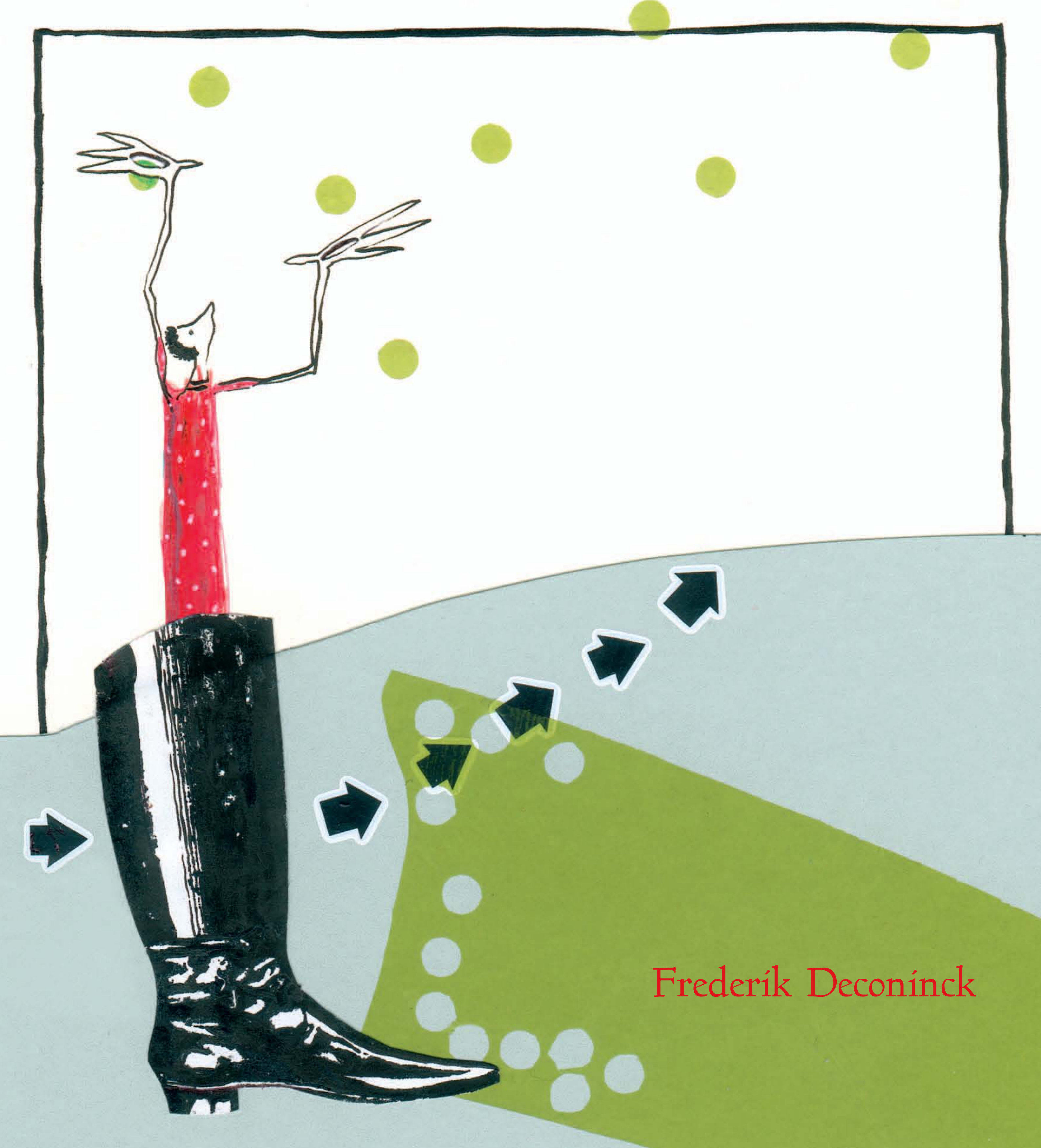

Frederik Deconinck

Kinematics of Developmental Coordination Disorder

Motor control of functional movement skills

UNIVERSITEIT GENT

Faculty of Medicine and Health Sciences
Department of Movement and Sports Sciences

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Frederik Deconinck

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Gent 2005

Supervisor

prof. dr. M. Lenior (UGent)

Co-supervisor

prof. dr. D. De Clercq (UGent)

Process supervisory board

prof. dr. M. Lenoir (UGent)
prof. dr. D. De Clercq (UGent)
prof. dr. G.J.P. Savelsbergh (VU Amsterdam, Manchester Metropolitan University)
prof. dr. R. Van Coster (UGent)
dr. A. Oostra (Centrum voor Ontwikkelingsstoornissen Gent)
lic. G. Dewitte (Centrum voor Ontwikkelingsstoornissen Gent)

Examination board

prof. dr. D. Cambier (UGent)
prof. dr. G. Cardon (UGent)
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prof. dr. B.C.M. Smits-Engelsman (Avans+ Breda, KULeuven, UMC St Radboud Nijmegen)
prof. dr. M. Lenoir (UGent)
prof. dr. D. De Clercq (UGent)
prof. dr. G.J.P. Savelsbergh (VU Amsterdam, Manchester Metropolitan University)
prof. dr. R. Van Coster (UGent)
dr. A. Oostra (Centrum voor Ontwikkelingsstoornissen Gent)

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CONTENTS

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Wetenschap is iets vreemd. Het gaat om weten, maar misschien nog meer om niet weten, om verwondering. Meeslepende fascinatie. Die verwondering over coördinatie en controle van beweging, over het verschil tussen motorische vaardigheid en onhandigheid, houdt me sinds vier jaar in haar greep. De voorbije vier jaar heb ik de kans gekregen om een kleine bijdrage te leveren aan de studie van beweging. Heel veel mensen hebben mij hierbij geholpen of gesteund. Tijd voor een dankjewel.

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je bracht me een zee
van ontspanning
en plezier - je deelde mee
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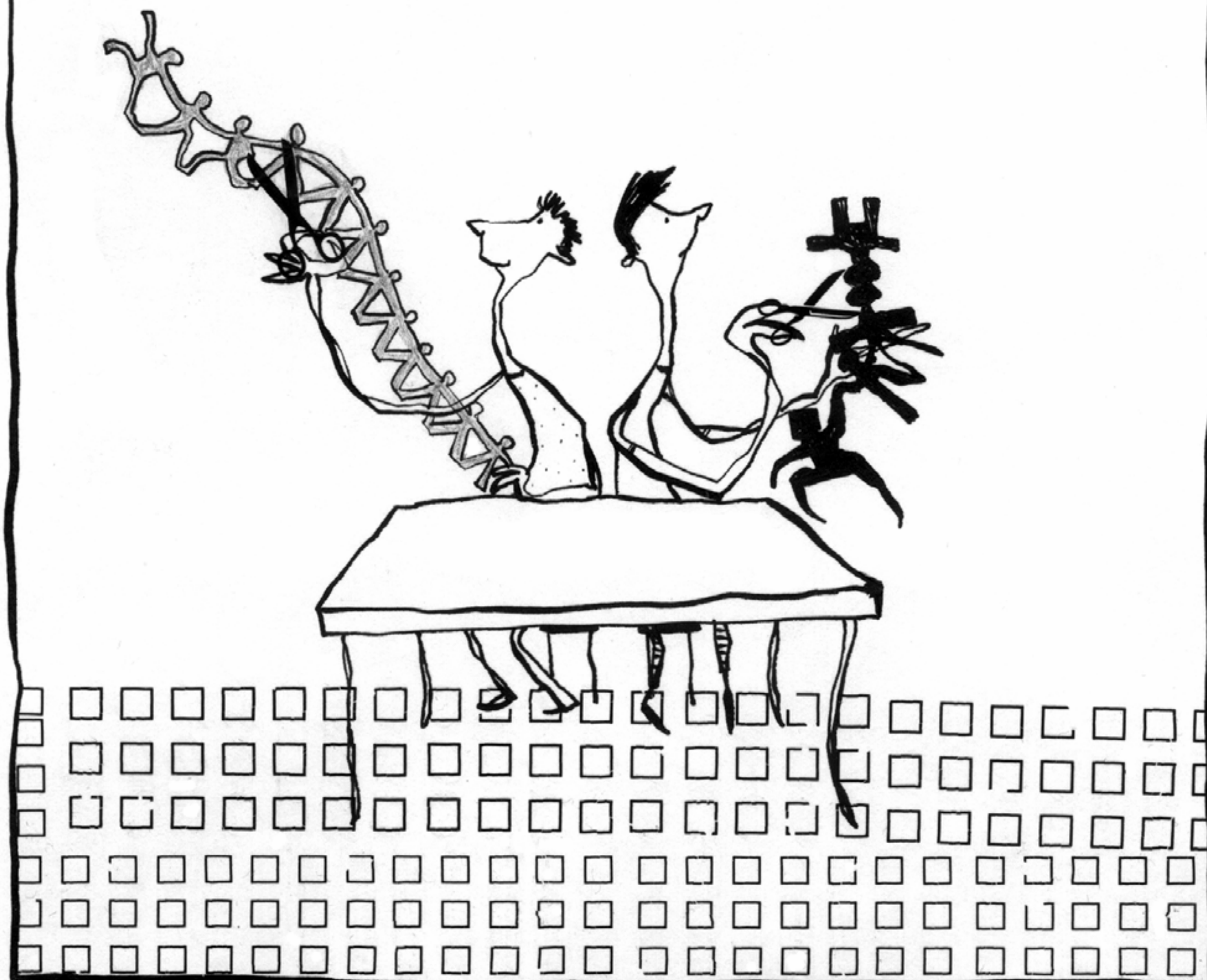
Frederik

december 2005

CHAPTER 1

GENERAL INTRODUCTION



1. Background

It is fascinating to see how a little newborn child, whose movement repertoire is ruled by basic reflexes, develops to a human being and step by step acquires all possible motor skills that enable him or her to master a broad spectrum of movement skills. This evolution takes place with such an ease that it is sometimes even more surprising when a school-aged child, without medical, behavioral or intellectual impairment, still is unable to perform fluent and goal-oriented movements. The movements of these children are aptly described as wooden, awkward or clumsy, because they seem to fail to coordinate the different components of the motor system to each other and to the task requirements. In the words of Bernstein: They do not succeed to master their redundant degrees of freedom into a controllable system (Bernstein 1967). Their lack of coordination prevents them of displaying skilled behavior in daily motor activities such as writing, reaching, throwing, catching and so forth.

This could be the end of the story and one could easily resign oneself to the wide diversity in movement performance and call upon the statistical knowledge that 'skilled' and 'clumsy' just represent the two extremities of a normal bell-shaped distribution. However, it has been shown that the coordination problems of children as described above constitute an undeniable and probably separable disorder of movement skill acquisition that cannot be ignored, even when no medical condition can explain the source of the impairments (Henderson and Barnett 1998). Already back in the early sixties scientists and physicians realized that failure to recognize similar problems may lead to aggravation of the symptoms and so to various behavioral problems in later life (British Medical Journal 1962). These findings resulted in an increase of diagnostic, etiological, and remedial attention in the past 30 years.

