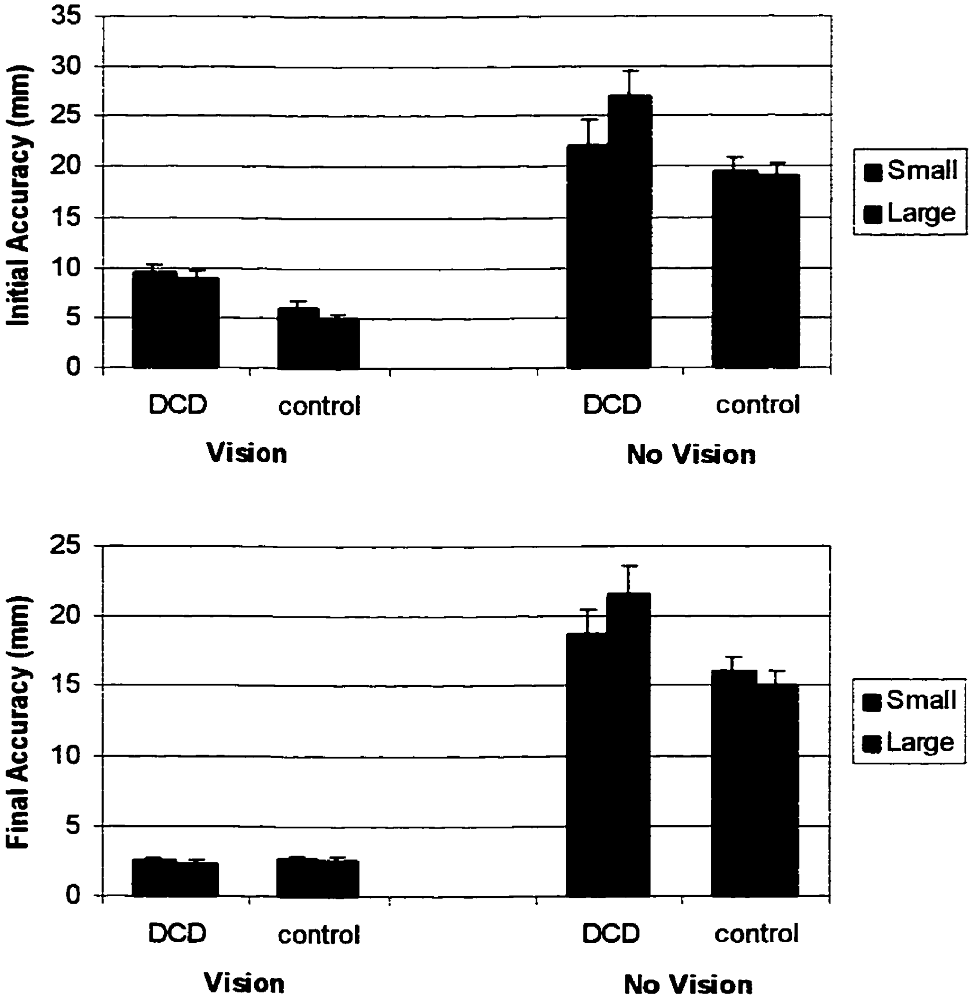
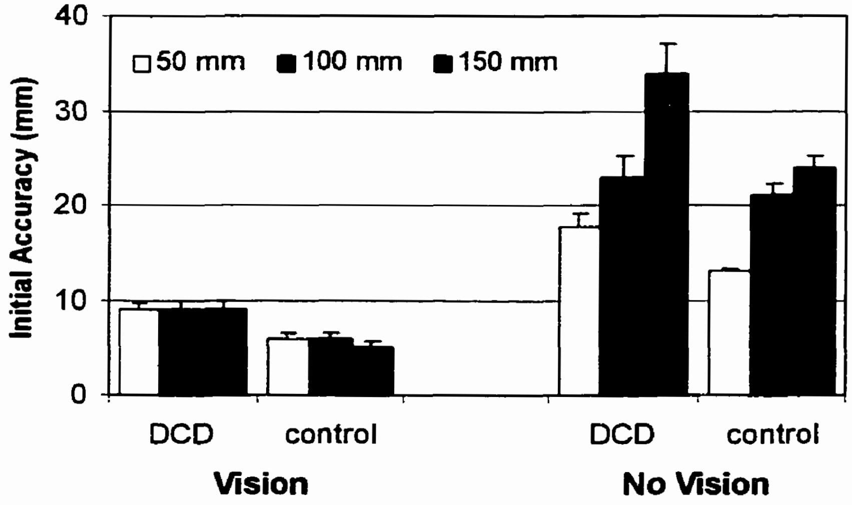


Figure 5.1.10. Interaction between Group, Feedback, and Size for initial (upper) and final (lower) accuracy in 10-12-year olds.

Consistent with the findings for initial accuracy, further analysis of the interaction between Group, Feedback, and Amplitude showed that the movement end-points of children with DCD were also significantly less accurate for the 150 mm amplitude target (e.g., far target) in the absence of visual feedback, $F(2, 34) = 22.43$, $p < 0.0001$ (see Fig. 5.1.11).



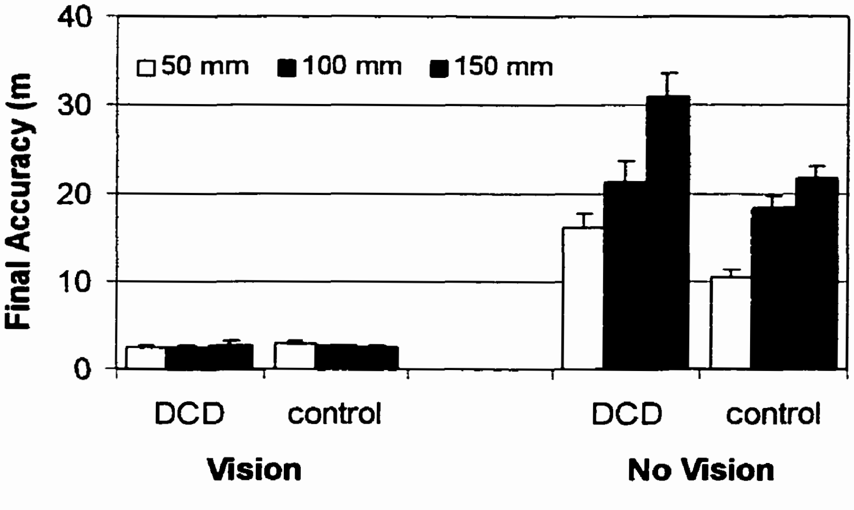


Figure 5.1.11. Interaction between Group, Feedback, and Amplitude for initial (upper) and final (lower) accuracy in 10-12-year olds.

The findings for initial and final accuracy of the 10-12-year-old DCD group are consistent with those of the 7-9-year-olds. When visual feedback of the moving hand is not available to children with DCD, they have significant difficulty planning (as reflected in initial accuracy) and controlling (as reflected in final accuracy) the spatial accuracy of their movements, particularly when the movements involve a greater degree of movement complexity, *i.e.*, with increases in movement amplitude. As stated earlier in response to the first question of interest for this research, the accuracy findings suggest that DCD may involve a difficulty in integrating complex visual information about the target with proprioceptive feedback of the moving hand.

Summary of kinematic parameters

Results for the 7-9-year-olds reveal that children with DCD do not benefit from visual feedback for movement control in the same way as their peers. They exhibit longer MTs, longer times in the feedback phase of the movement (i.e., TAPV), and higher frequencies of corrective movements to control their hand toward the target. Moreover, increases in task complexity (i.e., changes in target amplitude and size) have a greater impact on children with DCD in this age group with respect to feedback control when vision is available.

