ADAPTED PHYSICAL ACTIVITY QUARTERLY, 2006, **23**, 14-30

Adaptations to Task Constraints in Catching by Boys With DCD

Frederik J.A. Deconinck and Dirk De Clercq
Ghent University, Belgium

Geert J.P. Savelsbergh
Vrije Universiteit Amsterdam, The Netherlands

Rudy Van Coster
Ghent University, Belgium

Ann Oostra and Griet Dewitte
Centre for Developmental Disorders, Ghent, Belgium

Matthieu Lenoir
Ghent University, Belgium

One-handed catching behavior was studied in nine 6- to 8-year-old boys with Developmental Coordination Disorder (DCD) and nine matched typically developing boys. The participants performed a catching task under two conditions. In the first condition, one ball speed was used while three ball speeds were randomly presented in the second condition. Boys with DCD showed a significantly smaller maximal hand aperture and a lower maximal closing velocity in both the first and the second condition; however, the temporal structure of the catch as well as the adaptations to the varying ball speeds did not differ between groups. This leads to the suggestion that the motor problems of boys with DCD in one-handed catching are not primarily due to debilitated visuo-perceptual or planning processes but are more likely caused by problems at the execution level.

Developmental Coordination Disorder (DCD) is characterized by a failure to establish fluent and efficient coordination patterns for fine motor (e.g., shoe lacing, writing, eating with knife and fork, etc.) as well as gross motor tasks (e.g., walking,

---

Frederik J.A. Deconinck is with the Department of Movement and Sports Sciences, Faculty of Medicine and Health Sciences, Ghent University. E-mail: Frederik.Deconinck@UGent.be. Dirk De Clercq is with the Department of Movement and Sports Sciences, Ghent University. Geert J.P. Savelsbergh is with the Institute for Fundamental and Clinical Human Movement Sciences, Vrije Universiteit Amsterdam and Institute for Biophysical and Clinical Research into Human Movement, Manchester Metropoliton University. Rudy Van Coster is with the Department of Pediatrics and Medical Genetics, Ghent University. Ann Oostra and Griet Dewitte are with the Centre for Developmental Disorders of Ghent, Belgium. Matthieu Lenoir is with the Department of Movement and Sports Sciences, Faculty of Medicine and Health Sciences, Ghent University.

jumping, throwing, etc.) without a demonstrable medical condition (American Psychiatric Association, APA, 1994). Research on the underlying causes of the motor impairment can roughly be divided into two main lines of inquiry. The first line focuses on the sensory information process prior to and during the motor response, while the second focuses on the motor component itself. The information processing deficits associated with DCD are discussed in detail by Wilson and McKenzie (1998). Visuo-spatial processing as well as kinesthetic perception and cross-modal perception were found to contribute to the motor coordination impairments in children with DCD. A detailed discussion of the relative contribution of these factors to DCD goes beyond the scope of this paper, therefore only a brief review of the literature is provided given the importance of both modalities of perception in interception skills.

The role of the visual processing deficits in the movement coordination problems of children with motor problems was recognized by Lord and Hulme (1987). Later, these visual deficits were found to be present in tasks with and without a motor response (Schoemaker et al., 2001; Wilson & McKenzie, 1998), but it remains unclear whether or not a causal relationship exists between them. In other words, the fact that motor and visuospatial impairments are conjoined does not necessarily imply that the first is the result of the second, neither that both are caused by the same factor (Henderson, Barnett, & Henderson, 1994).

Laszlo and colleagues found that clumsy children also did not perform as well in tasks involving kinesthetic perception (Laszlo, Bairstow, Bartrip, & Rolfe, 1988), a finding that was corroborated by Smyth and Mason (1997), Sigmundsson et al. (1999), and Schoemaker et al. (2001). Children with DCD showed more problems with the processing of proprioceptive information than typically developing children in tasks that involved locating targets under a table-top with one hand while attempting to match the position of the target with the other on the table-top. In addition, children with DCD demonstrate deficits in the ability to integrate visual and kinesthetic information (Schoemaker et al., 2001; Sigmundsson, Ingvaldsen, & Whiting, 1997). However, one can argue that because of the difficulty to assess such deficits in a way that excludes pure motor control problems, it might be inappropriate to make assumptions about the functioning of the perceptual system (Wilson & McKenzie 1998). Thus, in spite of the existing evidence for deficits at the perceptual (visual spatial or kinesthetic) level, the exact relationship between these deficits and the motor impairment remains unclear (Schoemaker et al., 2001; Wilson & McKenzie 1998).

As a manifestation of the planning process, the temporal aspects of movement control have been examined in a vast number of studies on DCD (Williams, 2002). Children with DCD show general problems with timing expressed by slower reaction times (Henderson, Rose, & Henderson, 1992) and an increased variability in rhythmic coordination in tapping tasks and bimanual coordination (Geuze & Kalverboer, 1994; Volman & Geuze, 1998). An often suggested source of these problems is a deficit in an internal timing mechanism that is thought to be located in the cerebellum (Ivry & Keele 1989; Williams, Woollacott, & Ivry, 1992). Lundy-Ekman, Ivry, Keele, and Woollacott (1991) proposed that there exists a distinction between coordination problems associated with soft cerebellar signs and coordination problems associated with soft basal ganglia signs. A component analysis of the timing and force control in a tapping task showed that children with soft cerebellar signs experienced problems in time perception and production. Children with soft basal ganglia signs showed deficits in force control, although these inferences were not based on empirical neuromuscular data.

The underlying neuromuscular mechanisms of the disorder were discussed in a number of studies on postural stability by Williams and co-workers. It was found that children with DCD exhibit greater levels of muscular activity in both upper leg and trunk when standing upright (Williams, Fisher, & Tritschler, 1983). Next to these increased levels of muscle activation, Williams and Castro (1997) found disproportionate amounts of proximal muscle production (i.e., quadriceps muscle) compared to distal muscle activity (i.e., tibialis anterior) in a similar task, representing a less refined mode of motor control. This deficiency in the use of proximal muscles and the tendency to overuse muscles to fixate joints to provide stability was also suggested by Wilson and Trombly (1984) in a fine-motor task paradigm with children with sensory integration deficits. In sum, perceptual as well as motor control deficits have been suggested as the underlying factors of DCD. A test paradigm involving the interception of an object could be used to further investigate the role of both factors in a functional task in children with DCD.