2. Diagnosis: Developmental Coordination Disorder (DCD)

Although there seems to be agreement concerning the seriousness of the disorder, various theoretical approaches and different opinions with regard to the underlying mechanisms gave rise to a long-lasting terminology debate. As a result several terms have cropped up, some based upon the explicit manifestation of the disorder, such as 'physical awkwardness' (Wall et al., 1990), others referring to the assumed underlying mechanisms, such as 'sensory-integrative dysfunction' (Ayers 1972). Today the disorder is formally recognized by the American Psychiatric Association (APA) as well as by the World Health Organization (WHO) resulting in two different designations: Developmental Coordination Disorder (DCD; APA 1994) and Specific Developmental Disorder of Motor Function (SDD-MF; WHO 1992). Given the uncertainty about possible underlying mechanisms and the huge heterogeneity associated with the disorder, the main message of the continuing debate on terminology is that no single label or perspective can embrace the whole picture of the disorder. However, as a result of a consensus meeting held in 1994 (Polatajko et al. 1995) and stimulated by renowned researchers in the field, the term DCD is now most commonly used in scientific literature (Henderson and Barnett 1998; Henderson and Henderson 2002). The following citation aptly describes why this term is preferable.

> *"Given our implacable hostility to the association of the developmental disorder with those acquired disorders referred to as apraxias, our approval of the term coordination as a descriptor of the processing demands of movement control at various hierarchical levels and the eschewal of the problematic notion of specificity, we have no alternative but to endorse the label DCD." (Henderson and Henderson 2002)*

According to DSM-IV (APA, 1994) four criteria must be fulfilled in order to diagnose a child with DCD:

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 delay in achieving motor milestones (for example walking, crawling, sitting), dropping things, 'clumsiness', poor performance in sports, or poor hand writing.
B. The disturbance in Criterion A significantly interferes with academic achievement or activities in daily living.
C. The disturbance is not due to a general medical condition (for example cerebral palsy, hemiplegia, or muscular dystrophy) and does not meet the criteria for a Pervasive Developmental Disorder.
D. If mental retardation is present the motor difficulties are in excess of those usually associated with it.

The recognition of the disorder and the entry into DSM-IV (APA 1994) have helped to raise the profile of DCD, yet the qualitative nature of these two inclusion and two exclusion criteria for DCD often leads to uncertainty about how to put them into practice. According to Geuze et al. (2001), these qualitative descriptions have the advantage of allowing the criteria to be matched to the individual circumstances of the child and to the specific research goals, but still they complicate formal diagnosis. Thus, to enable and facilitate comparison and communication in clinical practice as well as scientific literature a certain degree of commonality is necessary and this requires some quantification.

An elaborate discussion on this topic by Henderson and Barnett (1998) and an extensive review of the use of the four criteria in DCD research by Geuze et al. (2001) yielded a number of recommendations regarding the diagnostic process. The absence of a gold standard with respect to motor functioning in activities of daily living complicates the assessment of motor coordination and forces to use standardized motor tests. None of the available tests enjoys the status of gold standard, but the Movement Assessment Battery for Children (MABC; Henderson and Sugden 1992) is widely used in clinical and scientific practice. It covers a broad range of motor skills and is particularly designed to identify children with coordination difficulties. Cut-off values of percentile 15 (-1 SD) or 5 (-1.65 SD) are proposed for clinical practice or research purposes respectively. Criterion B, which is directly related to criterion A, is difficult to objectify and to put into practice, since it is highly dependent on the individual situation of the child. In most research studies referral for treatment is taken as the prime indicator for interference of the movement problems with academic achievement or the activities of daily living. With regard to criterion C, the technological advances in brain imaging paradoxically enough complicate the diagnosis of DCD. Since Jongmans et al. (1993) found that DCD at school age might be associated with small but transient brain lesions at birth, the question arises as to what actually involves a medical condition. The high prevalence of soft neurological signs in children with DCD further supports the notion that DCD might be diagnosed as an extremely mild form of cerebral palsy (CP; Hadders-Algra 2000). From this perspective, it should be acknowledged that some neurological malfunctioning may be associated with DCD, but in cases were an overt medical condition can be assessed the diagnosis of DCD should be ruled out. Criterion D, finally, is implicitly present in the first criterion, where reference is made to ‘the chronological age’. Because of the unclear relationship between mental retardation (MR) and motor development Geuze et al. (2001) argue that this criterion is rather superfluous. This, however, does not preclude the possibility of co-occurrence of MR and DCD.

In sum, given the absence of a distinct medical condition and the uncertainty about the underlying factors clinicians have to rely on the qualitative criteria of DSM-IV in order to diagnose children with coordination problems. These criteria leave room for interpretation which allows that the diagnosis can be suited to individual circumstances. On the other hand they may hamper comparability and communication in clinical as well as in scientific practice. Therefore, the diagnostic process of children referred for motor problems without obvious medical explanation, requires a multidisciplinary team of specialists and a wide range of assessments including motor tests, intelligence profiles, and evaluation of the quality of activities of daily living.

3. Prevalence and outcome

The current prevalence of DCD, estimated on the basis of the above cited criteria, is as high as 6 % of all 5- to 11-years-old children (APA 1994). Over the years, a large variation of figures ranging up to 15.6% (Wright et al. 1994) has been reported, mostly depending on the modes of assessment and the use of different cut-off points. In line with the overrepresentation of boys in almost all developmental disorders, boys are diagnosed with DCD more than girls (2:1). This might be attributed cultural and genetic factors (Kadesjö and Gillberg 1998), although the true mechanism for this phenomenon still remains to be determined.

At present it is commonly recognized that children with DCD will not spontaneously ‘grow out’. Numerous studies have shown that the problems are very likely to persist into adolescence and adulthood (e.g. Cousins et al. 2003; Losse et al. 1991). Moreover, the motor problems of children with DCD have been shown to place them at an increased risk of developing psychosocial problems, which may continue to affect them when they grow older (Cantell et al. 1994). The inability to successfully participate in sports and games because of impaired motor skills, often leads to exclusion and ridicule in the playground (Smyth and Anderson 2000). This in turn, may negatively affect self-esteem and can result in higher levels of anxiety and other negative psychological and emotional outcomes (Schoemaker and Kalverboer 1994; Skinner and Piek 2001). In addition, because of their motor inability and the associated lack of confidence in their physical competences children with DCD are less inclined to participate in organized or recreational physical activity (Bouffard et al. 1996). This relatively inactive lifestyle compromises the development of physical fitness and frequently leads to overweight and obesity (Cairney et al. 2005) which puts children with coordination problems at a greater risk of developing cardiovascular diseases (Harsha 1995; Vaccaro and Mahon 1989), diabetes (Weill et al. 2004) or musculo-skeletal problems (Bailey and Martin 1994; Sothern et al. 1999).

Overall, the coordination problems experienced by children with DCD have far-reaching effects at different levels. Not only do they hamper the children with the execution of everyday motor activities, they also hinder them to be physically active and further restrict participation in social activities. Consequently, specialized and multidisciplinary attention is necessary in order to reduce the coordination difficulties, to provide the children strategies to cope with their difficulties and to avoid or diminish long-term effects.

4. Heterogeneity and comorbidity

The previous mentioned complexity of the diagnosis of DCD is further complicated by the variable picture of DCD. There are children with DCD where the problems are confined to fine motor skills, such as fluently writing, tying shoe laces, or properly eating with knife and fork. Others suffer mainly from gross motor deficits manifested in for example problematic ball catching, uncoordinated locomotor skills or the inability to perform a nice soccer kick. The most severely affected children with DCD display deficits in fine as well as gross motor skills. Every child is unique and this also applies to children with DCD, leading to a very heterogeneous picture. This commonly observed heterogeneity inspired several researchers to search for subtypes of DCD with the ultimate goal to find more specific evidence with regard to the etiology and to provide clues for effective therapeutic intervention (Hoare 1994; Macnab et al. 2001; Miyahara 1994; Wright and Sugden 1996).

Apart from their movement coordination problems, some children with DCD also exhibit symptoms of other developmental disorders such as attention deficit/hyperactivity disorder (ADHD), learning disabilities (LD) or autism (Jongmans et al. 2003; Kadesjö and Gillberg 1998; Piek and Dyck 2004). Developmental disorders appear to be typically comorbid and the frequent co-occurrence of inattention, hyperactivity, and motor control deficits even prompts Gillberg to use the concept of

DAMP, i.e. deficits in attention, motor control, and perception, in the case of concomitant DCD and ADHD (Gillberg 2003; Kadesjö and Gillberg 1998). According to Kaplan et al. (1998) the finding that co-morbidity seems to be the rule rather than the exception is indicative for a generalized neurodevelopmental disorder that stems from a putative disruption of early brain development of which the manifestation depends on the site and the extent of the damaged neural substrate. Indeed, DCD appears to have some pathophysiological similarities with other developmental disorders. Despite this common link however, there is evidence that the movement problems of children with DCD differ from those in children with LD (Jongmans et al. 2003), ADHD, or autism (Piek and Dyck 2004), suggesting slight differences in the way common putative neurophysiological deficiencies are expressed.

5. Underlying mechanisms – Etiology

The absence of an overt medical explanation for DCD incited several researchers to examine perceptual or cognitive processes contributing to organization of the movement. A considerable amount of these information processing studies, which attempt to identify deficits in the registration, interpretation and integration of sensory cues preceding a motor response, has been reviewed extensively by Wilson and McKenzie (1998). Their meta-analysis confirmed the earlier findings of Lord and Hulme (1988) that motor impairment often is associated with visuo-spatial deficits. Also kinesthetic perception (e.g. Bairstow and Laszlo 1981; Smyth and Mason 1998) and cross-modal perceptual integration (e.g. Mon-Williams et al. 1999; Sigmundsson et al. 1997) were found to be inferior in children with DCD. However, caution should be paid when interpreting these results because a conjoined incidence of motor impairment and similar deficits may not be mistaken for a causal relationship (Henderson et al. 1994; Van Waelvelde et al. 2004). Besides, it should be mentioned that several studies suggest that often not the uptake of perceptual information for movement control is the main problem. Possibly, the problem of children with DCD might be related more to their propensity to depend on feedback control, necessitating continuous perceptual monitoring, rather than to use a more mature, anticipatory control strategy (Rösblad and von Hofsten 1994; Smits-Engelsman et al. 2003; van der Meulen et al. 1991a, 1991b).

With regard to the study of the motor control aspects of children with DCD, a lot of attention has been paid to deficiencies in timing. Using aiming and tapping tasks children with DCD were found to have slower and more variable reaction times (Henderson et al. 1992; Huh et al. 1998). Further, they displayed less consistent rhythmic sequences and decreased adaptation to the task demands when performing either self-paced or metronome-paced repetitive tapping (Geuze and Kalverboer 1987; Williams et al. 1992). This poor timing performance, together with inferior perception of time intervals might point toward a potential general timing deficit that cuts across both sensory and motor functions of the nervous system. The poor timing control has also been linked to deficits at neuromuscular level, in particular to a perturbed control of intermuscular coordination and co-activation problems, resulting in lower levels of maximal strength and power in a knee flexion-extension task (Lundy-Ekman et al. 1991; Piek and Skinner 1999; Raynor 2001).