In contrast to the 7-9-year-olds, the 10-12-year-old children with DCD demonstrate minimal differences relative to the controls when visual feedback is available, indicating an improved ability to process sensory information. However, a comparison across feedback conditions for the DCD and control groups reveals that even older children with DCD do not benefit from visual feedback in the same way as their peers. While the control group is able to use visual feedback to move faster and in less time, particularly with increases in task complexity, children with DCD do not show such an advantage – they move in the same time and at the same velocity in both feedback conditions. When visual feedback is removed, the timing components of DCD children's movements in both age groups are similar to those of the controls; however, the spatial accuracy of their movements is significantly worse with increases in task demands (i.e., increasing amplitude).

These findings are consistent with those of previous research indicating that the timing components of movements (e.g., MT) in children with DCD are differentially affected by both the availability of visual feedback (e.g., Rösblad & von Hofsten, 1994; Smyth, 1991; van der Meulen et al., 1991) and task complexity (e.g., Henderson et al., 1992; Smyth, 1991). Moreover, the present study found that in the presence of visual feedback there were minimal differences between the DCD and control groups in the programming phases of movement (e.g., RT, TTPV) and significant differences in the feedback-controlled phases (e.g., TAPV, number of subpeaks). These findings suggest that DCD likely involves a difficulty in processing sensory feedback rather than in motor programming. That DCD children's movements were significantly less accurate for complex targets in the absence of visual feedback provides further support for this idea. Analyses of the kinematic profiles will provide further insight into the notion of a programming versus feedback deficit.

2. Description and Comparison of Kinematic Profiles

Analysis of the velocity profiles for the DCD and control groups revealed that the children used three different types of control for their manual aiming movements. This finding is consistent with the findings of Pryde and Roy (1998, 1999) and Hay (1979, 1984). The three different kinematic profiles are illustrated in Figure 5.2.1 and are described as follows: (i) "Step" movements involve several velocity peaks, accelerations, and decelerations and early braking activity without an initial ballistic movement (i.e., poorly programmed with a greater reliance on feedback). Young children with immature sensorimotor integration abilities and individuals with neurological impairments typically exhibit these movements as adaptive strategies. (ii) "Double Peak" movements consist of gradual acceleration and deceleration phases and two velocity peaks with values within five percent of each other. These movements appear to be, and have been previously described as, a progression of the immature step movements, yet still lack the feedforward or programming capabilities, which result in a smooth single peak profile (Pryde & Roy, 1998; 1999). (iii) "Mature" movement patterns are characterized by a single velocity peak, an initial ballistic phase and a smooth deceleration phase. These movements are typical of adult movement patterns.

Differences between the groups in the frequency of each profile were tested using Wilcoxon's rank sum tests (alpha = 0.05). These tests were conducted separately for each age range and each visual feedback condition. The frequency of kinematic profiles for each group and condition is displayed in Figure 5.2.2 in the form of percentages.

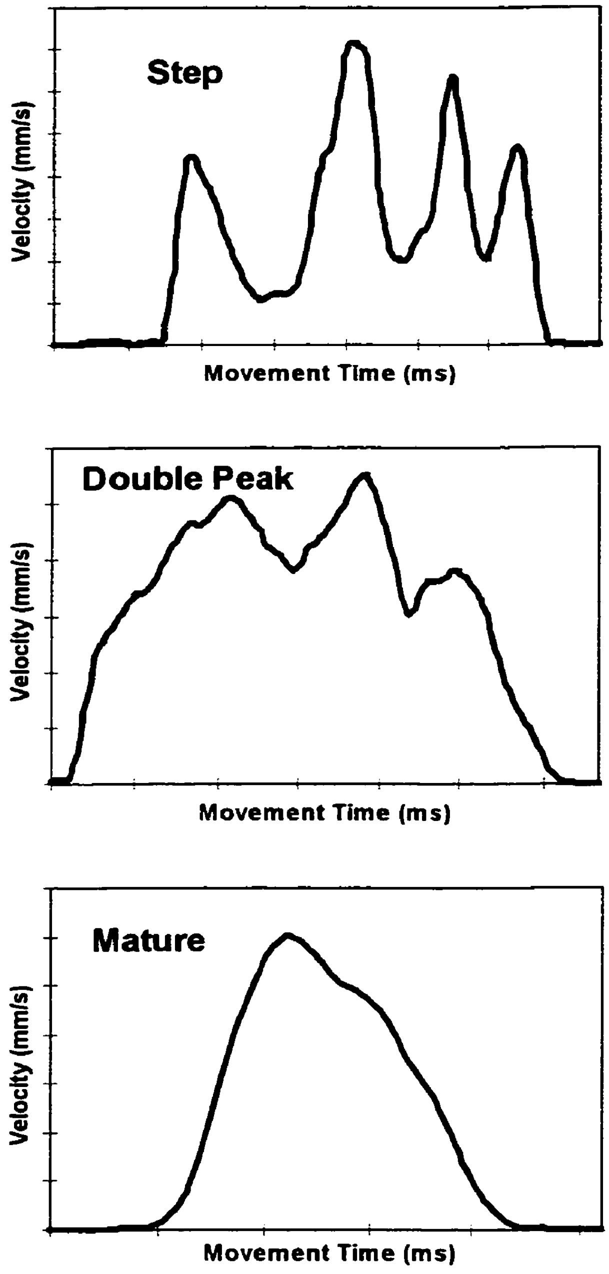


Figure 5.2.1. Velocity Profiles Representing the Kinematic Patterns: Step (upper), Double Peak (middle), and Mature (lower).

For the 7-9-year-olds, the analyses revealed that when visual feedback was available, DCD children exhibited significantly more double peak movements, z (20) = -1.82, $p < 0.034$, and significantly fewer mature movements, z (20) =

1.95, $p < 0.025$, than the control children. The analyses also revealed a trend for the DCD children to exhibit more step profiles than their same-age counterparts in the visual feedback condition, z (20) = -1.45, $p < 0.074$. When visual feedback was removed, children with DCD displayed significantly more step movements, z (20) = -2.28, $p < 0.017$, and significantly fewer mature profiles, z (20) = 1.78, $p < 0.052$. There were no differences between the groups for the double peak profiles in this feedback condition, z (20) = -1.14, $p > 0.256$ (see Fig. 5.2.2).