The act of reaching, grasping, and catching provides the opportunity to study the closely intertwined perceptual and motor aspects in a task that is externally constrained at the spatial as well as the temporal level. The rudimentary capacity to time and coordinate a reach and catch is already present in infancy (von Hofsten, 1983). Studies on coincidence timing in several contexts with children with DCD reveal that they seem to lack this ability. By qualitative observation, Larkin and Hoare (1991) identified problems at different levels such as difficulties in the prediction of the ball flight, poor control of posture, and positioning and deficits in the fine control of hands and fingers. Recently, Van Waelvelde, De Weerdt, De Cock, Peersman, and Smits-Engelsman (2004) suggested that poor catching performance of children with DCD is not a reflection of a developmental delay. Instead, it appeared that children with DCD made more grasp errors and used different movement strategies than younger typically developing children.

According to Fischman, Moore, and Steele (1992) the act of one handed catching begins to develop at 5 years of age and reaches mastery by age 12. Boys demonstrated to be better catchers than were girls. Additionally, it seems that even the young children (5 years old) selected the appropriate hand orientation for ball location (waist, above the head, out to the side), indicating that young children are able to tune their motor response at least partially to the perceptual information of the moving ball (see Savelsbergh, Rosengren, van der Kamp, & Verheul, 2003 for a review on the development on catching). In Lefebvre and Reid (1998), it was found that this prediction of the ball's line of flight is the primary causal factor for the limited catching performance of children with DCD. In a (simulated) trajectory occlusion task, they found that children with DCD verbally predicted ball flight worse than did children without DCD, indicating a distinct lack of knowledge of ball flight cues or a more general problem of visual perception (Lefebvre & Reid, 1998). This prediction problem corresponds to the general notion that children with DCD make less use of anticipatory control as van der Meulen, Denier van der Gon, Gielen, Gooskens, and Willemse (1991a, 1991b) found in their unilateral aiming and arm tracking experiment. Therefore, children with DCD rely more on feedback control than their peers do, a finding that was corroborated for both unilateral and bilateral reaching movements by Huh, Williams, and Burke (1998).

To our knowledge, Estil, Ingvaldsen, and Whiting (2002) were the first to carry out a kinematic catching study on children with DCD. The children sat at a table with the catching arm fixed to an armrest. The ball was fastened to a pendulum system and the children were instructed to make a clean catch. Children with DCD initiated their grasp earlier than typically developing children did, and they reached maximal hand aperture at an earlier stage as well. Estil et al. (2002) suggested that this might illustrate a compensation strategy for the deficits in visual information processing of the children with motor coordination problems. This strategy is consciously adopted in order to create a safety margin to initiate the temporally constrained closing of the hand. The fact that these children showed a more jerky pattern before starting hand closure supported this hypothesis of temporal uncertainty; however, from their results, Estil and colleagues (2002) could not conclude whether the adaptations were caused by a problem in the visual perceptual information processing or were the result of poor proprioception at the level of the fingers.

So far, little effort has been made to make a distinction between boys and girls with DCD in this introduction; however, given the difference in the developmental sequence of catching of boys and girls (Fischman et al., 1992), it is appropriate to investigate catching of boys and girls with DCD separately. Since the recruitment of children with DCD for the present study resulted in far more boys than girls (nine boys, one girl) it was decided to concentrate on the catching behavior of boys with DCD. This overrepresentation of boys in the population of children with DCD is in line with earlier studies (Gillberg, 2003).

The purpose of this study was to compare the control of one-handed ball catching in boys with and without DCD. Boys without DCD were typically developing children. Therefore, we used a protocol that is basically a replication of the study of Estil et al. (2002). Based on the findings on the overall timing and prediction problems exhibited by children with DCD, we can expect that boys with DCD will show a disturbance of the temporal structure of the catch. In addition, since motor coordination problems are also expressed as the inability to adequately adapt one's behavior to varying environmental constraints, we investigated if boys with DCD exhibited the same adaptive capabilities in a catching task as boys without DCD. This ability is frequently needed in daily life and sport activities. In order to study the adaptive abilities of boys with DCD in a catching task, different ball speeds were presented in a random order. In a tapping task where children were instructed to change tapping frequency either with or without external stimulus, Geuze (1990) found that a larger number of children with DCD did not meet the task requirements (i.e., speeding up or slowing down the tapping rate). In addition, children with DCD showed more variability than did children without DCD. Consequently, we expect boys with DCD to show less adaptive capability to the varying task constraints in a condition where ball speeds are randomized over trials. At the same time, this procedure allows us to test if boys with DCD indeed consciously adopt a compensation strategy to gain time for decision making as argued by Estil et al. (2002). If so, speeding up the projected balls would result in earlier movement initiations in boys with DCD as the temporal aspects become even more constrained.

Method

Participants

Recruitment of the boys with DCD was achieved with the help of 35 psychomotor physiotherapists and the Centre for Developmental Disorders (Ghent, Belgium). They were acquainted with the purpose of the study and with the inclusion and exclusion norms for the boys of the experimental group. These norms were based entirely on the qualitative description of the criteria for Developmental Coordination Disorder (DCD) in DSM IV (APA, 1994). By accurately screening the medical files of their patients, the therapists selected the boys who qualified for this study on the basis of prescribed criteria. All 6 to 8-year-old boys with a total score on the Movement Assessment Battery for Children (MABC; Henderson & Sugden, 1992) below the 15th percentile and without any clear neurological damage or anomaly as assessed by a physician were informed about the research project and invited to participate. According to the MABC manual (Dutch version) scores at or below the 5th percentile indicate distinct motor problems, and children who score between the 5th and the 15th percentile are suggested to be severely at risk for motor problems (Smits-Engelsman, 1998; see Apparatus section for more information on the MABC). Children with an IQ less than 75 were excluded. By this procedure, 9 boys with a mean age of 7.3 years (*SD* = 0.9) and a mean MABC percentile of 7.9 (*SD* = 4.34, range = 1-12) were included in the experimental group. Prior to the first test session, the boys completed a questionnaire together with their parents to assess their movement profiles. This form contained questions about the degree and nature of boys' daily activity and their favorite sports.