At several instances the above cited disturbances in perceptual processes and motor control have been related to different kinds of deficiencies at the level of the central nervous system. In this respect, Sigmundsson and co-workers suggested that the inter- and intramodal sensory difficulties of children with hand-eye coordination problems might be attributed to a left- or right-hemisphere insufficiency (dependent on the dexterity of the child) associated with a dysfunctional corpus callosum (Sigmundsson et al. 1999). Further, decreased sensitivity to visually presented motion and form patterns of clumsy children was suggestive for deficits in the ventral (occipito-temporal) and the dorsal (occipito-parietal) stream for processing visual information (Sigmundsson et al. 2003). Variable timing intervals and problems with time perception have been ascribed to cerebellar signs, while distorted functioning of the basal ganglia is assumed to be responsible for poor force control (Lundy-Ekman et al. 1991). On the other hand, according to Wilson and colleagues the basal ganglia appear to function well with regard to procedural learning. They believe that the neurocognitive underpinnings of DCD are more likely to be located at a parietal cortical level (Wilson et al. 2003). Overall, given the inconsistency in these findings and the complexity at the basis of the perceptuo-motor system, a simple mapping between a finite neural pathology and the motor impairment seems very implausible. Besides, research investigating the exact nature of these underlying processes is complicated by the huge heterogeneity of DCD and the overlap with other developmental disorders.

Insight in the variability of the patterns of motor difficulties of children with DCD is a prerequisite to better understand the nature of the disorder and therefore essential to comprehend the underlying mechanisms. So far, the knowledge of the heterogeneity of the picture of DCD is predominantly based on qualitative observations (Parker and Larkin 2003) or outcome scores on motor tests (e.g. Macnab et al. 2001). These are useful methods in clinical or diagnostic practice, but they fail in providing thorough information about the nature and the constituents of the motor problems of children with DCD. This in depth information about the entire movement trajectory is necessary in order to refine the picture of DCD and gain insight in the heterogeneity and the underlying mechanisms of the disorder. In addition, clear and detailed documentation of the motor impairments of children with DCD should eventually offer a kinematic basis to compare the movement problems of children with different developmental disorders in order to enhance our knowledge regarding comorbidity and its underlying factors.

6. Conclusion and aims

At present the existence of Developmental Coordination Disorder and the impact of clumsiness on the general well-being of the affected children have been widely recognized but the underlying mechanisms of the motor impairments are still unclear. The knowledge on the motor skills of children with DCD is currently restricted to outcome scores on a movement assessment battery and qualitative observations. While these may be very accessible, informative and helpful in clinical practice, they offer only limited insight into the real constituents of the movement problems.

Aim 1: To present an objective and quantitative in depth analysis of basic movement skills of children with DCD.

A detailed kinematic analysis of the movement pattern can provide additional information to the outcome scores on movement assessment batteries, such as the amount of balls caught or the time needed for a 10 m run. High frequency, three dimensional video-registrations enable us to investigate precisely if, how and where children with DCD differ from their peers without coordination problems on a broad range of basic movement skills. This should offer more insight in the reasons for their systematic inferior performance on several standardized motor tests (Geuze et al. 2001). As such, detailed movement analysis of children with poor performance on these motor tests can also serve as an alternative validation and kinematic underpinning of the performance on these instruments. This movement approach to DCD should further help to refine the picture of the disorder and in this way it can provide a way to map out and to better understand the concomitant heterogeneity. Besides, it allows a more thorough comparison of the movement problems of children with DCD and children with other developmental disorders, which can open doors in the study of comorbidity. Therefore, all children with DCD who participated in the studies, presented in this dissertation, were accurately screede and diagnosed with DCD according to the four DSM-IV criteria. When symptoms of other developmental disorders were present, the children were excluded. Obviously, this resulted in a very selected sample of children with a rather *pure* form of DCD. Given the variability within the disorder this may complicate generalization of our research findings.

The experiments that were part of this research project covered a broad range of functional movement skills. Registrations were made of catching, walking, jumping, and throwing. These skills occupy a relevant and functional part of the children's everyday life and can be registered and measured in a standardized manner and are well documented in literature which can facilitate comparison. This dissertation however, focuses on the results of the former two, catching and locomotion. Catching has been shown to be problematic for many children with DCD and therefore they are put at a severe disadvantage in numerous games and plays (Van Waelvelde et al. 2004). The catching task presented in *Chapter 2* requires precise visual tracking and well timed grasping which allows an in depth examination of the interception and manipulation skills of children.

Walking constitutes the most important way to transport the body through the world in order to interact with the environment and the social community. Hence, walking is also a prerequisite for an adequate, carefree development of the child. A study of Woodruff et al. (2001) demonstrated that children with DCD displayed an atypical walking pattern based on the calculation of a performance index, but they did not provide further details on the spatiotemporal parameters and the gait kinematics. The study reported in *Chapter 3* attempts to fill this gap and gives a detailed analysis and comparison of the gait pattern during walking on a treadmill of children with and without DCD. The results of this experiment will offer us insight in the children's execution of a cyclic task requiring a precise control of balance and propulsion. In a consecutive study (*Chapter 4*) these findings were extended to walking overground. Due to the specific nature of stepping on a walking belt, the finding treadmill findings cannot be extrapolated to typical overground walking (Savelberg et al. 1998; Stolze et al. 1997). Comparison of the results of *Chapter 3* and *4* reveals that this task-specificity indeed leads to some differences in nuance between the two walking modalities in children with DCD. *Chapter 4* also explores the role of vision in the control of locomotion and attempts to extend previous findings on increased need for visual monitoring in children with DCD (e.g. Rösblad and von Hofsten, 1994; Smits-Engelsman et al. 2003).

Finally, the study presented in *Chapter 5* investigates a fundamental component of virtually all voluntary movements: postural control. Given the important contribution of the three sources of sensory information (vision, proprioception and the vestibular system), postural control offers a useful paradigm to study perceptual integration in children with DCD.

Aim 2: To gain a better insight into the underlying perceptual and motor control deficits with regard to DCD.

Most knowledge concerning the underlying perceptual and motor control deficits of DCD stems from studies without or with only a limited motor component. In order to better understand the pathways to motor incoordination in everyday life, these psychophysical findings need to be generalized to a functional level. The precise temporal phasing required in tasks such as catching (*Chapter 2*) and walking (*Chapter 3 and 4*) enables us to investigate aspects of timing in children with DCD in realistic tasks with a link to daily life. Catching further provides a way to study the visual tracking capacities and the capability to plan an action in response to a visual stimulus. Finally, the role of visual information in the control of posture and walking and the integration of vision with other sensory modalities are subject of research in *Chapter 4 and 5*.

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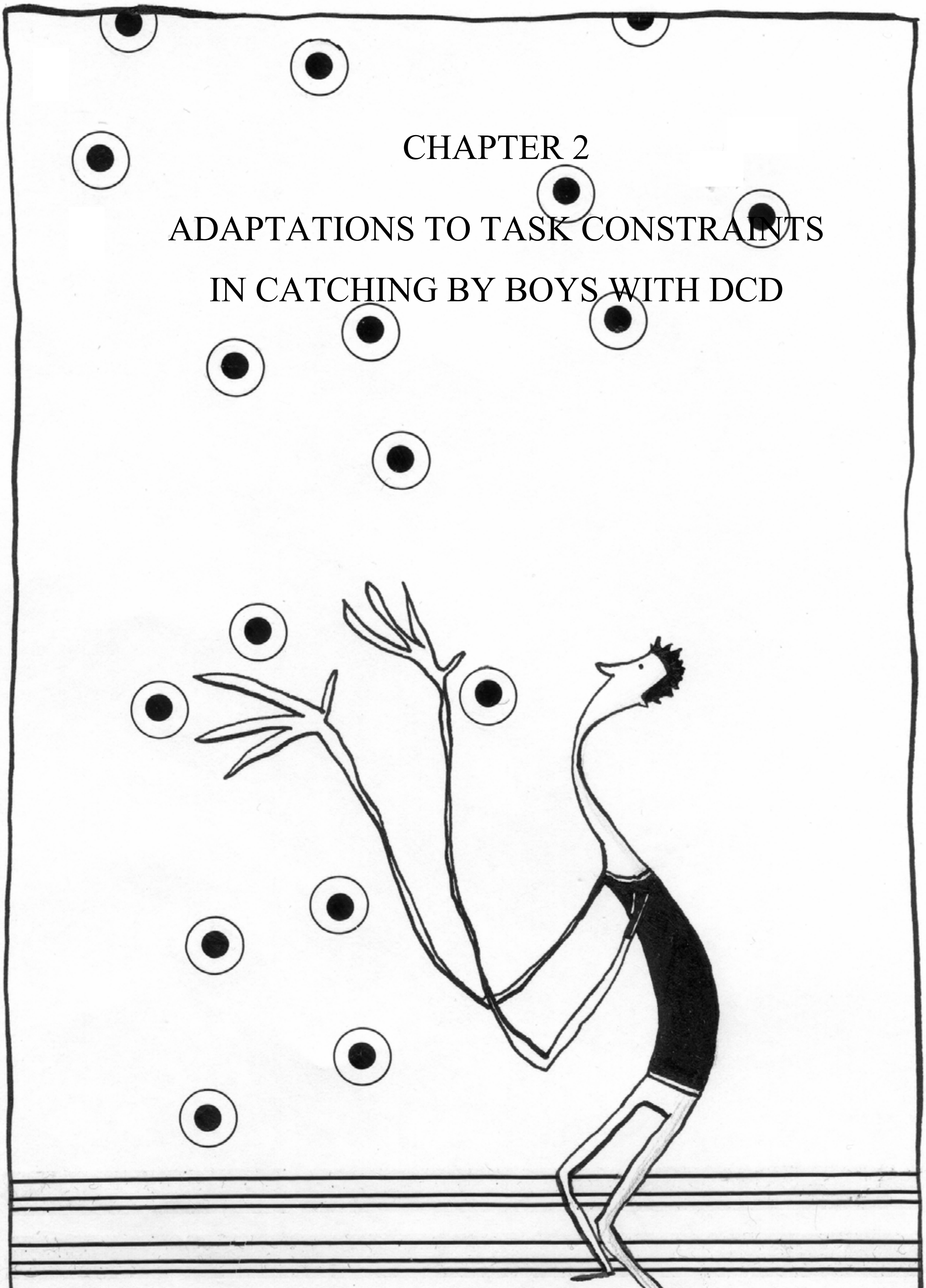
CHAPTER 2

ADAPTATIONS TO TASK CONSTRAINTS IN CATCHING BY BOYS WITH DCD



ABSTRACT

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 conditions. 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.

FJA Deconinck, D De Clercq, GJP Savelsbergh, R Van Coster, A Oostra, G Dewitte,and M Lenoir

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INTRODUCTION

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, jumping, throwing, etc.) without a demonstrable medical condition (American Psychiatric Association 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 and 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 et al. 1994).