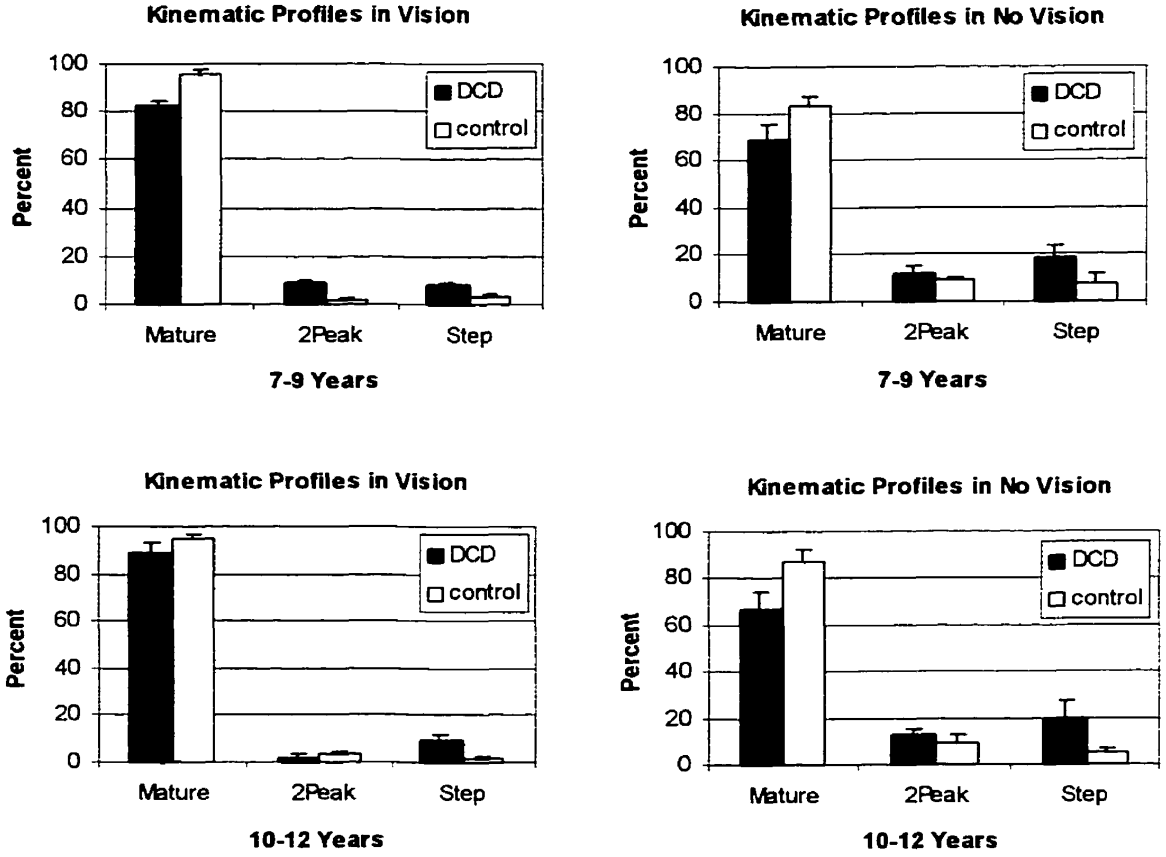


Figure 5.2.2. Percentage of Mature, Double Peak, and Step kinematic profiles for each group and feedback condition.

For the 10-12-year-olds, analyses revealed that in the presence of visual feedback, children with DCD differed from controls only with respect to a greater number of step movements, z (20) = -2.02, $p < 0.022$. When visual feedback was removed, DCD children exhibited a significantly greater number of step movements, z (20) = -1.75, $p < 0.039$, and significantly fewer mature movements, z (20) = 2.25, $p < 0.010$. There were no differences between the groups for the double peak profiles in this feedback condition, z (20,) = -1.63, $p < 0.103$ (see Fig. 5.2.2).

Summary of Kinematic Profiles

Comparisons of kinematic profiles between the DCD and control groups for each feedback condition and age range, reveal differences between the groups with respect to motor programming and control strategies. Children with DCD generally exhibited fewer mature or 'normal' movement profiles and more immature or 'abnormal' movements (e.g., step) relative to the controls indicating a difficulty in movement programming and an increased use of adaptive strategies to control their movements. Given these differences, it was of particular interest to investigate the relationship between the normal and abnormal movement profiles and the end-point accuracy of these movements. The question of interest here was to determine if the different control strategies led to differing degrees of accuracy in DCD and control children.

3. Relationship between Kinematic Profiles and Movement Accuracy

In order to examine the relationship between kinematic profiles and movement accuracy, individual movements had to be specified as accurate or inaccurate. This determination was made by converting raw scores for end-point accuracy into z scores using the mean scores and standard deviations of the control children for each target and age group. Accuracy z scores that were greater than two standard deviations above the mean were considered inaccurate. Each movement was then categorized according to kinematic profile (i.e., normal or abnormal) and end-point accuracy (i.e., accurate or inaccurate) within each visual feedback condition. This procedure resulted in four kinematic/accuracy patterns: Type I – Normal, Accurate; Type II – Normal, Inaccurate; Type III – Abnormal, Accurate; and Type IV – Abnormal, Inaccurate.

Differences between the DCD and control groups in the frequency of each pattern were tested using Wilcoxon's rank sum tests (alpha = 0.05). Again, these tests were conducted separately for each age range and feedback condition. The frequency of each kinematic/accuracy pattern for each group and condition is shown in Figure 5.3.1 in the form of percentages.

As shown in Figure 5.3.1, when visual feedback was available there were minimal differences between the kinematic/accuracy patterns for the DCD and control groups. Only for the 7-9-year-olds was a difference found, where the DCD children exhibited a higher frequency of Type III – abnormal, accurate movements, z (20) = -1.96, $p < 0.025$. This finding is consistent with the findings

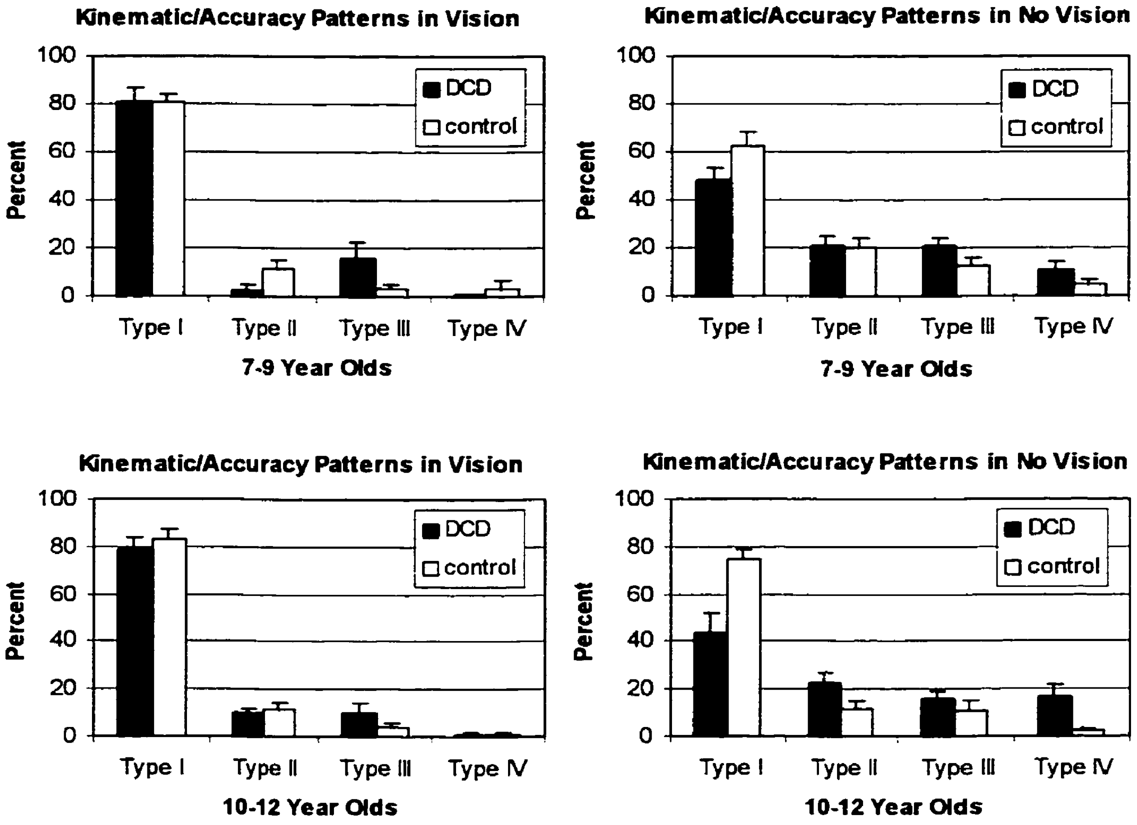


Figure 5.3.1. Kinematic profiles and end-point accuracy for DCD and control children in each feedback condition and age group. (Type I = normal, accurate; Type II = normal, inaccurate; Type III = abnormal, accurate; and Type IV = abnormal, inaccurate.)

for the comparisons of the kinematic parameters, indicating that DCD children in this age range tend to have significant difficulty benefiting from visual feedback, spending more time in the feedback control phase and making more corrections to control their movements.

In contrast to the patterns when visual feedback was available, patterns in the no visual feedback condition revealed several differences between DCD and control children. In the 7-9-year-old age band, children with DCD exhibited significantly fewer Type I patterns, z (20) = 1.75, $p < 0.048$, and a trend towards more Type III patterns, z (20) = -1.41, $p < 0.07$. The 10-12-year-old DCD children also exhibited significantly fewer Type I patterns, z (20) = 2.66, $p < 0.004$, as well as more Type II patterns, z (20) = -1.56, $p < 0.04$, and Type IV patterns, z (20) = -2.23, $p < 0.012$. In addition, there was a trend for the DCD children in this age band to show a higher frequency of Type III patterns, z (20) = -1.49, $p < 0.06$.