All 6 to 8-year-old children (*n* = 300) from two primary city schools in Ghent completed the same questionnaire. Nine age, weight, and stature-matched typically developing boys with a similar movement profile as the boys with DCD were selected to serve as the comparison group (see Table 1). Since intelligence profiles were not available, intelligence was matched by means of the latest marks for mathematics, which previously has been shown to correlate significantly with IQ for a Flemish population (Brusselmans-Dehairs et al., 2002). To ensure that none of the typically developing boys had delayed or disturbed motor development, the nine boys were tested on the MABC. All of them scored above the 33rd percentile (*M* = 66.6, *SD* = 21.92, range = 33 - 92). Parents provided informed consent prior to the first test session. The study was approved by the Ethical Committee of the Ghent University.

Apparatus

The MABC of Henderson and Sugden (1992) was used to assess the participants' motor performance. This test for motor coordination consists of eight tasks, divided into three performance areas: manual dexterity (three items), ball skills (two items), and static and dynamic balance (three items). The raw performance score is converted into a score between 0 and 5. The summation of all scores and comparison with the percentile norms in the manual gives an indication of the general motor performance of the participant. Similarly, the scores on the three performance areas separately are indicative for the performance in that specific area. The MABC has been proven to be valid and is widely used in the field to

Table 1 Means (M), Standard Deviations (SD), and *t* Test Values Relative to Demographic Data of Boys With and Without DCD

	Boys With DCD		Boys Without DCD (typically developing)		*t* (16)
Variable	*M*	*SD*	*M*	*SD*	
Age (years)	7.3	0.9	7.5	0.9	.370
Body length (m)	1.28	0.075	1.31	0.053	.947
Body weight (kg)	25.6	4.28	27.6	4.36	.982
Hand length (mm)	155	13.6	154	11.5	.168
PA school (h/w)	3.5	1.75	3.7	1.55	.202
PA leisure (h/w)	2.0	1.57	2.7	1.86	.838
Math grade (%)	88	8.3	91	7.2	.891
MABC percentile	7.9	4.34	66.6	21.91	7.878*

Note. PA school = amount of physical activity at school in hours per week (i.e., sum of the hours of physical education and playground activities). PA leisure = amount of regular physical activity in leisure time in hours per week.

* $p < .001$

detect motor coordination problems (Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001).

For the catching task, the participants sat on a chair at a table with their dominant arm (the side of the writing hand, as experienced in the assessment of the MABC) fixed to an armrest leaving the hand free to catch the ball. The height of the chair was adjusted so that the child could adopt a comfortable position with the knees and elbow 90° flexed and the shoulder in approximately 45° flexion (see Figure 1).

A foam ball (6.5 cm in diameter), fastened to the lower end of a rigid, metal pendulum (length: 2.0 m) was projected toward the participant. The height of the system was adjusted to the position of the catching hand so that the ball slightly touched the hand at the base of the angle between index and middle finger in the area of the metacarpophalangeal joints when the pendulum was in vertical resting position. The ball was released manually from a height of 0.20 – 0.40 – 0.70 m relative to the resting position resulting in horizontal ball velocities of 2.0, 2.9, and 3.7 m/s, respectively. The horizontal distances from the ball at release height to the hand of the child was 0.87 m for the lowest velocity, 1.22 m for the moderate velocity, and 1.52 m for the fast velocity. The times of the ball flights (from release to ball-hand contact) were 625 ms, 655 ms, and 675 ms, respectively.

Data Capturing and Processing

Reflexive markers were attached to the nail of the index, the nail of the thumb, the processus styloideus of the ulna and the pendulum. Seven ProReflex cameras

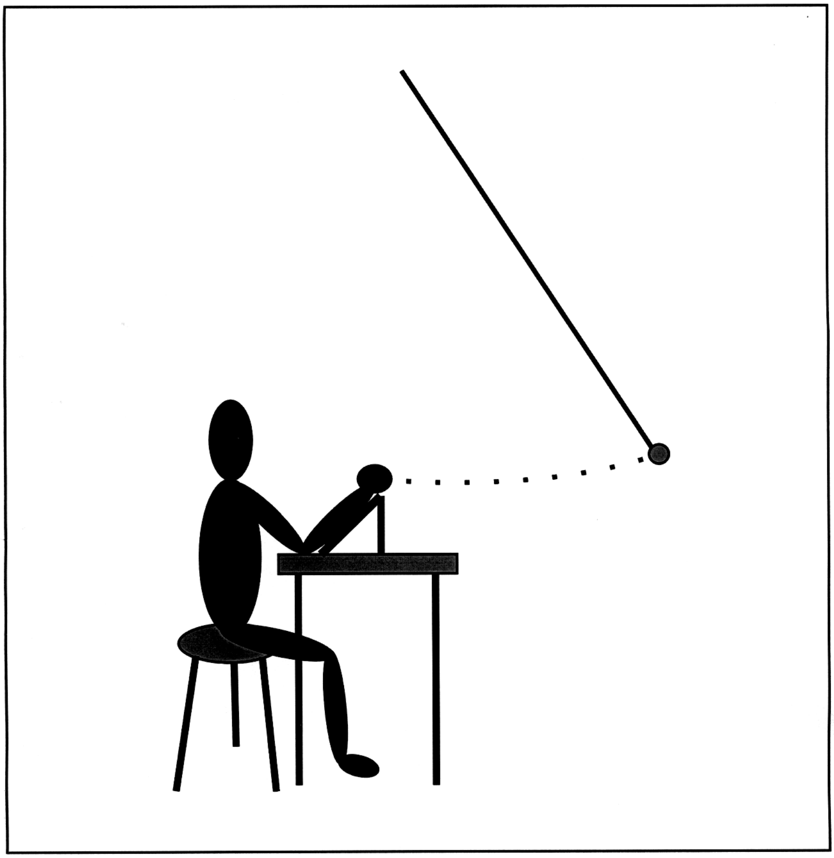

Figure 1 — Sagittal view of the experimental set up. See text for explanation.