Laszlo and colleagues found that clumsy children also did not perform as well in tasks involving kinesthetic perception (Laszlo et al. 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 et al. 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 and McKenzie 1998). Thus, in spite of the existing evidence for deficits at the perceptual (visuo-spatial or kinesthetic) level, the exact relationship between these deficits and the motor impairment remains unclear (Schoemaker et al. 2001; Wilson and 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 et al. 1992) and an increased variability in rhythmic coordination in tapping tasks and bimanual coordination (Geuze and Kalverboer 1994; Volman and Geuze 1998). An often suggested source of these problems is a deficit in an internal timing mechanism which is thought to be located in the cerebellum (Ivry and Keele 1989; Williams et al. 1992). Lundy-Ekman and colleagues (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 et al. 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 and colleagues (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 and co-workers (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 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 et al. 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 children without DCD, indicating a distinct lack of knowledge of ball flight cues or a more general problem of visual perception (Lefebvre and Reid 1998). This prediction problem corresponds to the general notion that children with DCD make less use of anticipatory control as van der Meulen and colleagues (1991a, 1991b) found in their unilateral aiming and arm tracking experiment. Therefore, children with DCD rely more on feedback control than their peers, a finding that was corroborated for both unilateral and bilateral reaching movements by Huh et al. (1998).

To our knowledge, Estil and co-workers (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, 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. By adopting this strategy, children with DCD are thought 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 is in support of 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 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.

METHODS

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 and 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 7.5 years (SD = 0.9) and a mean MABC percentile of 7.9 (SD = 4.34, range = 1 – 12; See Appendix Ia for details) 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 (See Appendix II).

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 (See Appendix III).

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			t_{16}
Variable	*M*	*SD*		*M*	*SD*		
Age (years)	7.5	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.
* $p < .001$

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 detect motor coordination problems (Geuze at al. 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 90º flexed and the shoulder in approximately 45º 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.

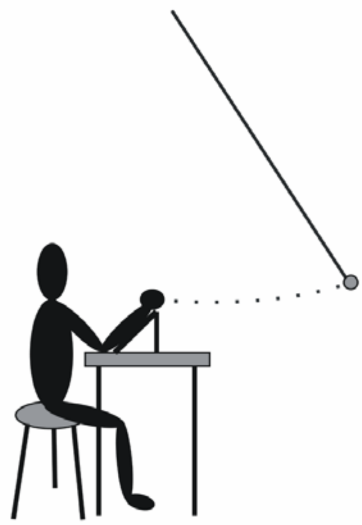

Figure 1 Sagittal view of the experimental set up. See text for explanation.

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 (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 minutes 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 et al. 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 ($D_{max-rel}$). 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 centre 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 which 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) x 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 sub-scores for ball skills revealed that all boys of the group with coordination problems scored at or below the 15th percentile, of which five scored below the 5th percentile. All the typically developing boys had sub-scores 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, ω^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, ω^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 x 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, ω^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	
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).

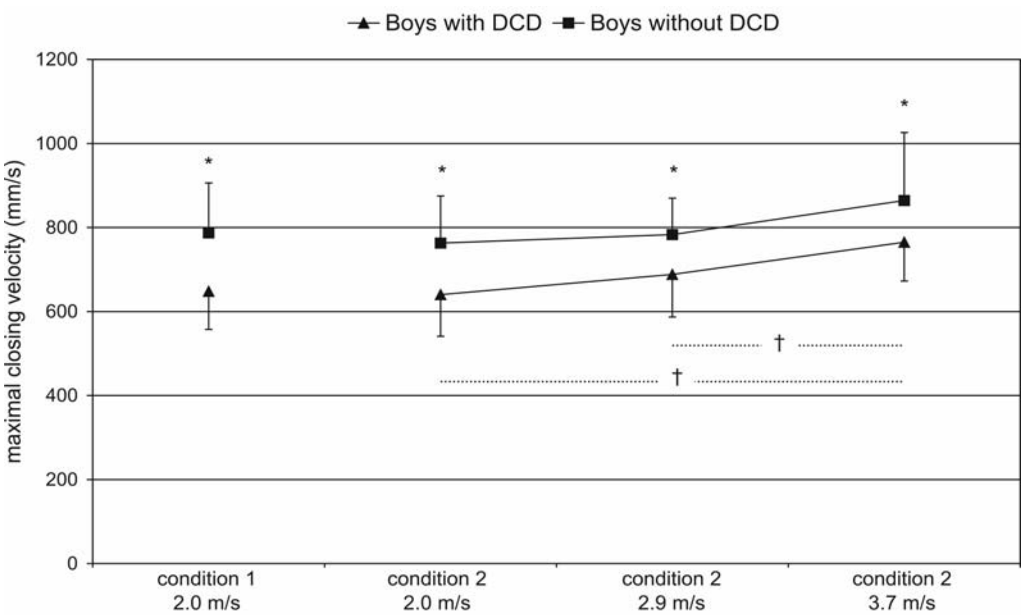

Figure 2 Maximal closing velocity of the hand for both groups for condition 1 (stable ball speed) and 2 (varying ball speeds). Group differences ($p < .05$) are indicated with *. The effects of ball speed $p < .01$) are indicated with †.

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.

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 DCD					
	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 towards 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. In addition, part of the explanation for the absence of temporal differences may lie the rigorous selection procedure used in the present study. The children with DCD were accurately screened and had no symptoms of other developmental disorders. Further, children with overt minor neurological dysfunctions were excluded. This could have resulted in a sub-group of children with unaffected basic interceptive and temporal capacities.

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 and colleagues (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, a similar increase in maximal closing velocity was 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 observations 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 repetitive 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, which 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 sub-scores 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 and 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 from 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 et al. 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). Though, this hypothesis cannot be supported by empirical evidence and warrants further research with the use of EMG instrumentation.

In conclusion, the boys with DCD in the present study 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 the 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. However, some caution is warranted when extrapolating these findings to the entire, heterogeneous population of DCD. It is not unlikely that the selection procedure resulted in a sub-group of boys with DCD with rather good interceptive capacities compared to children with more severe motor coordination problems and/or other co-occurring disorders.

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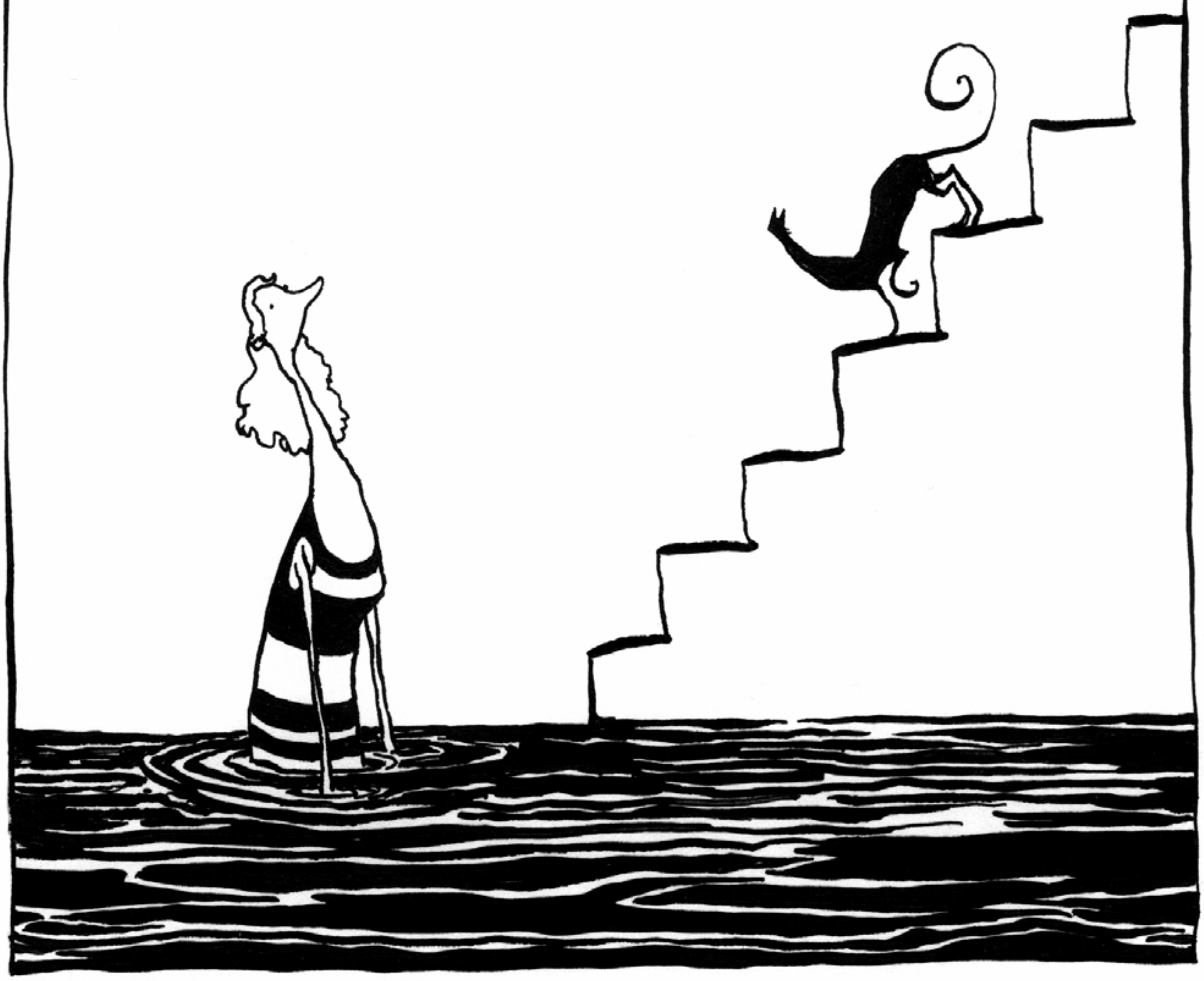
CHAPTER 3

DIFFERENCES IN GAIT BETWEEN CHILDREN WITH AND WITHOUT DEVELOPMENTAL COORDINATION DISORDER



ABSTRACT

In the present study the walking pattern of 10 children with DCD was investigated and compared to that of 10 typically developing, matched control children. All children walked at a similar velocity that was scaled to the length of the leg on a motor-driven treadmill. Three dimensional kinematics were recorded with a ProReflex camera system (Qualisys–Sweden). The spatiotemporal parameters of the gait pattern revealed that children with DCD walked with shorter steps and at a higher frequency than the typically developing children. In addition, the children with DCD exhibited a body configuration that was more flexed with an increased trunk inclination during the entire gait cycle and enhanced knee flexion during the first part of the stance phase. At toe off a less pronounced plantar flexion of the ankle was observed in children with DCD. In conclusion, it appeared that children with DCD make adaptations to their gait pattern on a treadmill in order to compensate for problems with neuromuscular and/or balance control. These adaptations seem to result in a safer walking strategy where the compromise between equilibrium and propulsion is different compared to typically developing children.

FJA Deconinck, D De Clercq, GJP Savelsbergh, R Van Coster, A Oostra, G Dewitte, and M Lenoir

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INTRODUCTION

Locomotion is fundamental for an optimal child development. The ability to smoothly and adequately navigate through the environment enables the child to interact with the environment and to gain different kinds of experiences. Locomotion is not only a prerequisite to fulfill primary needs like the search for food (Patla 1997). It is also a key factor from a psycho-social point of view, since it facilitates social interaction and participation in sports and games. It may be clear that children with movement disorders which involve problems in the locomotor activity therefore are put at a disadvantage with regard to their development. In this respect cerebral palsy (CP) has been the subject of a considerable amount of research (e.g., Damiano and Abel 1996; Massaad et al. 2004; Sutherland 1978). Less attention has been paid to milder movement disorders, such as Developmental Coordination Disorder (DCD).