That DCD children in the 7-9-year-old age band did not exhibit more significant differences relative to their older counterparts for the less efficient movement patterns is likely due to the fact that 7-9-year-old control children also use a range of inefficient movement strategies to cope with their immature sensorimotor integration abilities (Hay, 1979; 1984; Pryde & Roy, 1998; 1999). Nevertheless, in general, DCD children differed from the controls in the absence of visual feedback having significantly lower percentages of movements performed perfectly (i.e., bell-shaped profiles and accurate end-points). While the goal of this analysis was to determine if deteriorations of kinematic profiles were coupled with decreases or increases in end-point accuracy, the pattern of results in the no visual feedback condition would suggest that this was not the case – there was no prevalence of any one kinematic/accuracy pattern beyond the Type I pattern. DCD children in both age bands exhibited a range of less efficient kinematic/accuracy patterns.

Figure 5.3.2 provides a detailed analysis of the kinematic/accuracy patterns in individual DCD children. The pattern of results for individual children reveals that, indeed, there is a large degree of variation in the kinematic/accuracy patterns

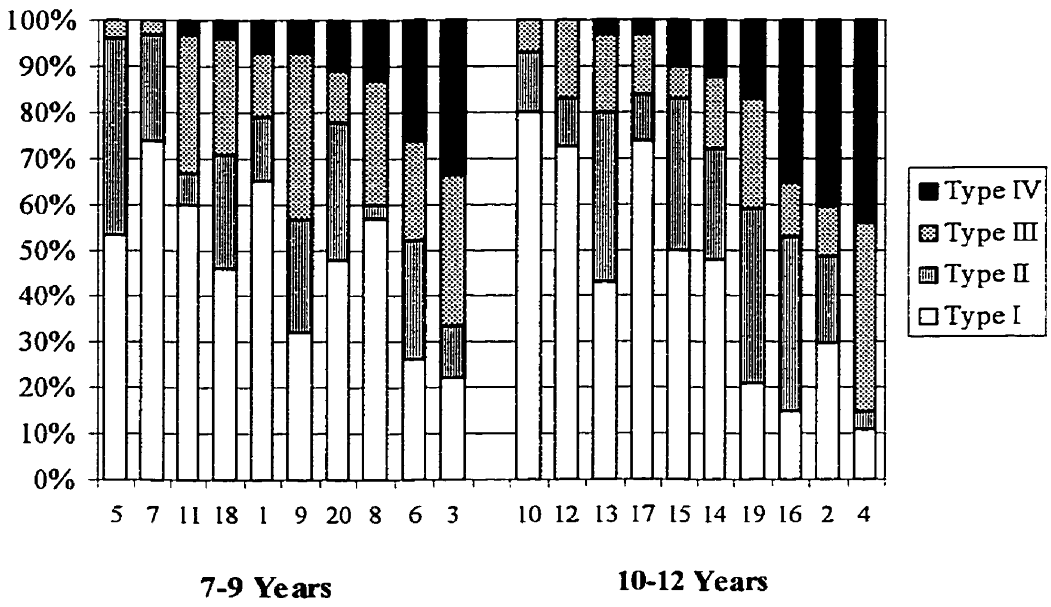


Figure 5.3.2. Kinematic profiles and end-point accuracy patterns of movements made by DCD children in the no visual feedback condition. (Type I = normal, accurate; Type II = normal, inaccurate; Type III = abnormal, accurate; and Type IV = abnormal, inaccurate.)

exhibited by children with DCD. For example, Type I normal/accurate patterns were most prevalent in participants 1, 7, 10, 12, and 17 – patterns similar to the average performance of controls. Participants 5, 13, 16, and 19 demonstrated percentages of Type II normal/inaccurate patterns above normal limits, and participants 3, 4, and 9 exhibited significantly higher percentages of Type III abnormal/accurate patterns. Finally, participants 2, 3, 4, 6, and 16 exhibited percentages of Type IV abnormal/inaccurate patterns above normal limits.

Given that there were prevalent types of kinematic/accuracy patterns within individual children with DCD, the next question of interest was to determine whether these individual patterns were related to standardized measures of sensorimotor functioning. This question stems from previous research suggesting that different sensorimotor processes may underlie disparate patterns of performance (Pryde & Roy, 1999).

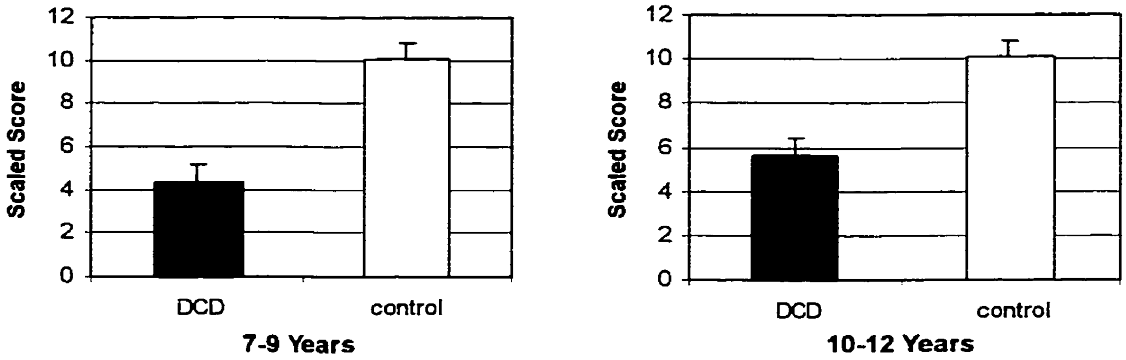
4. Relationship between Kinematic Patterns and Standardized Measures of Sensorimotor Functioning in Children with DCD

Prior to examining the relationship between kinematic patterns and standardized measures, differences between DCD and control groups for the measures of visual perception (MFVPT), proprioception (NEPSY – IHP), visual-motor integration (VMI), and complex motor functioning (GPT) were compared using *t* tests. As in previous sections, all statistical comparisons are made separately for 7-9- and 10-12-year-olds.

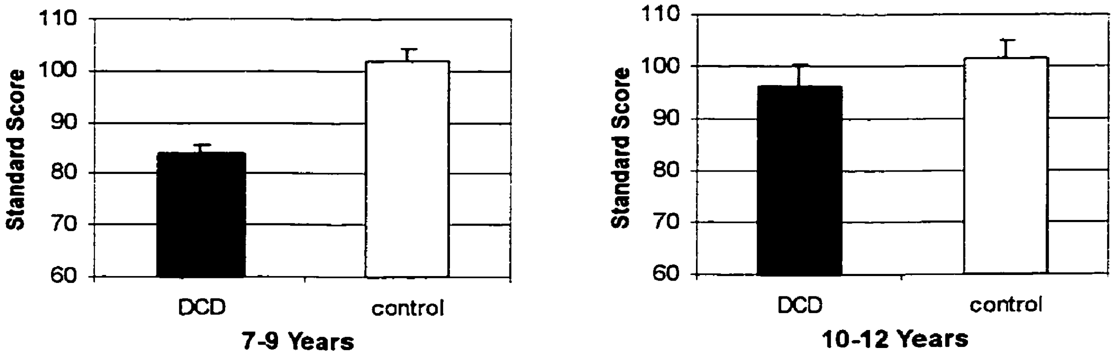
On the measure of visual perception (MFVPT), there were no differences between DCD and control children within either age band, $t_{.025}\ (18) = 0.94$, $p = 0.36$, $t_{.025}\ (18) = 1.20$, $p = 0.25$, for 7-9- and 10-12-year-olds, respectively. On the measure of proprioception (IHP), DCD children in both age bands scored significantly lower than their same-age counterparts, $t_{.025}\ (18) = 5.18$, $p < 0.0001$, $t_{.025}\ (18) = 4.20$, $p = 0.0003$, for 7-9- and 10-12-year-olds, respectively (see Fig. 5.4.1a).