(MCU 240), placed around the table, registered the positions of the fingers and the wrist and the trajectory of the ball. Sampling frequency was 240 Hz. Qualisys Track Manager software reconstructed the three dimensional trajectories of every marker. The raw data were exported to Excel and filtered with a lowpass Butterworth-filter at a cut-off frequency of 8 Hz before calculation of the velocity and acceleration profiles.

Testing Procedure

There were two identical test sessions with an interval of three weeks. In each test session kinematics of four fundamental movement skills (walking, jumping, throwing, and catching) were examined. Attention was paid to make the tasks attractive and fun and, if necessary, space for resting or distraction was given. The first session served as acclimatization, and only the data of the second test session were used for further analysis. The second test session started with the assessment of the MABC. All participants were assessed with the MABC by the researchers in accordance with the guidelines specified in the manual (Smits-Engelsman, 1998).

The catching procedure was separated into two conditions. The first condition contained only the slowest ball speed (2.0 m/s). The participant was told to make a clean one-handed catch of the ball. In a demonstration, the necessary instructions and advice were provided followed by two practice trials. If the tester observed that the boy did not carry out the task as expected, augmented feedback and one more practice trial was given. Then, six test trials were recorded.

After a short break, participants completed the second condition in which the adaptations to the varying task constraints were investigated. To avoid anticipation effects, ball velocity was randomized over trials. Before beginning this part, the child could practice catching the faster balls in two additional practice trials per speed (2.9 and 3.7 m/s). Finally, three blocks of six balls were released in a random order (with a maximum of two subsequent repetitions of the same ball speed) and with a rest of two min between blocks. A total of six trials per speed condition was recorded.

To ensure that the trials would be registered appropriately, a clear and consistent protocol was followed. Each trial was preceded by the following standard words by the tester behind the desktop: “Ok, *Aaron*, pay attention! Look to the ball carefully. Keep your hand ready. Let’s catch the ball!” After this, the tester in charge of the pendulum had 1 to 5 s to release the ball. After each trial, the tester or the parents congratulated or encouraged the participant. Prior to the test, instructions were given to the parents to stay positive during the whole test session so that the participant felt comfortable and relax. Anthropometric measures of the hand were obtained after the experiment.

Dependent Variables

The primary focus of this experiment was on the control processes during the catch rather than a comparison of performance scores. The pendulum system used in this experiment is useful to investigate the process of catching in different populations or conditions, even when no differences in performance scores (number of ball catches) are present (Estil et al., 2002; Savelsbergh, Whiting, & Bootsma, 1991). Therefore, performance scores are not discussed in detail. Overall, 3.5% of all trials resulted in a failure (3.7% in boys with DCD and 3.2% in typically developing boys), which was attributed to either a pendulum trajectory that did not project the ball exactly to the palm of the child’s hand, or to a moment of distraction of the child.

The temporal structure of the grasp movement was studied by means of four time variables. These temporal variables were measured relative to the time of ball-hand contact resulting in negative values (in milliseconds) for moments occurring before and positive values for moments after ball-hand contact. Ball-hand contact was defined as the moment that the acceleration curve became negative, e.g., the frame right after the ball reached its maximal velocity. The kinematic variables were derived from the hand aperture (in millimeters) and the velocity of finger opening-closing profiles (in millimeters/second).

Moment of Grasp Onset (T_{on}). This is the time at which the first movement of the fingers occurs, that is the point in time at which the finger opening velocity exceeded a velocity of 10 mm/s followed by a continuous increase in at least fifteen consecutive frames (63 ms).

Moment of Hand Closure (T_c). Time of hand closure is the time at which the closing of the fingers is initiated. It is determined as the moment of the last peak in the hand aperture diagram, before the final closing of the fingers.

Moment of Completion of the Catch (T_{end}). This is the moment at which the catch is completed, i.e., the moment of minimal thumb-index distance.

Total Movement Time (MT). This is the period of time from first finger movement until completion of the catch, that is the sum of $|T_{on}|$ and T_{end}.

Maximal Hand Aperture (D_{max}) and Relative Maximal Hand Aperture ($D_{max\text{-}rel}$). D_{max} is defined as the maximal 3-dimensional distance between thumb and index marker. $D_{max\text{-}rel}$ was calculated by dividing D_{max} by the length of the hand, measured from top of the middle finger to the center of the processus styloideus ulnaris (wrist).

Hand Aperture at Completion (D_{compl}). Hand aperture at completion is defined as the 3-dimensional distance between the marker of the index and thumb at the moment of completion.

Closing Distance. This is the distance that is covered by both fingers in the closing action of the hand. It is calculated as the difference between maximal hand aperture and the hand aperture at completion.

Maximal Closing Velocity (V_{max}). The velocity of the hand opening or closing was calculated as the first derivative of the thumb-index distance. Since closing of the fingers results in a decrease of the thumb-index distance, V_{max} is actually negative.

Data Analyses

The trials resulting in a failure were excluded from the analysis. A total of 208 catches for the boys with DCD and 209 catches for the boys without DCD were analyzed. For each participant and each condition, dependent variables of the six trials were averaged. In order to compare catching behavior in a stable and predictable condition a *t* test for independent measures was carried out to compare the means of the first condition. In order to evaluate the adaptive capabilities of both groups a 2 (group) × 3 (ball velocity) analysis of variance (ANOVA) with repeated measures on the last factor was used for comparison of the second condition. Post-hoc comparisons were conducted with an LSD-test. For all comparisons the alpha-level was set at $p < .05$. Effect size (ω^2) was calculated according to Vincent (1995).