The diagnosis of DCD refers to children with movement disorders which are characterized by coordination difficulties in several gross and/or fine motor tasks. These difficulties hamper the children significantly to fulfill a broad range of activities of daily living. The children have a normal intelligence and in contrast with for example CP or muscular dystrophy, an overt neurological disease or any other medical condition is absent. Despite the strict criteria formulated by the American Psychiatric Association (APA) in the Diagnostic and Statistical Manual of Mental Disorders (DSM IV; APA 1994) some children with DCD exhibit motor behavior that is reflective for minor neurological dysfunctions such as difficulties with the regulation of muscle tone or an increased knee tendon reflex in the absence of hard neurological evidence (Hadders-Algra 2000 & 2002; Lundy-Ekman et al. 1991).

According to Patla and co-workers (1991) successful locomotion requires (1) producing a locomotor pattern for supporting the body against gravity and propelling it forward, while (2) maintaining the body in balance, and (3) adapting the pattern to meet environmental demands. The bipedal walking pattern that humans have adopted over time constitutes an elegant way to meet these requirements in an efficient and economic way. Several findings with respect to motor control in children with DCD however, indicate that they could have problems to meet (some of) these constraints. A first potential limitation is related to the neuromuscular control in children with DCD. Raynor (2001) observed decreased muscular strength and power in children with DCD, accompanied by increased levels of co-activation in a unilateral knee flexion and extension task. Similar neuromuscular problems, indicating difficulties with the selective muscle control necessary for rhythmic coordination, were found in a unilateral tapping task by Lundy-Ekman et al. (1991). Likewise Volman and Geuze (1998) showed that these rhythmic coordination difficulties of children with DCD are not restricted to the control of unilateral tapping. By means of a bimanual flexion-extension paradigm they found that relative phase stability of children with DCD was less stable than in controls. Further investigation is warranted to examine whether similar interlimb coordination problems are present in the lower limbs. However, it is needless to say that if this is the case, it might be harmful for establishing a propulsive bilateral gait pattern that supports the body against gravity.

Second, with regard to balance various researchers agree that children with DCD show deficits in the control of posture as observed in the increased levels of postural sway during quiet stance (Geuze 2003; Przysucha and Taylor 2004; Wann et al. 1998). Data of postural control collected recently in our own lab nicely showed that the increased levels of postural sway of children with DCD are accompanied by a greater dependency on vision and difficulties in the re-weighting of the sensory modalities in response to the environmental constraints (Deconinck et al. submitted). From studies where upright stance was perturbed by means of a sudden displacement of a moveable platform it was concluded that the balance recovery strategy of children with DCD was different (Williams 2002). Their strategy was characterized by a top-down muscular activation pattern compared to the distal-proximal pattern displayed by children without DCD, which was argued to be more efficient. In stance the projection of the center of mass has to be kept within the borders of the base of support, in order to maintain balance. For locomotor balance however, one must achieve a compromise between the forward propulsion of the body, which involves a highly destabilizing force, and the need to maintain the overall stability (Winter 1995). Taking into account this complexity with respect to the control of posture during locomotion it can be hypothesized that the balance problems experienced by children with DCD might be a limiting factor for their locomotor activity.

So far, descriptions of the gait pattern of children with DCD are limited to some qualitative observations. Larkin and Hoare (1991) have notified for example poor head control, bent arms in a guard position, jerky limb to limb transitions, excessive hip flexion, pronounced asymmetry, wide base of support, short steps, foot strike with flat foot and toe-walking. In an attempt to quantify the gait pattern of children with DCD, Woodruff and colleagues (2002) developed an Index of Walking Performance. This index is based on a comparison of four spatio-temporal gait parameters (time of opposite toe-off, single stance time, total stance time and step length) with reference parameters of the San Diego database (Sutherland et al. 1988). From their calculations Woodruff et al. concluded that the walking pattern of 6 out of 7 children with DCD indeed was atypical. This one-dimensional measure of walking performance is useful for classifying and evaluation of gait performance in clinical practice; however, it does not explain the nature or source of atypical gait. In addition, comparison of gait variables with a reference population without controlling for stature (or leg length) and body weight might obscure deviations and lead to imprudent conclusions, since the walking pattern is highly dependent on anthropometrical characteristics (Hof 1996; Stansfield et al. 2003). Therefore, in order to gain insight into the gait pattern of children with DCD, more detailed and quantitative data are needed.

The present study investigates whether the previous (qualitative) findings of atypical walking in children with DCD could be confirmed by detailed, kinematic analysis of the walking pattern and by a comparison with rigorously matched control children. The results will add quantitative data to the existing qualitative descriptions and as such extend the picture of the disorder. It is hypothesized that the postural control as well as the interlimb coordination difficulties of children with DCD, as found in previous studies, will induce significant adaptations to the gait pattern. Problems with posture and/or neuromuscular control might force children with DCD to accommodate the specific relation between balance and propulsion during locomotion, resulting in a different gait pattern with regard to the spatiotemporal control of the gait cycle as well as to the joint kinematics.

METHODS

Participants

The children with DCD were recruited out of the patient files of 35 collaborating psychomotor therapists. By scanning the personal file of each child it was verified whether the children met the DSM IV criteria for DCD (APA 1994). Before being referred for (psychomotor) therapy all children were subjected to an extensive neurological examination in order to preclude neuromuscular or neurological dysfunctions. This examination included the assessment of the (postural and peripheral) muscle tone, muscle force, peripheral reflexes, balance, the quality of voluntary movements, and the integrity of the cranial nerves. In addition, gestation of all children was normal and without complications and children were born at term without unfavourable obstetrical conditions. Further, the children were assessed to be mentally healthy and based on their poor scores on the Movement Assessment Battery for Children (MABC; Henderson and Sugden 1992), they were referred for therapy. If at the time of the current study their score on the MABC still was below the 15th percentile, the children were invited to participate. By means of this selection procedure ten children, 9 boys and 1girl with a mean age of 7.4 years (SD = 0.86), were recruited. Four participants scored below percentile 5 and the remaining 6 between the percentile 5 and 15 (range: 1 - 12). A closer look at the scores on the three MABC-clusters (fine motor skills, ball handling skills and balance skills) indicated that 4 children scored below percentile 5 for fine motor, manipulative skills while 6 scored between percentile 5 and 15. The same was true for ball handling, but for balance all children scored above the 15th percentile. The latter, however, did not imply that the children with DCD did not experience problems with the control of posture, since a related study revealed that all these children exhibited increased levels of postural sway as assessed with a Clinical Test of Sensory Interaction on Balance (Deconinck et al. submitted).

Table 4 Means (M), standard deviations (SD), and *t*-test values relative to demographic data of children with and without DCD.

	Children with DCD			Children without DCD			t_{18}
Variable	*M*	*SD*		*M*	*SD*		
Age (years)	7.4	0.86		7.5	0.85		.408
Stature (m)	1.28	0.070		1.31	0.051		1.130
Leg length (m)	0.59	0.057		0.59	0.037		.070
Body weight (kg)	25.3	4.11		28.0	4.35		1.427
PA school (h/w)	3.5	1.65		3.7	1.46		.275
PA leisure (h/w)	2.0	1.48		2.5	1.84		.687
Math grade (%)	88	8.3		91	7.2		1.393
MABC percentile	7.3	4.50		69.1	22.17		8.638*

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. Intelligence was matched by means of the math grade. It has been shown that this value correlates well with the total IQ (Brusselmans-Dehairs et al., 2002).
* $p < .001$

All children completed a physical activity questionnaire with assistance of at least one of their parents. This questionnaire was developed to administrate the degree and nature of the physical activity of the child. For the recruitment of children for the control group the same questionnaire was distributed to the 6-8 years old children of two primary schools (N=300) in the neighborhood of the Department for Movement and Sports Sciences. After a rigorous matching procedure, taking into account sex, age, intelligence, stature, body weight and degree and nature of daily physical activity a group of 10 typically developing (TD) children was selected to serve as a control group. The TD-children were free from medical conditions or behavioral disorders. Their score on the MABC was higher then percentile 33. Details of the demographic data of both groups and inferential statistics are given in Table 1. The protocol of this study was in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethical Committee of the Ghent University. All parents gave their written informed consent prior to participation and the children assented to the testing.

Instrumentation

Children walked barefoot on a motor driven treadmill (STAR TM505, 1HP) at an imposed velocity which was scaled to the length of the leg according to the Froude number (Fr).

$$Fr = \frac{v^2}{g.L}$$

where v is the walking velocity; g is the acceleration due to gravity and L is the leg length. Walking at an equal Froude number results in *dynamic similarity* where lengths, times, frequencies, velocities and forces are proportional to each other (Zatsiorsky et al. 1994). The Froude number was set at 0.15, which resulted in a mean walking velocity of 0.85 m/s on average for both groups.

Three-dimensional kinematic data were collected with an eight ProReflex camera system (Qualisys, Sweden). Spherical markers (Ø 6 mm) were placed bilaterally on seven bony landmarks: the caput of the 5th metatarsale, malleolus lateralis (ankle), epicondylus lateralis femoris (knee), trochanter major femoris (hip), acromion (schoulder), epicondylus lateralis of the humerus (elbow) and the processus styloideus of the ulna (wrist).

Procedure

Three to four weeks before the test the children were invited for a practice and habituation session which was identical to the actual experiment. This first session started with a short acquaintance with the three testers, the lab and the equipment. Next, the children were tested with the MABC.

All participants were naïve to treadmill walking and before recordings the children were given a practice period of approximately 10 minutes to become familiar to the treadmill. According to Wall and Charteris (1981) habituation mainly occurs during the first minutes of locomotion. In Stolze et al. (1997) a similar period of time appeared to sufficient for children to produce a stable walking pattern. Before the child took place on the treadmill, one of the experimenters demonstrated the whole course of the experiment. Meanwhile, he explicated to keep on walking at a steady state velocity in between the two lines of tape fixed to the treadmill frame while looking ahead. Subsequently, the child mounted on the treadmill, holding the hand of the experimenter at his or her right side. The velocity of the walking belt was gradually increased to the desired scaled velocity by the tester while the child was encouraged to initiate stepping and instructed to look ahead. During the first two minutes, the child walked hand in hand with a tester at the right side of the body, while a second tester stood at the left side to ensure the security. Then, hands were released and the child kept on walking independently for two more minutes. After that, the speed of the belt was decelerated to zero. This training protocol was repeated twice and subsequently two sequences for data-analysis were registered with the 3D camera system. When the child was ready the tester increased the speed gradually to the desired velocity. After about 30 seconds of walking steady state, a sequence of ten seconds was registered by the camera system. One minute later, the walking belt was gradually stopped and after a short rest of one minute a second sequence was recorded.

Data processing

Following data collection, the three dimensional trajectories were labeled and smoothed with a low-pass Butterworth filter at a cutoff frequency of 6 Hz. Next, the consecutive foot strikes (FS) and toe offs (TO) from both feet were identified as the moments of maximal forward excursion of the ankle markers and the moment of maximal backward excursion of the toe markers. This method has been used previously by Donker and colleagues (2001). Eight consecutive strides, beginning with left FS and finishing FS of the ipsilateral foot of the second sequence were selected for further analyses.