The 7-9-year-old DCD group scored significantly lower than controls on the VMI, $t_{.025}\ (18) = 6.41$, $p < 0.0001$, while those in the 10-12-year-old age range did not show any differences relative to controls, $t_{.025}\ (18) = 0.97$, $p = 0.17$ (see Fig. 5.4.1b). For the test of complex motor functioning (GPT), movement times were

(a) NEPSY – Imitating Hand Positions



(b) Visual-Motor Integration



(c) Grooved Pegboard Test

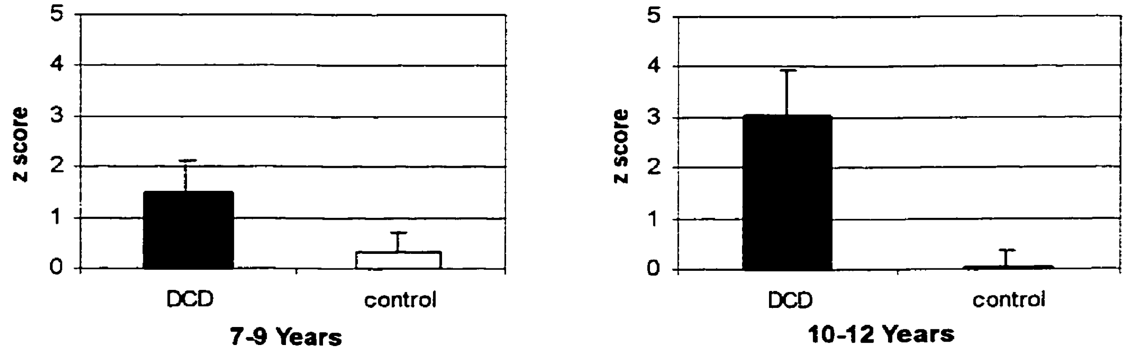


Figure 5.4.1. Differences between DCD and control groups for the IHP (a), VMI (b), and GPT (c) standardized measures.

converted to z scores due to the differences in administration procedures (e.g., younger children have decreased task demands and therefore shorter times) and then subjected to *t* tests. Figure 5.4.1c reveals that DCD children in both age bands demonstrated significantly longer movement times than controls, $t_{.025}$ (18) = -1.77, p = 0.047, $t_{.025}$ (18) = -3.24, p = 0.002, for 7-9- and 10-12-year-olds, respectively.

The results of the standardized measures indicate that, in general, children with DCD have less developed abilities directly related to sensorimotor functioning (e.g., proprioception, visuomotor integration, motor functioning). To determine whether DCD children's scores on these sensorimotor measures were related to the percentages of kinematic/accuracy patterns, correlations were analyzed. For this analysis, the percentage of movements of each type for each participant was correlated with their score (e.g., standard, scaled, or z score) on each of the standardized measures. Because correlations were performed within the DCD group only, both age groups were combined to increase the number of observations. Interestingly, the results of the correlation procedures indicated that there were no relationships between any of the sensorimotor measures and kinematic/accuracy patterns. Correlation coefficients shown in Table 5.4.1 show no significant associations across these measurement domains.

In contrast to the hypothesis of Pryde and Roy (1999), these findings indicate that different kinematic patterns of performance in children with DCD are not related to discrete underlying sensorimotor processes as assessed by standardized tests. Table 5.4.2 provides additional support for this finding, illustrating the wide variation in individual patterns of performance across kinematic and standardized measures in the DCD groups. The children do not show any consistencies between the different kinematic/accuracy profiles and the standardized measures. While some DCD children demonstrate normal kinematic patterns, they perform relatively poorly on all or the majority of standardized measures (e.g., participants 1, 7, 10, 17 and 18). In contrast, some children exhibit high percentages of abnormal kinematic patterns, yet they perform within normal limits on the standardized measures (e.g., participants 6, 8, and 15). Finally, there is a subset of children who demonstrate below average performances on many of the kinematic patterns and standardized measures (e.g., participants 9, 14, 16, and 19). These diverse patterns within the DCD group are consistent with the range of findings exhibited in the kinematic profiles and the kinematic/accuracy patterns of performance presented earlier.

Table 5.4.1. Correlation coefficients and probabilities for standardized measures and kinematic/accuracy patterns.

		NEPSY - IHP	**VMI**	**GPT**
Type I	r	-0.024	-0.086	-0.026
	p	0.919	0.717	0.912
Type II	r	-0.337	-0.227	0.121
	p	0.146	0.336	0.612
Type III	r	-0.017	0.138	-0.018
	p	0.943	0.560	0.941
Type IV	r	0.313	0.180	-0.053
	p	0.179	0.446	0.824

		Kinematic/Accuracy Patterns				Standardized Measures		
ID	Age Group	Type I	Type II	Type III	Type IV	IHP	VMI	GPT
1	7-9	66	14	14	7	1	82	2.1
3	7-9	22	11	33	33	4	93	0.6
5	7-9	54	43	4	0	3	80	2.5
6	7-9	28	26	22	26	9	87	0.1
7	7-9	73	23	3	0	2	78	-0.6
8	7-9	57	3	27	13	9	87	0.5
9	7-9	32	25	36	7	2	77	4.6
11	7-9	72	10	17	0	4	82	0.9
18	7-9	46	25	25	4	4	86	4.2
20	7-9	48	30	11	11	5	89	0.2
2	10-12	30	19	11	41	9	90	2.6
4	10-12	11	4	41	44	5	111	1.7
10	10-12	80	13	7	0	4	105	3.2
12	10-12	72	10	17	0	6	124	4.5
13	10-12	43	37	17	3	5	96	0.9
14	10-12	48	24	16	12	9	88	3.6
15	10-12	50	33	7	10	8	92	1.1
16	10-12	15	38	12	35	5	97	8.5
17	10-12	73	10	13	3	4	79	5.5
19	10-12	21	38	24	17	1	79	-1.4

Table 5.4.2 Individual patterns of performance across all kinematic/accuracy patterns and standardized measures within DCD groups. Shaded cells indicate scores outside of normal limits.

6. DISCUSSION

Review of Findings

The purpose of the present research was twofold: 1) to investigate whether deficits in sensorimotor mechanisms in DCD could be characterized using kinematic and psychometric analyses, and 2) to determine whether subtypes of sensory and/or motor deficits could be identified within a group of children identified with DCD. Five questions of interest were determined to guide this investigation: 1) How will the availability of visual feedback affect the performance of children with DCD relative to children without motor difficulties? 2) Will children with DCD be differentially affected by task requirements such as movement amplitude and target size relative to their peers? 3) Will DCD differentially affect the preprogrammed and/or feedback controlled components of goal-directed movement? 4) What is the relationship between movement kinematics and spatial accuracy in children with DCD relative to their peers? Is this relationship different within a group of children with DCD? 5) What is the relationship between kinematic/accuracy patterns of performance and neuropsychological measures in children with DCD? Questions one through three were concerned with analyses of the kinematic parameters of movement, while questions four and five were concerned with kinematic profiles and their relationship to movement accuracy and standardized measures of sensorimotor functioning.

In response to questions one through three, the analyses of the kinematic parameters revealed that the effects of visual feedback and movement complexity (i.e., target size and amplitude) in children with DCD interact to a large degree. When visual feedback is available and movement demands are high (i.e., the target is small or far away), children with DCD are not able to move as efficiently as their peers. This pattern was most prevalent in younger children with DCD (i.e., 7-9-year-olds) whose movement times were significantly longer with decreases in target size and increases in amplitude. Specifically, these younger children demonstrated longer times in the feedback phase (i.e., TAPV) with a higher frequency of corrections to generate more complex movements. When visual feedback was removed, the 7-9-year-old children with DCD exhibited movements with normal timing components relative to their peers; however, their movements to more complex targets were significantly less accurate.