Results

Analysis of the MABC subscores for ball skills revealed that all boys of the group with coordination problems scored below the 15th percentile, of which five scored below the 5th percentile. All the typically developing boys had subscores above the 15th percentile, indicating that ball handling skills of all participants of this group were in accordance with their age (Smits-Engelsman, 1998).

Analysis of the first condition revealed that boys with DCD initiated their grasp at the same time as the boys without DCD. This was also the case for the start of the closing action of the hand, the moment of hand closure (T_c). The typically developing boys completed their catch a 60 ms before the boys with DCD, $t(16) = 2.71$, $p < .05$, $\omega^2 = .30$. Total movement time, however, did not differ significantly. Maximal hand aperture fluctuated around 11 cm for both groups, which corresponded to 74% of the length of the hand on average for both groups. No differences were found for the hand opening at completion and the distance covered by the fingers either. Contrarily, a clear difference was found for the closing velocity profile where V_{max} was significantly smaller in the DCD-group $t(16) = 3.38$, $p < .01$, $\omega^2 = .40$. The results of these dependent variables are shown in Table 2.

Second, it was investigated whether both groups exhibited the same adaptations to the varying ball velocities. No significant interactions (group × velocity) or main group effects occurred for the moment of grasp onset and the moment of hand closure. Boys with DCD initiated hand opening and reached maximal hand aperture at about the same points in time as the typically developing boys. A significant group effect was found for T_{end}. Typically developing boys finished their catch on average 29 ms earlier than boys with DCD, $F(1, 16) = 5.56$, $p < .05$, $\omega^2 = .26$, though this did not result in a significantly longer movement time. Ball speed had no effect on the temporal pattern of the catch.

Table 2 Means (M) and Standard Deviations (SD) for all Dependent Variables for Boys With and Without DCD for Condition 1, Stable Ball Speed (2.0 m/s)

	Boys With DCD		**Boys Without DCD (typically developing)**	
Dependent variable	***M***	***SD***	***M***	***SD***
Moment of grasp onset (ms)	–238	41.8	–251	31.4
Moment of hand closure (ms)	– 74	37.9	– 57	23.0
Moment of completion (ms)	220*	56.3	160*	34.8
Total movement time (ms)	458	74.8	411	49.7
Maximal hand aperture (mm)	111	8.4	117	5.5
Relative maximal hand aperture (%)	72	5.6	76	6.4
Hand opening at completion (mm)	51	5.3	53	5.2
Closing distance (mm)	60	6.2	64	7.5
Maximal closing velocity (mm/s)	669*	65.3	808*	105.5

Note. Negative values refer to moments in time before ball-hand contact.

* $p < .05$

As far as concerns the kinematic variables, a significant difference was found for D_{max}, $F(1, 16) = 4.39$, $p = .05$, $\omega^2 = .20$. Maximal hand opening was almost 1 cm smaller in boys with DCD, but when D_{max} was scaled to the length of the hand, the difference disappeared. Hand opening at completion and the closing distance did not differentiate significantly between the groups. As in the first analysis, a main group effect was found for the maximal closing velocity, $F(1, 16) = 9.39$, $p < .01$, $\omega^2 = .49$. Peak velocity of boys with DCD was 16% lower in the slowest ball speed condition and 15% and 14% in the moderate and fast ball speed condition respectively (see Figure 2).

Ball velocity had no effect on D_{max} and $D_{max\text{-}rel}$ but affected hand opening at completion significantly so that the distance between the fingers at completion became smaller when ball speeds were higher, $F(2, 16) = 5.85$, $p < .01$, $\omega^2 = .29$. Post-hoc analysis revealed that D_{compl} at low ball speeds was larger than at moderate and fast ball speeds, while there was no difference between D_{compl} at moderate and fast ball speeds. Further, the closing distance increased with increasing ball speed as well, $F(2, 16) = 13.40$, $p < .001$, $\omega^2 = .75$. Similarly, peak closing velocity increased significantly with increasing ball speed, $F(2, 16) = 7.20$, $p < .01$, $\omega^2 = .38$ (see Figure 2). Post-hoc analysis revealed that V_{max} was larger in the high ball speed condition compared to both moderate and low ball speeds. Peak closing velocity did not differ between moderate and low ball speeds.

Significant interactions were absent for all these kinematic variables. All results of this second analysis are shown in Table 3.

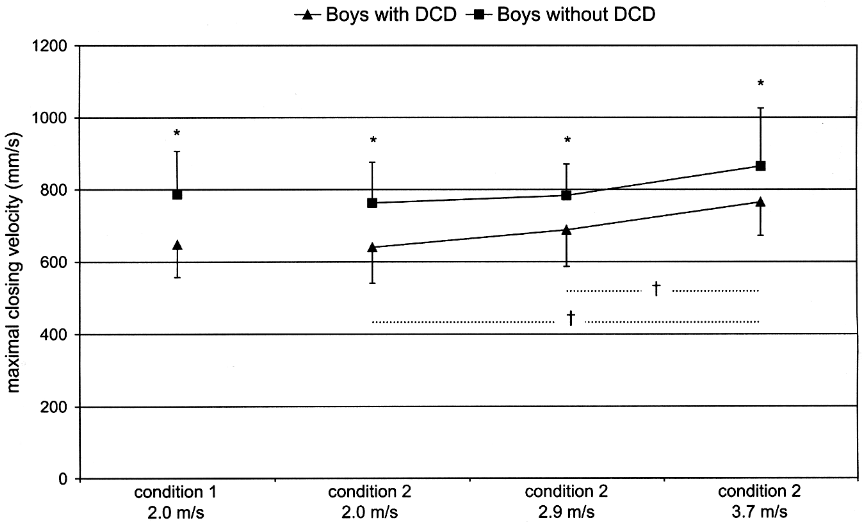

Figure 2 — Maximal closing velocity of the hand for both groups for condition 1 (stable ball speed) and 2 (varying ball speeds). Group differences ($p < .05$) are indicated with *. The effects of ball speed ($p < .01$) are indicated with †.