Spatial step kinematics were calculated based on the location of the ankle marker. Step length was defined as the anterior-posterior distance from ankle to ankle at FS. The sum of two consecutive steps resulted in the stride length. Absolute step width was determined as the medio-lateral distance from right ankle to left ankle at FS. Since this distance is highly dependent on the body morphology, step width ratio was calculated as the absolute step width divided by the medio-lateral distance between left and right trochanter major.

The temporal variables of interest were the total stride time (from FS to FS of the ipsilateral foot) which is divided in the support phase (from FS to TO of the ipsilateral foot) and the swing phase (from TO to FS of the ipsilateral foot). The support phase can be divided into an initial double support phase (from FS to opposite TO, i.e. TO of the contralateral foot), a single support phase which equals the swing phase of the contralateral foot (from opposite TO to opposite FS) and a second double support phase (from opposite FS to TO)

Segment angles of the foot, leg, thigh and trunk were determined at critical moments in the gait cycle, at FS, opposite TO, opposite FS and TO. According to Winter (1991), segment angles are defined as the angle between the frontal side of the segment and the horizontal. To facilitate the interpretation of the joint kinematics also relative joint angles of ankle, knee and hip were calculated. In Figure 1 the time course of these joint angles are displayed relative to the critical gait events.

The Index of Walking Performance was introduced by Woodruff et al. (2002) to compare the spatial-temporal pattern with that of a group of 139 children (3-7 years of age) of the San Diego database (Sutherland et al. 1988). It is a one-dimensional measure of normality based on the occurrences of opposite toe off, opposite foot strike, single stance and the step length all normalized to the duration or length of the gait cycle. Hotelling's T2 statistics and matrix calculations are used to combine the children's four scores into a single number. The cut-off value 2.69 was found to correspond to the 95th percentile and correspondingly all indices larger than 2.69 were classified as *abnormal*. See Woodruff et al. for a detailed description of the calculation of the Index of Walking Performance.

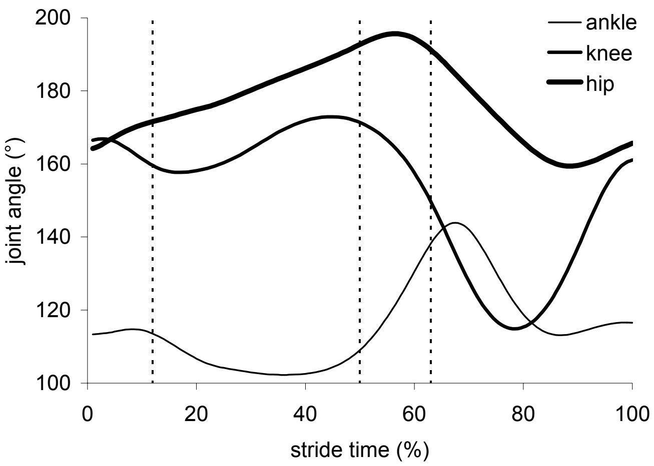

Figure 3 Typical time course of the joint angles of ankle, knee and hip of a child (7.0 years old) relative to the total stride time expressed in %. Broken vertical lines represent respectively opposite TO, opposite foot strike and TO.

Statistical analysis

A reliability analysis of the eight consecutive strides yielded Intra Class Coefficient above 0.85 for all dependent variables with the exception of the Index of Walking Performance ($\alpha = .74$ for children with DCD and $\alpha = .77$ for TD-children). This allowed us to average the values of the eight consecutive strides of each individual in order to further investigate the group differences (Portney and Watkins 1993). The lower ICC for the Index of Walking Performance calls for caution when interpreting the analysis on the basis of the individual means. Differences between TD-children and children with DCD were then evaluated with an independent samples *t*-test on each dependent variable. Alpha level for statistical significance was set at .05. Cohen's *d* was calculated to measure effect sizes.

RESULTS

The temporal phasing of the gait cycle is shown in Figure 2. Differences between children with and without DCD were found for all absolute temporal variables. Stride time of children with DCD was significantly shorter ($t_{18} = 2.817$, $p < .05$, $d = 1.752$), which was attributed to both a shorter support ($t_{18} = 2.773$, $p < .05$, $d = 1.161$) and a shorter swing phase ($t_{18} = 2.699$, $p < .05$, $d = 2.013$). Children with DCD also spent less time in double support ($t_{18} = 2.182$, $p < .05$, $d = 1.202$). However, when these temporal measures were scaled to the duration of the entire gait cycle, all differences disappeared, indicating that the relative phasing of the walking pattern of both groups was similar (see Figure 2).

As shown in Table 2, the shorter stride time of the children with DCD resulted in a significantly higher cadence (t_{18} = 2.713, p < .05, d = 2.079). The stride length of children with DCD was shorter (t_{18} = 2.115, p < .05, d = 1.205), but neither step width or step width ratio differed between groups.

Table 5 Means (M) and standard deviations (SD) of the gait parameters.

	Children with DCD			Children without DCD	
Variable	*M*	*SD*		*M*	*SD*
Stride length (mm)	711*	84.5		799*	101.0
Absolute step width (mm)	146	15.6		141	15.5
Step width ratio	0.63	0.097		0.57	0.086
Cadence (steps/min)	146*	16.4		128*	16.9
Index of Walking Performance	4.07*	3.197		1.28*	0.743

* p < .05

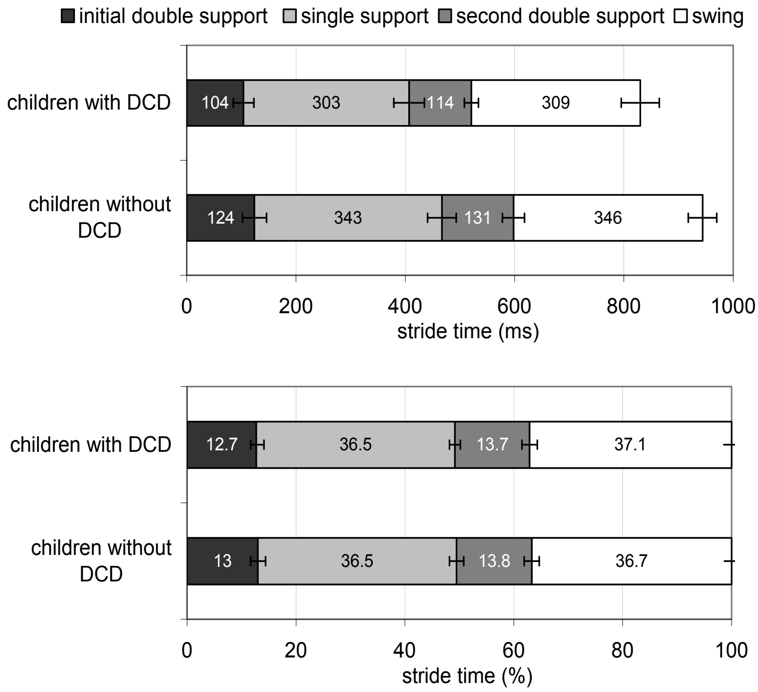

Figure 4 Temporal gait parameters of the children with and without DCD. Error bars indicate the standard deviations. Absolute values are displayed in the upper panel, values relative to the total stride time are shown in the lower panel

Table 3 displays the segment at initial FS, opposite TO, opposite FS and TO. Body kinematics throughout the gait cycle differed mainly at the level of the trunk. In children with DCD the trunk was inclined more to the horizontal at initial FS (t_{18} = 2.236, $p < .05$, d = 1.528), opposite TO (t_{18} = 2.133, $p < .05$, d = 1.507), opposite FS (t_{18} = 2.600, $p < .05$, d = 2.035) and TO (t_{18} = 2.109, $p < .05$, d = 1.666). At FS leg angle was slightly more flexed in the children with DCD (t_{18} = 2.172, $p < .05$, d = 1.226), and the angle of the thigh was more in anteversion (t_{18} = 2.338, $p < .05$, d = 1.169). The latter still was more flexed at opposite TO (t_{18} = 2.572, $p < .05$, d = 1.377), and at TO (t_{18} = 2.195, $p < .05$, d = 1.184). At TO the foot angle of children with DCD was less in plantar flexion than that of the typically developing children (t_{18} = 2.877, $p < .05$, d = 2.037).

Table 6 Means (M) and standard deviations (SD) of the segment angles.

Angle		Group		FS	Opposite TO	Opposite FS	TO
foot (°)		children with DCD	*M* *SD*	169.0 6.86	161.9 3.76	144.4 5.60	109.6* 7.39
		children without DCD	*M* *SD*	172.7 6.65	161.2 3.68	141.1 9.23	101.0* 5.97
leg (°)		children with DCD	*M* *SD*	97.1* 3.68	83.4 2.84	63.6 3.13	43.2 3.41
		children without DCD	*M* *SD*	101.2* 4.73	86.6 5.17	63.4 6.69	42.3 3.99
thigh (°)		children with DCD	*M* *SD*	117.9* 2.16	112.3* 2.59	83.2 4.34	90.5* 3.99
		children without DCD	*M* *SD*	115.0* 3.57	108.6* 3.80	78.9 5.84	85.6* 5.85
trunk (°)		children with DCD	*M* *SD*	82.3* 6.42	83.7* 6.76	76.2* 5.14	79.1* 5.36
		children without DCD	*M* *SD*	88.5* 5.74	89.9* 5.82	82.0* 4.03	84.0* 4.16

Note. FS = foot strike, TO = toe-off
* $p < .05$

In Table 4 it can be observed that this pattern of segment angles resulted in several differences at the level of the joint angles. At FS the angles knee and hip were significantly more flexed in children with DCD (knee: t_{18} = 2.883, $p < .05$, d = 1.606 and hip: t_{18} = 3.172, $p < .05$, d = 2.198). Knee angle still was smaller at opposite TO (t_{18} = 2.530, $p < .05$, d = 1.316), while hip angle remained more flexed during the entire time course (at opposite TO: t_{18} = 3.005, $p < .05$, d = 1.919, at opposite FS: t_{18} = 3.190,

$p < .05$, $d = 2.456$, and at TO: $t_{18} = 3.007$, $p < .05$, $d = 2.243$). The ankle was found to be significantly less extended in children with DCD at TO ($t_{18} = 2.812$, $p < .05$, $d = 1.650$). Joint kinematics at initial FS and TO are illustrated by the stick figures in Figure 3.

Table 7 Means (M) and standard deviations (SD) of the joint angles.