In the older age group, children with DCD also demonstrated challenges performing movements in the visual feedback condition, although the effects were somewhat different from the 7-9-year-olds. The older DCD group did not demonstrate significantly longer movement times relative to their peers when vision was available; however, they also did not benefit from having visual feedback in the same way as their peers when their movements were compared across feedback conditions. That is, while children in the control group were able to move in shorter amounts of time with visual feedback than in the absence of vision, children with DCD did not demonstrate any differences from controls in movement time across the feedback conditions. However, consistent with their younger counterparts, the 10-12-year-old DCD group demonstrated significant difficulty generating spatially accurate movements in the absence of visual feedback under conditions with greater degrees of movement complexity. While previous findings have concluded that children with DCD are as equally affected by the removal of visual feedback as their peers (Rösblad & von Hofsten, 1994; Smyth, 1991), the findings of the present research indicate that this is not the case. When visual feedback is removed from a group of children with DCD during complex movements, their movements are significantly less accurate.

Overall, the patterns of performance on the aiming task are consistent with previous research suggesting that as task complexity increases, children with DCD demonstrate increased difficulty contending with the demands of the task (Henderson, 1992; Smyth, 1991; Smyth & Mason, 1998). When visual feedback is available, this difficulty is evidenced primarily through a slowness in on-line control – longer MT and TAPV, lower PV, and a higher frequency of corrective movements. In the absence of vision, the difficulty is largely evidenced through decreases in spatial accuracy. Thus, the effects of sensory feedback on movement execution in the DCD population are largely dependent on several factors including age, feedback, and task complexity.

Why do the effects of visual feedback on DCD change with age? In younger children, the effects of vision on kinematic parameters in the DCD group are quite dramatic relative to children without motor difficulties. Older children with DCD show more subtle differences relative to their same-aged peers. The decreased effect of visual feedback on older children with DCD may be the result of an increased capacity to deal with and integrate visual feedback during the execution of goal-directed movement. Such an increased capacity could be the result of experience and/or improved motor control strategies for contending with the complex nature of visual information and visuomotor integration. In younger children with motor difficulties, integrating visual and proprioceptive feedback of the moving hand as well as challenging target characteristics, such as a small size or distant amplitude, may be too taxing on their systems. This "overload" would result in the greater slowness and frequency of corrective movements observed in the younger DCD group. The pattern of results in the no visual feedback condition of this study would suggest that the removal of visual feedback lessens the processing load to some extent, since both DCD groups demonstrated kinematic parameters similar to controls. However, that the children with DCD in both age groups demonstrated a higher degree of spatial inaccuracy, both initial and final, when moving to more complex targets, indicates that the removal of visual feedback poses a challenge to both the programming (reflected in initial accuracy) and control components (reflected in final accuracy) of movement in this population. It is likely that situations requiring children with DCD to execute movements while simultaneously contending with multiple sources of environmental stimuli results in less efficient motor responses. Future studies using a dual-task paradigm might provide further evidence of, and insight into, the processing load challenges in DCD.

Consistent with previous research (Hay, 1979, 1984; Pryde & Roy, 1998, 1999), analysis of the velocity profiles revealed that children in both DCD and control groups exhibited three types of kinematic profiles in their manual aiming movements: step, double-peak, and mature. Comparisons of these profiles between the DCD and control groups yielded evidence of qualitative differences between the groups, where children with DCD generally exhibited relatively fewer "normal" movements (e.g., mature) and more immature, "abnormal" movements (e.g., step) relative to their peers. The higher frequency of irregular, multi-peaked velocity profiles observed in children with DCD is consistent with the findings of the kinematic parameters, indicating that they experienced difficulty organizing and generating movements to contend with the demands of the manual aiming task.

The high frequency of abnormal, accurate movements for the 7-9-year-old children with DCD in the presence of visual feedback (e.g., Fig. 5.3.1) was consistent with the earlier age-related findings. This finding provides additional support for the notion that integration of visual information presents a processing challenge to younger children with DCD during movement execution. In order for these younger DCD children to execute accurate movements, they rely more heavily on visual feedback for the on-line control of their hand toward the target. This increased dependence on feedback would lead to an increased prevalence of multi-peaked, irregular movement profiles. Thus, it appears that visual feedback is somewhat of a "double-edged sword" for younger children with DCD. Particularly when faced with complex target characteristics (i.e., targets that are small or far away) visual feedback presents a processing challenge for these children, yet visual feedback of their hand enables guidance to an accurate end-point. When visual feedback was removed, both DCD age groups demonstrated significantly fewer "perfect" movements – bell-shaped profiles with accurate end-points – than exhibited by controls. This, too, is consistent with the results of the kinematic parameters analyses and further supports the idea that the removal of visual feedback poses a significant challenge to the programming and control of goal-directed movements in the DCD population. This challenge leads to a variety of poorly organized movement patterns.

What do these findings reveal about the deficit(s) underlying DCD? The comparisons between the DCD and control groups for the kinematic parameters and profiles in this study primarily lead to the kind of inconclusive results prevalent in the DCD literature. Children with DCD appear to have difficulty processing both visual and non-visual feedback leading to longer movement times and/or decreased accuracy and a higher frequency of irregular velocity profiles. A reconsideration of the model of sensorimotor functioning that has been offered by motor control theorists (see Fig. 2.1, p. 16) enables several explanations of the findings to be postulated. One possible explanation may be that the increased incidence of abnormal, multi-peaked movements in the DCD group is the result of a generalized programming deficit (e.g., Geuze & Kalverboer, 1988; Rösblad & von Hofsten, 1994; Smyth, 1991; van der Meulen et al., 1991), causing children in this population to experience difficulty generating the normal, bell-shaped profiles predominantly exhibited by their peers. As a result, children with DCD spend more time using feedback to control their movements. However, the analyses of the kinematic parameters do not reveal significant differences between the DCD and control groups with respect to the TTPV or RT measures – indicators of the preprogrammed component of movement. Furthermore, some children with DCD executed movements with kinematic profiles comparable to those of controls (e.g., Fig. 5.3.2). Given these latter findings, a generalized programming deficit in the DCD population seems unlikely.

Since children with DCD generally spend more time using feedback to control their movements, an alternative explanation could be that DCD is the result of a generalized deficit in feedback control, both visual and proprioceptive. This explanation would account for the longer movement times in the visual feedback condition and the spatially inaccurate movements in the no visual feedback condition demonstrated by the DCD group. However, the higher frequency of abnormal, multi-peaked movements and the variation in the kinematic/accuracy patterns in children with DCD relative to the controls (e.g., Figs. 5.3.1 and 5.3.2) indicates some signs of deficient programming and that some children are able to use feedback in ways comparable to their peers. Thus, these findings speak against the hypothesis of a generalized feedback deficit.

Interestingly, even a more detailed investigation of movement trajectories and movement accuracy (e.g., MT, velocity measures, accuracy, kinematic profiles) in groups of children with and without DCD does not provide conclusive evidence explaining the deficient motor performance in DCD. It is only when analyses of movements in individual DCD children as well as performance on standardized measures are examined (e.g., research questions 4 and 5) that a more plausible explanation of the nature of the movement deficits in DCD is revealed. This alternative explanation stems from the assumption that DCD is a heterogeneous disorder and suggests that the disorder may be the result of a more global deficit in sensorimotor functioning characterized by variations in the expression of motor difficulties. This explanation suggests that the entire sensorimotor system illustrated in Figure 2.1 may be implicated in DCD.