Table 3 Means (M) and Standard Deviations (SD) for all Dependent Variables for Boys With and Without DCD for Condition 2, Varying Ball Speeds (2.0 m/s, 2.9 m/s, 3.7 m/s)

	Boys With DCD						**Boys Without DC**					
	Ball Speed (m/s)						**Ball Speed (m/s)**					
	2.0		**2.9**		**3.7**		**2.0**		**2.9**		**3.7**	
Dependent variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Moment of grasp onset (ms)	–253	34.0	–259	43.0	–278	39.3	–265	39.5	–260	44.8	–278	45.3
Moment of hand closure (ms)	– 92	39.3	– 90	52.6	– 82	43.5	– 96	40.9	– 60	22.8	– 57	18.0
Moment of completion (ms)	188*	70.5	163*	31.8	186*	25.4	152*	35.4	147*	18.8	151*	26.5
Total movement time (ms)	440	73.8	423	44.4	464	57.8	417	39.9	408	58.4	428	57.1
Maximal hand aperture (ms)	109*	7.6	109*	9.0	111*	7.7	116*	5.5	116*	6.9	117*	5.1
Relative maximal hand aperture %	70	5.7	70	6.1	72	6.7	76	8.0	76	7.9	77	7.3
Hand opening at completion (mm)	52†	6.6	49†	4.3	47	5.0	54†	4.5	51†	5.6	49	5.3
Closing distance (mm)	57†	7.0	60†	6.7	64†	9.0	62†	6.4	64†	7.7	68†	7.8
Maximal closing velocity (mm/s)	646*,†	103.3	674*,†	95.5	756*,†	93.3	770*,†	116.4	790*,†	88.7	880*,†	112.6

Note. Negative values refer to moments in time before ball-hand contact.
† indicates a ball speed effect at the level $p < .01$
* indicates a group effect at the level $p < .05$

Discussion

The first purpose of this study was to identify differences in the control of catching between boys with and without DCD. Contrary to the proposed hypothesis, boys with DCD did not show a different temporal structure of the catch, except for the duration of the grip phase in both catching conditions. However, maximal closing velocity was consistently faster for boys without DCD. The second purpose was to determine whether boys with impaired motor coordination adapted differently to changing task constraints. We expected that the temporal structure of the catch of boys with DCD under this increased task constraints would be even more disrupted. It was found that both groups showed similar adaptations to varying task constraints, with no changes in the temporal control, but distinct changes in peak closing velocity.

The temporal structure of a simple catching task before ball-hand contact did not differ between boys with and without coordination problems. Difference in the moment of movement onset and the moment of hand closure were absent. This is in contrast to Estil et al. (2002), who found boys with DCD to initiate their movement earlier in compensation to the temporal uncertainty exhibited by this group. In this respect, the present results do not provide supporting evidence for this compensation-strategy. Our findings do not support the hypothesis of slower information uptake and processing suggested by Bairstow and Laszlo (1989) and Henderson et al. (1992) either, since there were no differences between the groups in time needed to initiate the movement. The contrast with the results of Estil et al. (2002) may be explained by the fact that the time of the ball flight was considerably shorter in the present study (± 650 ms vs. 1025 ms). Under these conditions, a latency time (i.e., the time span from ball release to movement initiation) similar to that of the children of the control group in Estil et al. (2002; i.e., 651 ms) would have prevented the typically developing boys of the present study from catching the ball. In addition, as the temporal constraints were so demanding in all speed conditions, the latency times of the present study reflect a reaction time rather than a time span in which participants have the possibility to wait and choose their moment of initiation. This may be an explanation for the finding that the latency times of the present study are shorter and lean more toward the values of the group with coordination problems of the study of Estil et al. (2002). Apparently, making the task constraints more challenging made the groups behave similarly in terms of temporal control.

The temporal variables, in particular the moments of movement onset and hand closure, do not seem to depend on ball velocity for either group. According to Laurent, Montagne, and Savelsbergh (1994), some minor time shifts were expected in the moment of onset, but the differences in flight duration of the balls at the three velocities were probably too small to cause a similar effect. The only adaptation to the changing ball speeds occurred in the maximal closing velocity. In a study by van der Kamp (1999) where adults had to catch balls at different velocities in a similar set up, such an increase in maximal closing velocity was also observed. He suggested that the maximal opening and closing velocity may be regulated by the rate of change of the relative rate of constriction of the gap between the ball and the hand. Consequently, a greater approaching speed of the ball causes a higher peak movement velocity of the hand. The smaller hand opening at completion and the greater distance covered when balls came faster can be a result of this higher movement velocity.

The finding that boys with DCD adapt to the varying conditions and that the adaptation resembles that of typically developing boys contradicts earlier findings of Geuze et al. (1990). They found that children with DCD performed worse when asked to adjust their behavior to varying external task demands. However, the task in that study consisted of continuous tapping and accommodating the tapping rate to an auditive stimulus. In the discrete catching task presented in the current study, it appeared that boys did tune their behavior to the visual information provided by the upcoming ball. This leads to the conclusion that the adaptive capacity of boys with DCD is task specific. Moreover, it indicates that boys with DCD do not lack the capacity to adequately use the visuo-perceptual information of the environment and adjust their behavior dependent on the nature of that information.

While the adaptations to the changing ball speeds were similar for both groups, some of the kinematic variables differed between the boys with DCD and the boys without DCD. A first finding is that boys with DCD seem to open their hand less than boys in the comparison group in the preparation of a catch. Inspection of Table 1 reveals that this result was not simply caused by a difference in hand length between the two groups. Though when this maximal hand aperture was measured relative to the length of the hand, this difference was eliminated. In addition, the smaller maximal hand aperture of the boys with DCD did not result in a significant shorter distance covered during the closing action. Apparently, the difference found in the maximal hand aperture was too subtle to cause effects in a later stage of the catch. A more distinct kinematic group difference was found for the maximal closing velocity of the hand, which was consistently slower in boys with DCD.