Angle		Group		FS	Opposite TO	Opposite FS	TO
ankle (°)		children with DCD	*M* *SD*	108.0 4.86	101.4 4.40	99.0 4.45	113.4* 5.78
		children without DCD	*M* *SD*	109.5 4.37	105.5 4.48	102.3 4.31	121.3* 6.77
knee (°)		children with DCD	*M* *SD*	159.1* 4.67	151.0* 4.60	160.4 6.07	132.7 4.27
		children without DCD	*M* *SD*	166.4* 6.43	158.1 7.63	164.5 11.88	136.7 9.10
hip (°)		children with DCD	*M* *SD*	144.4** 7.15	151.2** 7.65	172.6** 8.89	168.5** 8.74
		children without DCD	*M* *SD*	154.3** 6.37	162.0** 7.96	184.2** 6.68	179.3** 6.81

Note. FS = foot strike, TO = toe-off
* $p < .05$, ** $p < .01$

Figure 5 Stick-figures of the body configuration at initial FS (left) and TO (right). Grey lines represent the TD-children without DCD, black lines represent the children with DCD. Feet with broken lines are the contralateral feet. Arrows indicate significant differences of the joint angles ($p < .05$)

The mean Index of Walking Performance was significantly larger, i.e. worse, for the children with DCD compared to the typically developing children (t_{18} = 2.280, $p < .05$, d = 2.840) (See Table 2). Moreover, the mean Index of the DCD-group fell in the abnormal range (>2.69). On the contrary, the mean of the TD-group did not reach abnormal values. Figure 4 illustrates the stride by stride Indices of Walking Performance for each child. Close observation indicates that 6 out of 10 children with DCD had a mean Index larger than 2.69, while this was the case in none of the TD-children. Out of 80 strides covered by the children with DCD 35 (43.75%) had an Index above 2.69, compared to only 7 (8.75 %) for the TD-children. This diagram further indicates that both inter and intra-variability were distinctly larger in children with DCD. Statistical analysis of the standard deviations of the individuals' means revealed that this difference was significant ($t18$ = 3.573, $p < .05$, d = 5.982).

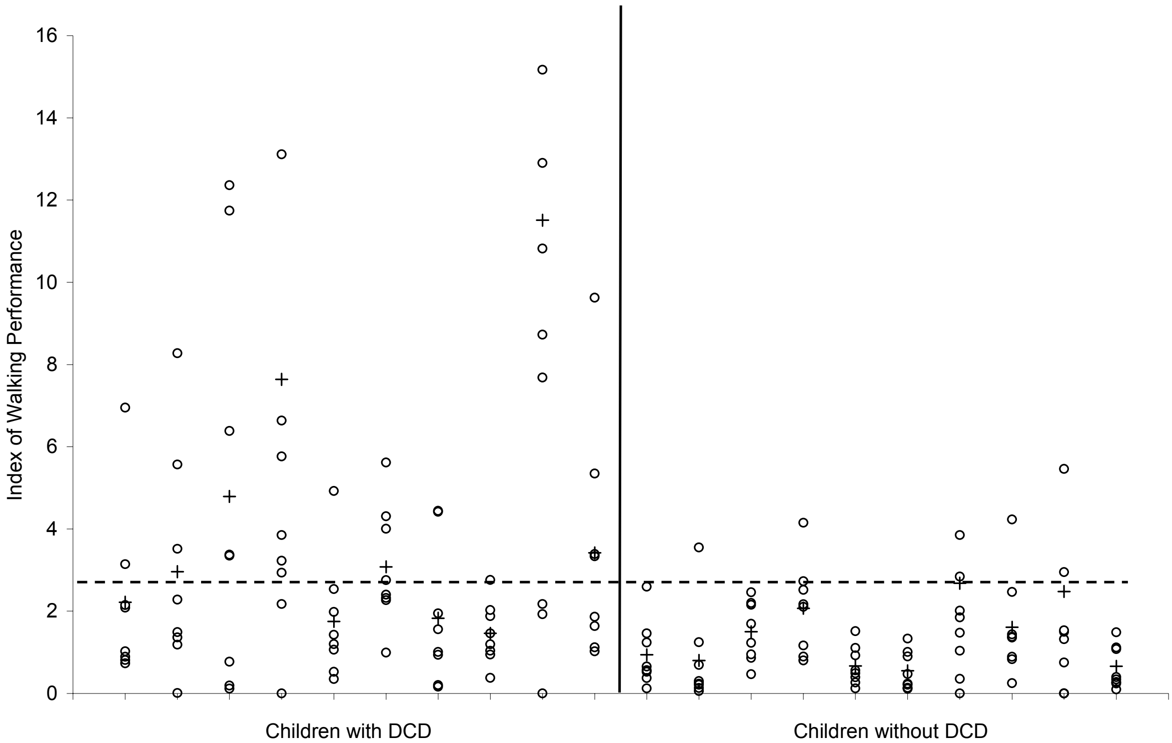

Figure 6 Index of Walking Performance of the 10 children with and the 10 children without DCD. Values of the separate strides are indicated with ○, means per child are indicated with +. The horizontal broken line indicates the cut-off value (2.69) according to Woodruff et al. (2002).

DISCUSSION

The present study attempted to identify if and how the gait pattern of children with DCD differed from that of their typically developing peers. In accordance with Woodruff et al. (2002), it was found that children with DCD had significantly more Indices of Walking Performance above the cut-off point indicating aberrant walking behavior. Whereas each child with DCD displayed at least one stride with an Index in the abnormal range, four of them had a mean Index below the cut-off value. This lack of consistency together with the limited explanatory power of a one-dimensional index with regard to potential underlying factors of the deviant walking pattern incite to carry out a more detailed gait analysis.

Based on the four spatio-temporal gait parameters that are part of the index Woodruff et al. (2002) could not find differences between 6 year old children with DCD and the 3-7 year old reference population of Sutherland et al. (1988). Conversely, in the present study, where the typically developing children were rigorously matched to the children with DCD, it was found that the latter displayed a gait pattern with shorter strides in both time and space, while stepping at a higher frequency than their typically developing peers. When scaled to the total gait cycle duration, the reduction of the separate gait phases did not imply a distortion of the relative phasing, indicating that children with DCD did succeed to establish a normal and rhythmic locomotor pattern, although shortened in time and space. In addition, the trunk of children with DCD was inclined more towards the ground and they displayed increased knee flexion at initial foot contact and less plantar flexion at toe off.

A temporal and spatial shortening of the gait cycle is a strategy that is also adopted by newly walkers (Sutherland et al. 1988). In children with DCD these adaptations were accompanied by other changes that are indicative for an immature gait pattern like the propensity to place to foot flatter at initial contact and the less pronounced toe off of children with DCD. However, while several gait characteristics of children with DCD may have similarities with a less mature gait pattern, this does not necessarily imply that with further maturation children with DCD will overcome their problems. Previous research has shown that children with DCD do not spontaneously recover from their coordination problems (Henderson and Barnett 1998). Therefore, an alternative explanation is that the similarities with immature gait result from reactions to a primary impairment which appears to force the children with DCD, like newly walkers, to adopt a safer walking strategy. Extensive study on the onset and the development of walking has pointed towards the primary role of force and posture (Adolph et al. 2003; Clark and Phillips 1988; Thelen 1986). The ability to hold the body upright while propelling it forward and catching it at contact depends on both strength in the leg muscles and postural control. The causes for the conservative walking strategy displayed by children with DCD may be sought in that direction.

In this context, the shorter time spent in single support by children with DCD might be a reflection of diminished neuromuscular maturity and limb instability as proposed by Sutherland et al. (1988). The ability to support the body on one leg largely depends on the strength of the supporting leg. Likewise, the less pronounced plantar flexion preceding toe off can be an expression of lack of strength to propel the body forward. A decrease of the ankle plantar flexion during terminal stance will likely reflect a decrease in the ankle plantar flexion torque, which is responsible for the most important energy generation phase of the gait cycle (Winter 1991). In sum, these differences may be a kinematic manifestation of the neuromuscular problems that have been found to occur in children with DCD (Raynor 2001). However, further kinetic and EMG-analysis is warranted to investigate the extent of these problems in walking.

Like in elderly people, the walking pattern of children with DCD might also be a protective adaptation to a perceived threat to stability (Menz et al. 2004). Anticipatory and reactive postural control of children with DCD in response to perturbations in static conditions has been shown to be less accurate and efficient (Johnston et al. 2004; Williams 2002). As a result, the less pronounced plantar flexion preceding toe off and correspondingly the smaller steps, may be interpreted as a strategy to produce a smaller destabilizing momentum at toe off, just before the body initiates the most unstable phase. Therefore, the gait adaptations of children with DCD could be viewed as different control patterns stemming from altered central nervous considerations in response to perceived threats to balance or postural control, as suggested by Latash and Anson (1996).

Another balance-related gait parameter is the placement of the foot relative to the centre of mass, expressed as the step width (Mackinnon and Winter 1993). Populations with balance problems often show an increase of the step width to conquer destabilizing torques in the frontal plane ratio (Sutherland et al. 1978 & 1988). In the present study, absolute step widths of both groups (146 ± 15.6 mm for children with DCD and 141 ± 15.5 mm for TD-children) are large compared to reference values for treadmill walking available in literature (106 ± 23.2 for children of 6.6 years old in Stolze et al. 1997). This might suggest an increase of the base of support, although no differences were found between the children with and without DCD.

However, it appears that children with DCD adapt their walking pattern at another level in order to meet the balance requirements. The enhanced forward inclination of the trunk with correspondingly smaller hip angles over the entire gait cycle and increased knee flexion during stance, result in a lowering of the centre of mass (see Figure 3). This implies that the destabilizing effect of the gravitational torque about the supporting foot decreases (MacKinnon and Winter 1993). With these kinematic accommodations children with DCD reduce the stability constraints on walking which might make additional adaptations such as wider foot placement unnecessary.

The balance problems experienced while walking on a treadmill may be partially related to the peculiarities of the task itself. As reported in several studies that compare treadmill and overground walking, factors such as the change of afferent sensory input or the work transferred between the subject and the treadmill may also have influenced the walking pattern in the present study (Savelberg et al. 1998; Stolze et al. 1997; Wall and Charteris 1981). Indeed, in correspondence with previous findings, our results suggest that cadence tended to be higher and step length appeared to be shorter than in overground walking. Nevertheless, treadmill walk testing is found to be appropriate for group comparison when similar conditions are used, although some caution is warranted when interpreting the results and extrapolating the findings to overground walking (Alton et al. 1998).

In this context the influence of the visual flow pattern on the gait parameters is of particular interest (Prokop et al. 1997). Treadmill walking offers a unique situation where visual flow remains virtually absent. From various accounts it can be acknowledged that children with DCD have an increased dependency on visual information and cannot as adequate tune inflow of proprioceptive, visual and vestibular information to the environment as children without coordination problems (Wilson and McKenzie 1998). Moreover, children with DCD were shown to experience more harm in situations with conflicting sensory modalities for maintaining balance (Deconinck et al. submitted; Wann et al. 1998). Therefore it can be assumed that the children with DCD of this study were more susceptible to the sensory conflict between the lack of visual flow and the vestibular and proprioceptive input related to treadmill walking than

TD-children. As a consequence, the sensory integration deficits of children with DCD may also be part of the explanation of their different gait pattern on the treadmill.