Support for such a generalized sensorimotor deficit comes from several findings in the data. Firstly, the majority of children with DCD were found to perform significantly below average on standardized tasks requiring the integration of visual and proprioceptive information with motor functions. On the manual aiming task, this difficulty was exacerbated in the no visual feedback condition, which required children to integrate visual and proprioceptive information in a unique way (e.g., visual feedback of the target and proprioceptive feedback of the hand). Children with DCD reacted to this insecurity by using various adaptive strategies for movement execution (e.g., Fig. 5.3.2). Some children primarily adopted a strategy of hesitant, on-line control leading to abnormal, multi-peaked movements. For some, this strategy was successful and led to an accurate end-point (e.g., Type III – abnormal, accurate), while for other DCD children this strategy resulted in significant spatial inaccuracy (e.g., Type IV – abnormal, inaccurate). There was another sub-group of DCD children who performed kinematically normal movements to inaccurate locations (e.g., Type II – normal, inaccurate). Possibly these children are not aware of or underestimated their system's difficulty in integrating sensorimotor information for certain tasks. Finally, there was a subset of children with DCD who generated "perfect" movements with normal, bell-shaped profiles and a level of accuracy that was commensurate with their same-age peers (e.g., Type I – normal, accurate). Since this latter group of children fully met the criteria for DCD and performed below average on many of the standardized measures, their performance on the aiming task suggests that they adopted some effective strategies for coping with the deficiencies of their sensorimotor systems. Such a range of adaptive movement strategies due to central processing deficits has been previously described in the literature (Hermsdörfer, Mai, Spatt, Marquardt, Veltkamp & Goldenberg, 1996).

As previously suggested by Pryde and Roy (1999), different kinematic/ accuracy patterns of performance exhibited by individual children with DCD may be related to differential deficits within the sensorimotor system (e.g., proprioception or motor execution). However, the lack of a correlation between the standardized measures of sensory and motor functioning and the kinematic/accuracy patterns suggests that it is unlikely that there are discernible and stable subtypes of sub-system deficits detectable from conventional tests of sensorimotor functions. Some children with DCD demonstrated normal kinematic/accuracy patterns yet performed relatively poorly on all or the majority of standardized sensorimotor measures (e.g., participants 1, 7, 10, and 18 in Table 5.4.2, p.76). Other children exhibited high frequencies of abnormal kinematic/ accuracy patterns, yet performed within normal limits on the standardized measures (e.g., participants 6, 8, and 15 in Table 5.4.2). Finally, another subset of children demonstrated a range of difficulties across kinematic/accuracy patterns and sensorimotor measures (e.g., participants 3, 9, 16, and 19 in Table 5.4.2). Certainly, it is possible that the standardized measures employed in the present study were not sensitive enough to discern differences in performance on the aiming task. However, the diverse pattern of results suggests that the method of subtyping children with DCD using current standardized measures may not be the most useful approach. Indeed, given the variation in movement responses exhibited within the DCD group, alternative measures are needed that will enable researchers and clinicians to better examine the qualitative nature of movements in this population.

A consideration of recent research on the neural substrates underlying sensorimotor functioning may help shed further light on the patterns of performance within the DCD population. Research on neural substrates may not necessarily go beyond the "black box" theoretical models frequently offered by motor control theorists (e.g., the model of sensorimotor functioning in Fig. 2.1); however, it may elucidate neural underpinnings of processes identified in the motor control theories. One process in particular that has been identified is the integration of sensory information with the control of movement.

The Neural Substrates of Sensorimotor Functioning

While it is well recognized that the integration of sensory information into discrete motor plans occurs in cortical, subcortical, and cerebellar areas in a dynamic, parallel manner, it is generally accepted that the right hemisphere (RH) plays a specialized role in sensorimotor functioning (Beery, 1997; Goldberg & Costa, 1981; Gur et al., 1980; Lezak, 1983; Rourke, 1995). Based on research providing evidence of the RH's specialized role, Rourke posits a model in which failures of development or disruption of white matter neural connections inherent to the RH (e.g., commissural, association, and projection) lead to visual-motor and other integrative dysfunctions in behaviour. Such dysfunctions occur as a result of the crucial nature of RH white matter for the development and maintenance of its integrative functions used to manage novel, complex information processing task challenges. Rourke (1987, 1989, 1995) observes that children who exhibit disturbance of white matter functioning demonstrate symptoms of a Nonverbal Learning Disability (NLD). These symptoms include a pattern of deficits in visual-spatial, complex psychomotor, and strategy generation/problem-solving skills, as well as social competence, attention, and activity level. Other symptoms include academic deficits in reading comprehension, mechanical arithmetic, and subjects involving complex concept formation such as science.

Rourke's model (1995) hypothesizes a spectrum of neurodevelopmental disorders characterized by variations in the severity of expression of the NLD syndrome. For example, the syndrome is manifested most clearly in disabilities resulting from callosal agenesis, high-functioning cases of fetal alcohol syndrome, Asperger's syndrome, autism, and traumatic brain injury. Other manifestations of the NLD syndrome, such as cerebral palsy and leukodystrophies, are less well defined but exhibit a considerable majority of the assets and deficits. It is within this latter level of the NLD syndrome that DCD might be characterized within the context of the NLD spectrum.

Recent work by Henderson and colleagues (1993, 1999) have examined the impact of the duration of neonatal "flares" -- echodensities -- in periventricular white matter in preterm infants on neurological status and motor competence at 6 years of age. Forty-four children with neonatal flares (identified on ultrasound scans), subdivided into three groups according to the duration of flares (< 7 days, 7-14 days, or > 14 days), and 62 children with normal scans were formally assessed on measures of neurological, sensorimotor, and cognitive functioning. While no differences in cognitive abilities were found between the groups, the results of the motor assessments showed that performance decreased significantly with increasing duration of flares. Henderson et al. concluded that persistent periventricular densities, *i.e.*, mild leukomalacia, might be the mechanism by which motor impairments such as those observed in DCD are produced.

The findings of Henderson et al. (1993, 1999) have important implications for understanding the nature of DCD within the context of Rourke's model of the NLD syndrome. Since leukomalacia is a form of white matter disturbance (Brett & Kaiser, 1997) and can lead to deficits as severe as cerebral palsy or as mild as poor perceptual-motor functioning (Fanaroff et al., 1999; Jongmans et al., 1993), it seems plausible to consider DCD within the context of Rourke's (1995) model of NLD. In this way, the results of the present study can provide us with some insight into the nature of the motor impairments exhibited by children with DCD. In situations where novel and/or complex motor functioning is required, as in the visual and no visual feedback conditions of the aiming task, children with DCD demonstrate deficits in the ability to efficiently contend with the demands of the tasks. These deficits are evidenced through increases in the on-line control of movement, decreased accuracy in the absence of visual feedback, and difficulties in demonstrating age-appropriate movement strategies. Furthermore, on the majority of standardized tests of sensorimotor functioning, children with DCD generally perform well-below average relative to their peers. These patterns of performance are consistent with many of the neuropsychological deficits observed by Rourke (1987, 1989, 1995) in children with NLD. That the 10-12-year-old children with DCD show more subtle effects on the visual feedback task and do not show below-average performance on the Test of Visual-Motor Integration (Beery, 1997) is also consistent with the NLD syndrome. Rourke (1995) observes that while children with NLD demonstrate significant difficulty with many skills early in childhood, they often improve over time with increased practice (e.g., graphomotor skills emphasized in school; increased experience processing visual stimuli).

Implications for Intervention in DCD

The lack of age-appropriate movement strategies and the improved performance with experience observed in DCD children in the present study bodes well for intervention strategies for this population. Remediation that focuses on teaching children appropriate strategies for dealing with novel and/or complex movement situations to reach a specific goal and fostering the generalization of learned strategies and concepts would seem most beneficial to children with DCD. The results of the present study would suggest that, indeed, there are children who demonstrate the diagnostic characteristics of DCD yet are able to generate movements that are comparable to those of their same-age peers. Interestingly, the remediation strategies outlined above have been and are currently being used by many occupational therapists (Mandich, Polatajko, Missiuna & Miller, in press; Martini & Polatajko, 1995; Missiuna, 1995; Wilcox & Polatajko, 1994). The programs being implemented by these practitioners involve a cognitive or verbal self-guidance approach where children are taught in a systematic fashion to talk themselves through the steps of identifying the goal, executing, and assessing the effectiveness of their movement. So far, the results of these programs have proven to be effective with the DCD population. Rourke (1995) also advocates similar intervention approaches with the NLD population.