This smaller maximal hand aperture and slower maximal closing velocity for boys with DCD, both in the stable and predictable context (condition 1) and in the condition of varying ball speeds (condition 2), together with the absence of temporal differences and the similar adaptations to the changing ball speeds, tend to indicate a difference at the level of task execution, rather than at the level of planning or information processing. In other words, boys with DCD seem to know how to control the timing of the catching movement, but they fail to apply this correctly. This subtle difference in execution was not strong enough to cause a difference in the output score of this constrained catching task, though it indicates a disparity at the functional level that can be harmful in a more open catching task, as can be observed in the subscores for ball handling of the MABC of the boys with DCD.

An explanation for the smaller maximal hand aperture may be found in the previously cited dysfunction at the neuromuscular level (Williams et al., 1983; Williams & Castro, 1997). According to Wilson and Trombly (1984), exaggerated co-contraction leads to tiring and stiff fixation of the joints. Similar inferences were made in timing studies of Lundy-Ekman et al. (1992) and Piek and Skinner (1999), however without empirical data on the neuromuscular control (EMG). In these studies, the inconsistency in force amplitude and longer contact intervals in a simple tapping task manifested by children with DCD was suggested to originate in a disturbed cooperation of the agonist and antagonist muscles. In support of this possibility, Huh et al. (1998) suggested that faster movements of children with normal neuromotor development in a bilateral aiming task may be the result of a more efficient activation strategy of the agonist and antagonist muscle contractions.

From this point of view, it could be that the observed similar temporal pattern in our study is the result of a normal muscle activation pattern for initiation of the movement and the closure (Savelsbergh, Whiting, Burden, & Bartlett, 1992). However, an incorrect timing (too early) or level of activation (too high) of antagonist muscles could have prevented boys with DCD to reach a similar maximal hand aperture. In this respect, the smaller maximal closing velocity found in this study may be linked to the hypothesis, assuming that children with DCD show an increased level of coactivation, as found by Raynor (2001); however, this hypothesis cannot be supported by empirical evidence and warrants further research with the use of EMG instrumentation.

In conclusion, boys with DCD did not show significant differences in the timing of the moments of grasp onset and hand closure in a simple one-handed catching task with boys without DCD apart from a longer grip phase. Their adaptations to the changing environmental constraints are similar to those of the typically developing boys, but they fail to achieve a maximal hand opening and peak closing velocity as high as their age matched peers. These results lead to the suggestion that coordination problems of a simple one-handed catch for boys with DCD are situated more at the level of execution than at the level of information processing or planning. With regard to the teaching of catching, these findings indicate that simplifying the task by reducing the spatial and postural constraints increases the chance for success. Therefore, a simplified catching task similar to the one used in the present study can serve to initiate the teaching process, followed by a gradual increase of the spatial and postural requirements.

References

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: Author.

Bairstow, P.J., & Laszlo, J.I. (1989). Deficits in the planning, control and recall of hand movements in children with perceptuo-motor dysfunction. *British Journal of Developmental Psychology*, **7**, 151-273.

Brusselmans-Dehairs, C., Valcke, M., Van Damme, J., Van de Gaer, E., Van den Broeck, A., & Opdenakker, M. (2002). *Vlaanderen in TIMSS* (Flanders in the Third International Mathematics and Science Study). Brussels: Ministerie van de Vlaamse Gemeenschap.

Estil, L.B., Ingvaldsen, R.P., & Whiting, H.T.A. (2002). Spatial and temporal constraints on performance in children with movement coordination problems. *Experimental Brain Research*, **147**, 154-161.

Fischman, M.G., Moore, J.B., & Steele, K.H. (1992). Children's one-hand catching as a function of age, gender, and ball location. *Research Quarterly for Exercise and Sport*, **63**, 349-355.

Geuze, R. H. (1990). Variability of performance and adaptations to changing task demands in clumsy children. In A.F. Kalverboer (Ed.), *Developmental biopsychology: Experimental and observational studies in children at risk* (pp. 207-222). Ann Arbor: University of Michigan Press.

Geuze, R.H., Jongmans, M.J., Schoemaker, M.M., & Smits-Engelsman, B.C.M. (2001) Clinical and research diagnostic criteria for developmental coordination disorder: A review and discussion. *Human Movement Science*, **20**, 7-47.

Geuze, R.H., & Kalverboer, A.F. (1994). Tapping a rhythm: A problem of timing for children who are clumsy and dyslexic. *Adapted Physical Activity Quarterly*, **11**, 203-213.

Gillberg, C. (2003). Deficits in attention, motor control, and perception: A brief review. *Arch Dis Child,* **88**, 904-910.

Henderson, S. E., Barnett, A., & Henderson, L. (1994). Visuospatial difficulties and clumsiness: On the interpretation of conjoined deficits. *Journal of Child Psychology and Psychiatry*, **35**, 961-969.

Henderson, L., Rose, P., & Henderson, S. (1992). Reaction time and movement time in children with Developmental Coordination Disorder. *Journal of Child Psychology and Psychiatry*, **33**, 895-905.

Henderson, S.E., & Sugden, D.A. (1992). *Movement Assessment Battery for Children: Manual*. London: The Psychological Corporation.

Huh, J., Williams, H.G., & Burke J.R. (1998). Development of bilateral motor control in children with Developmental Coordination Disorders. *Developmental Medicine and Child Neurology*, **40**, 474-484.

Ivry, R., & Keele, S. W. (1989). Timing functions of the cerebellum. *Journal of Neurophysiology*, **52**, 305-322.

Larkin, D., & Hoare, D. (1991). *Out of step*. Perth, Western Australia: Active Life Foundation.

Laszlo, J.I., Bairstow, P.J., Bartrip, J., & Rolfe, U.T. (1988). Clumsiness or perceptuo-motor dysfunction? In A.M. Colley & J.R. Beech (Eds.), *Cognition and action in skilled behaviour* (pp. 293-309). Amsterdam: Elsevier.