Future research investigating the nature of the various response strategies exhibited by children with DCD would be useful from a practical point of view. For example, it would be interesting to examine and characterize the strategies used by children with DCD who demonstrate normal patterns of performance on the aiming task. It would also be interesting to determine whether or not these children are aware of and able to explain the strategies they used (e.g., meta-cognitive strategies). This kind of information might shed further light on the effectiveness of particular teaching methods within the DCD population.

Conclusion and Directions for Future Research

In summary, the results of the current research indicate that the manifestations of DCD depend on a complex relation between the nature of the task, the role of specific types of sensory feedback information, and age. Task demands requiring novel and/or complex motor responses are particularly challenging for children with DCD and result in a range of kinematic differences and a variety of adaptive strategies. Instead of arguing distinct sub-system deficits (e.g., sensory vs. programming) as previously suggested in the literature

(Hoare, 1994; Pryde & Roy, 1999; Wright & Sugden, 1996), the culmination of the present findings suggest that DCD is the result of a more generalized deficit in sensorimotor functioning. In situations that tax their sensorimotor systems, children with DCD implement a variety of adaptive motor control strategies to contend with this deficit. Some children compensate by primarily using a strategy that results in kinematically degraded movements that may or may not be accurate, while some children use efficient strategies that enable them to execute movements as well as their peers. There also appears to be a subgroup of children who do not compensate for their system's deficit and generate kinematically normal movements that do not hit the intended target position. Future research using individual analyses to investigate the nature of these movement strategies would be useful for more fully characterizing motor control assets and deficits in DCD (c.f., Hoare, 1994; Pryde & Roy, 1999; Wright & Sugden, 1996).

The nature of the sensorimotor difficulties revealed in this research suggest that DCD may be a subset of the NLD syndrome posited by Rourke (1987, 1989, 1995), although it is not possible to draw such conclusions based on the context of the present research alone. Children with DCD demonstrate the neuropsychological deficits in complex psychomotor functioning and strategy generation that are characteristic of the NLD syndrome. Recent research by Henderson and her colleagues (1993, 1999) investigating neonatal flares has provided evidence of white matter disturbance in children with DCD characteristics. Thus, it may be that the nature and extent of such white matter disturbances affect not only the degree of sensorimotor impairment in DCD, but also the ability to generate adaptive motor responses in spite of such deficits. Certainly, future research gathering developmental histories and using neuroimaging techniques to investigate DCD will shed considerable light on the functioning of the sensorimotor systems in this population.

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APPENDICES

APPENDIX A

Definition of Developmental Coordination Disorder

(American Psychiatric Association, 1994, pp. 53-55)

315.4 Developmental Coordination Disorder

Diagnostic Features

The essential feature of Developmental Coordination Disorder is a marked impairment in the development of motor coordination (Criterion A). The diagnosis is made only if this impairment significantly interferes with academic achievement or activities of daily living (Criterion B). The diagnosis is made if the coordination difficulties are not due to a general medical condition (e.g. cerebral palsy, hemiplegia, or muscular dystrophy) and the criteria are not met for Pervasive Developmental Disorder (Criterion C). If Mental Retardation is present, the motor difficulties are in excess of those usually associated with it (Criterion D). The manifestations of this disorder vary with age and development. For example, younger children may display clumsiness and delays in achieving developmental motor milestones (e.g. walking, crawling, sitting, tying shoelaces, buttoning shirts, zipping pants). Older children may display difficulties with the motor aspects of assembling puzzles, building models, playing ball, and printing or handwriting.

Associated Features and Disorders

Problems commonly associated with Developmental Coordination Disorder include delays in other non-motor milestones. Associated disorders may include Phonological Disorder, Expressive Language Disorder, and Mixed Receptive-Expressive Language Disorder.

Prevalence

Prevalence of Developmental Coordination Disorder has been estimated to be as high as 6% for children in the age range of 5-11 years.

Course

Recognition of Developmental Coordination Disorder usually occurs when the child first attempts tasks such as running, holding a knife and fork, buttoning clothes, or playing ball games. The course is variable. In some cases, lack of coordination continues through adolescence and adulthood.

Differential Diagnosis

Developmental Coordination Disorder must be distinguished from motor impairments that are due to a general medical condition. Problems in coordination may be associated with **specific neurological disorders** (e.g. cerebral palsy, progressive lesions of the cerebellum), but in these cases there is definite neural damage and abnormal findings on neurological examination. If **Mental Retardation** is present, Developmental Coordination Disorder can be diagnosed only if the motor difficulties are in excess of those usually associated with the Mental Retardation. A diagnosis of Developmental Coordination Disorder is not given if the criteria are met for a **Pervasive Developmental Disorder**. Individuals with Attention-Deficit/ Hyperactivity Disorder may fall, bump into things, or knock things over, but this is usually due to distractibility and impulsiveness, rather than to a motor impairment. If criteria for both disorders are met, both diagnoses can be given.

Diagnostic criteria for 315.4 Developmental Coordination Disorder

A. Performance in daily activities that require motor coordination is substantially below that expected given the person's chronological age and measured intelligence. This may be manifested by marked delays in achieving motor milestones (e.g. walking, crawling, sitting), dropping things, "clumsiness," poor performance in sports, or poor handwriting.

B. The disturbance in Criterion A significantly interferes with academic achievement or activities of daily living.

C. The 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.

D. If Mental Retardation is present, the motor difficulties are in excess of those usually associated with it.

APPENDIX B

Descriptions of Motor and Intelligence Measures

Movement Assessment Battery for Children

(Henderson & Sugden, 1992)

Overview

The Movement Assessment Battery for Children (M-ABC) is concerned with the identification and description of impairments of motor function in children. As such, the scores on the M-ABC indicate the extent to which a child falls below the level of his or her peers. The battery does not attempt to differentiate between children who perform above this level.

Structure of the M-ABC Test

The M-ABC Test is designed to be administered individually and requires the child to perform a series of motor tasks in a standard way. The Test consists of a total of 32 items organized into four sets of eight tasks, each designed for use with children of a different age band (i.e., 4-6, 7-8, 9-10, and 11-12). The requirements of the eight tasks in each level of the test are identical and are grouped under three headings: Manual Dexterity, Ball Skills, and Static and Dynamic Balance.

Scoring

The Test yields various estimates of movement competence. The overall performance score across all eight tasks is the Total Impairment Score, which is the sum of scores on the eight items that each child attempts during a formal assessment. This score is then interpreted in terms of age-related norms. The Test also provides percentile norms for each of the three subscores representing competence in Manual Dexterity, Ball Skills, and Static and Dynamic Balance.

Kaufman Brief Intelligence Test

(Kaufman & Kaufman, 1990)

Overview

The Kaufman Brief Intelligence Test (K-BIT) is a brief, individually administered measure of the verbal and non-verbal intelligence of children and adults aged 4 to 90 years.

Structure

The K-BIT is composed of two subtests: Vocabulary (Part A: Expressive Vocabulary and Part B: Definitions) and Matrices. Vocabulary measures verbal, school-related skills by assessing a person's word knowledge and verbal concept formation. Matrices measures nonverbal thinking skills and the ability to solve new problems by assessing an individual's ability to perceive relationships and complete analogies.

Scoring

Individual test items are scored as 1 or 0. The number of items answered correctly on each subtest yields a raw score, which can later be converted to a standard score with a mean of 100 and a standard deviation of 15. Similar to other standard tests of intelligence, the K-BIT yields an IQ Composite score that reflects a global measure of intelligence. The K-BIT correlates well with other major intelligence tests; the IQ Composite correlated .80 with the WISC-R Full Scale IQ.