Laurent, M., Montagne, G., Savelsbergh, G.J.P. (1994). The control and coordination of one handed catching: The effect of temporal constraints. *Experimental Brain Research*, **101**, 314-322.

Lefebvre, C., & Reid, G. (1998). Prediction in ball catching by children with and with Developmental Coordination Disorder. *Adapted Physical Activity Quarterly*, **15**, 299-315.

Lord, R., & Hulme, C. (1987). Perceptual judgements of normal and clumsy children. *Developmental Medicine and Child Neurology*, **29**, 250-257.

Lundy-Ekman, L., Ivry, R., Keele, S., & Woollacott, M. (1991). Timing and force control deficits in clumsy children. *Journal of Cognitive Neuroscience*, **3**, 367-376.

Piek, J. P., & Skinner, R. A. (1999). Timing and force control during a sequential tapping task in children with and without motor coordination problems. *Journal of the International Neuropsychological Society*, **5**, 320-329.

Raynor, A. J. (2001). Strength, power, and coactivation in children with Developmental Coordination Disorder. *Developmental Medicine and Child Neurology*, **43**, 676-684.

Savelsbergh, G.J.P., Rosengren, K., van der Kamp, J., & Verheul, M. (2003). Catching action development. In G.J.P. Savelsbergh, K. Davids, J. van der Kamp, S.J. Bennet (Eds.), *Development of movement co-ordination in children* (pp. 191-212). London: Routledge.

Savelsbergh, G.J.P., Whiting, H.T.A., & Bootsma, R.J. (1991). Grasping Tau. *Journal of Experimental Psychology: Human Perception and Performance*, **17**, 315-322.

Savelsbergh, G.J.P., Whiting, H.T.A., Burden, A.M., Bartlett, R.M. (1992). The role of predictive visual temporal infromation in the coordination of muscle activity in catching. *Experimental Brain Research*, **89**, 223-228.

Schoemaker, M. M., van der Wees, M., Flapper, B., Verheij-Jansen, N., Scholters-Jaegers, S., & Geuze, R. H. (2001). Perceptual skills of children with Developmental Coordination Disorder. *Human Movement Science*, **20**, 111-133.

Sigmundsson, H., Ingvaldsen, R. P., & Whiting, H. T. A. (1997). Inter- and intra-sensory modality matching in children with hand-eye coordination problems. *Experimental Brain Research*, **114**, 492-499.

Sigmundsson, H., Whiting, H.T.A., & Ingvaldsen, R.P. (1999). Proximal versus distal control in proprioceptively guided movements of motor impaired children. *Behavioural Brain Research*, **106**, 47-54.

Smits-Engelsman, B.C.M. (1998). *Movement assessment battery for children: Handleiding*. Lisse, The Netherlands: Swets.

Smyth, M.M., & Mason, U.C. (1997). Planning and execution of action in children with and without Developmental Coordination Disorder. *Journal of Child Psychology Psychiatry*, **38**, 1023-1037.

van der Kamp, J. (1999). The *information-based regulation of interceptive timing* (Doctoral Dissertation). Nieuwegein, The Netherlands: Digital Printing Partners Utrecht.

van der Meulen, J.H.P., Denier van de Gon, J.J., Gielen, C.C.A.M., Gooskens, R.H.J.M., & Willemse, J. (1991a). Visuomotor performance of normal and clumsy children. I: Fast goal-directed arm-movements with and without visual feedback. *Developmental Medicine and Child Neurology*, **33**, 40-54.

van der Meulen, J.H.P., Denier van de Gon, J.J., Gielen, C.C.A.M., Gooskens, R.H.J.M., & Willemse, J. (1991b). Visuomotor performance of normal and clumsy children. II: Arm-tracking with and without visual feedback. *Developmental Medicine and Child Neurology*, **33**, 118-129.

Van Waelvelde, H., De Weerdt, W., De Cock, P., Peersman, W., & Smits-Engelsman, B.C.M. (2004). Ball catching performance in children with Developmental Coordination Disorder. *Adapted Physical Activity Quarterly*, **21**, 348-363.

Vincent, W.J. (1995). *Statistics in kinesiology*. Champaign, IL: Human Kinetics.

Volman, M.J.M., & Geuze, R.H. (1998). Relative phase stability of bimanual and visuomanual rhythmic coordination patterns in children with Developmental Coordination Disorder. *Human Movevement Science*, **17**, 541-572.

von Hofsten, C. (1983). Catching skills in infancy. *Journal Experimental Psychology: Human Perception Performance*, **9**, 75-85.

Williams, H.G. (2002). Motor control in children with Developmental Coordination Disorder. In S.A. Cermak & D. Larkin (Eds.), *Developmental coordination disorder* (pp. 117-137). Albany, NY: Delmar.

Williams, H.G., & Castro, A. (1997). Timing and force characteristics of muscle activity: Postural control in children with and without developmental coordination disorders. *Australian Educational and Developmental Psychologist*, **14**, 43-54.

Williams, H.G., Fisher, J., & Tritschler, M. (1983). Descriptive analysis of static postural control in 4-, 6-, and 8-year old motorically awkward children. *American Journal of Physical Medicine*, **62**, 12-26.

Williams, H.G., Woollacott, M.H., & Ivry, R. (1992). Timing and motor control in clumsy children. *Journal of Motor Behavior*, **24**, 165-172.

Wilson, B., & Trombly, C. (1984). Proximal and distal function in children with and without sensory integrative dysfunction: An EMG study. *Canadian Journal of Occupational Therapy*, **51**, 11-17.

Wilson, P. H., & McKenzie, B. E. (1998). Information processing deficits associated with Developmental Coordination Disorder: A meta-analysis of research findings. *Journal of Child Psychology Psychiatry*, **39**, 829-840.

Acknowledgments

This research project was supported by a grant form Ghent University (BOF 01112902). We would like to thank all the children, their parents, COS Ghent, the physical therapists and the graduate students for their contribution to this study.