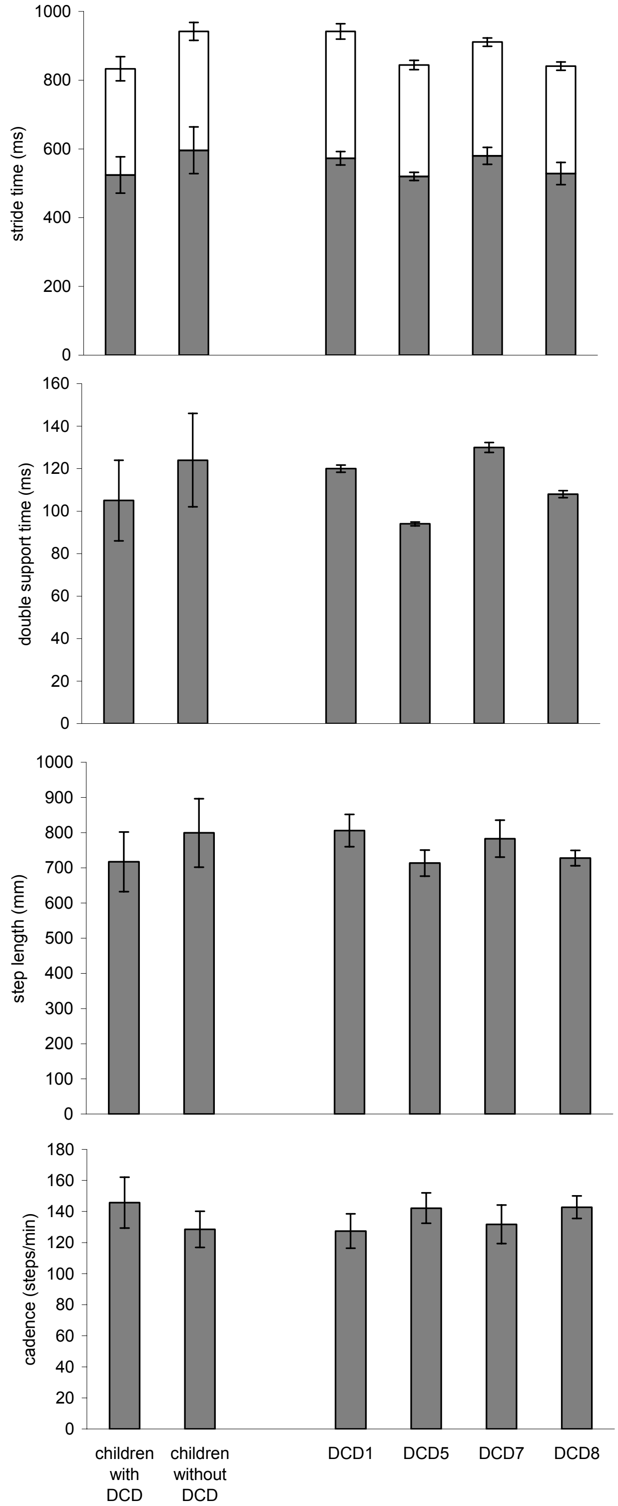

Figure 7 Stride time, double support time, step length and cadence of the children with DCD, with an Index of Walking Performance above the cut-off value in comparison with the means per group. Error bars indicate the standard deviations. Stride time is divided into support phase (grey bar) and swing phase (white bar).

Table 5 Individual means (M) and standard deviations (SD) of the joint angles of the participants with DCD, with a mean Index of Walking Performance in the normal range.

Angle	Participant		FS	Opposite TO	Opposite FS	TO
ankle (°)	DCD1	*M*	108.7	101.3	101.7	121.0
		SD	1.61	3.45	5.43	6.21
	DCD5	*M*	99.7	95.7	95.1	105.4
		SD	2.90	2.94	3.52	5.22
	DCD7	*M*	102.7	99.7	93.7	111.6
		SD	1.63	3.19	1.88	3.90
	DCD8	*M*	110.3	102.3	94.8	112.1
		SD	2.30	4.96	3.18	1.08
knee (°)	DCD1	*M*	154.1	144.4	155.9	128.3
		SD	4.03	4.93	5.59	4.15
	DCD5	*M*	155.5	148.5	155.9	128.0
		SD	3.20	3.14	2.44	4.59
	DCD7	*M*	166.8	152.1	158.9	129.8
		SD	5.06	2.38	3.53	3.45
	DCD8	*M*	165.9	154.3	170.5	139.9
		SD	5.27	3.83	4.33	4.06
hip (°)	DCD1	*M*	145.3	151.8	172.2	171.0
		SD	2.38	3.31	3.42	4.10
	DCD5	*M*	141.7	147.3	170.7	164.0
		SD	2.52	1.85	3.56	5.58
	DCD7	*M*	141.7	146.1	165.4	164.6
		SD	2.20	3.23	2.31	2.32
	DCD8	*M*	157.9	164.8	189.4	184.8
		SD	3.16	3.99	3.83	4.56

In general, children with DCD appear to experience more problems with finding the optimal compromise between forward propulsion and dynamic stability while walking on a treadmill. Even though the picture of the Index of Walking Performance appears to contradict this view in some occasions, a careful look into its spatiotemporal components, together with analysis of other kinematic parameters helps to better comprehend the nature of the walking pattern of children with DCD. To illustrate this, a single-subject analysis of the four children with DCD who had an Index in the normal range (DCD1, DCD5, DCD7 and DCD8) was carried out. From Figure 5, which presents the individual results for the spatiotemporal variables that discriminated between the groups with and without DCD, it is clear that DCD5 and DCD8 tend towards the mean of the children with DCD. The spatiotemporal variables of DCD1 and DCD7 however, approximated the means of the children without DCD. While spatiotemporal adaptations of the gait pattern in these children appeared to remain absent, their joint angles at critical moments of the gait cycle clearly showed deviations in the direction of the children with DCD. Similar findings were noticed for DCD5, but adaptations to the joint angles were virtually absent in DCD8. Overall these single-subject results indicate that all children with DCD who obtained Index values in the normal range displayed adaptations to the gait pattern at one or another level. Consequently, a 'normal' Index of Walking Performance can be the result of a complex of successful adaptations to the gait pattern.

In summary, the gait pattern of children with DCD was studied by means of spatiotemporal and kinematic joint variables and revealed distinct differences with typically developing children. When walking on a treadmill at a similar scaled velocity the gait cycle of children with DCD was shorter in time and space which resulted in a higher cadence. In addition, the body configuration of children with DCD appeared to be more bent than in their typically developing peers. The differences found might be interpreted as the kinematic outcome of accommodations caused by problems at neuromuscular or postural control level, and in this sense the gait pattern of children with DCD should be considered adaptive rather than abnormal. While this ensemble of adaptations may be not always present in each individual child with DCD, one or another kind of adjustment was present in all of them. The present results indicate that even a fairly easy locomotor task can challenge children with DCD. Whereas they seem to have found strategies to cope with their movement difficulties in a structured, uncluttered environment, it might be clear that these strategies could fail in daily living or sport situations.

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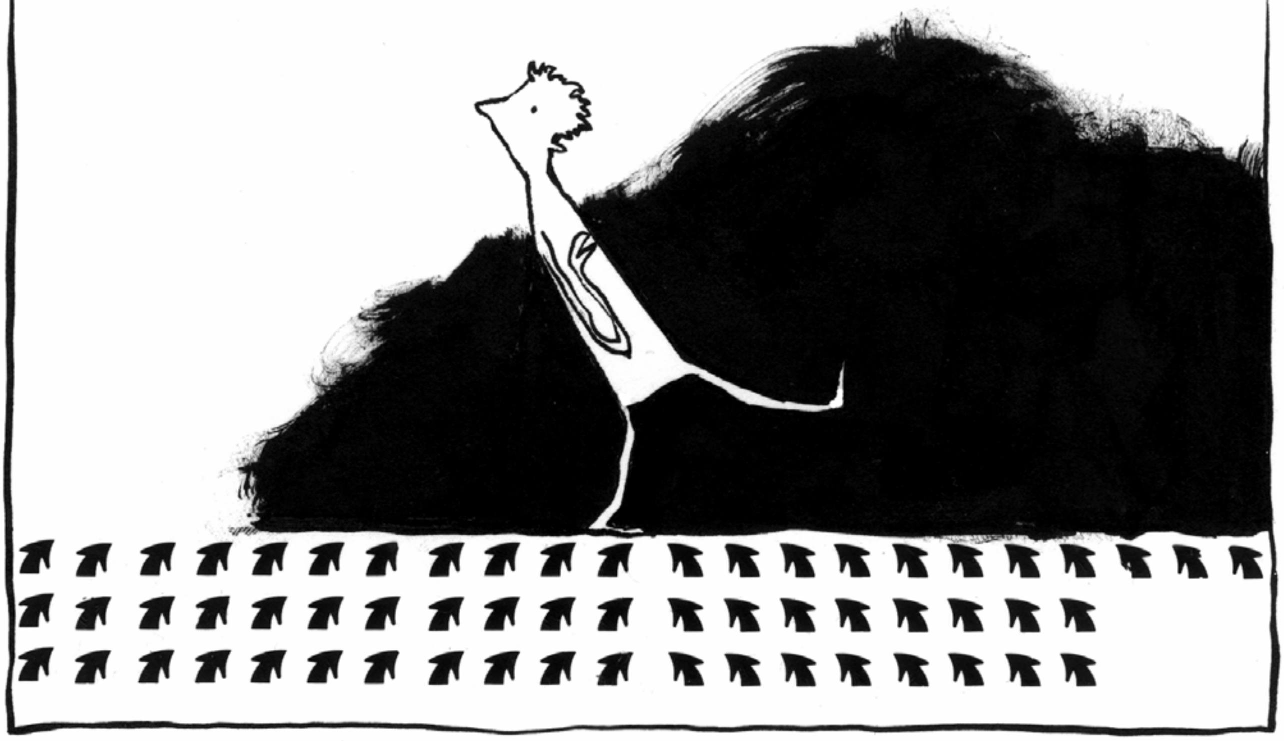
CHAPTER 4

VISUAL CONTRIBUTION TO WALKING IN CHILDREN WITH DCD



ABSTRACT

The present study investigates the contribution of vision to the control of walking in children with DCD. Children walked at their preferred speed on a straight, firm, and uncluttered walkway in a condition with normal lighting and in a dark condition, without visual information. Spatiotemporal gait variables were assessed by means of a three-dimensional ProReflex camera system and compared with the gait pattern of matched, typically developing (TD) children. In normal lighting the gait patterns of both groups were similar, with the exception of a prolonged double support phase in children with DCD. In the dark, step frequency and step length were decreased in children with DCD, resulting in a significantly slower walking velocity. In addition, an increase of the medio-lateral excursion of the centre of mass was observed in this group. In TD-children, adaptations to the spatiotemporal pattern remained absent. These results suggest that children with DCD are more dependent on global visual flow information for the maintenance of balance and the control of velocity during walking than TD-children. This increased dependency on visual control might be associated with a poorly developed internal sensori-motor model.

FJA Deconinck, D De Clercq, GJP Savelsbergh, R Van Coster, A Oostra, G Dewitte, and M Lenoir

Child: Care, Health, and Development, submitted

INTRODUCTION

According to DSM-IV (American Psychiatric Association [APA] 1994), the clumsy, uncoordinated movements in everyday motor tasks displayed by children with Developmental Coordination Disorder (DCD) do not stem from a medical condition. Because of the absence of muscular diseases, overt neurological conditions or mental retardation that could explain the impaired motor function, the search for potential underlying mechanisms has concentrated for a long time on information processing deficits. In this respect, the role of visual perception and the use of visual information in movement control in DCD has intrigued several researchers (e.g. Henderson et al. 1994; Lord and Hulme 1987; Smyth et al. 2001). Indeed, in a meta-analysis of 50 experimental studies on information processing deficits in DCD carried out by Wilson and McKenzie (1998), visuo-spatial processing deficiencies turned out to show the largest effect sizes, indicating that the motor coordination problems are most frequently associated with visual perception problems. Likewise, kinaesthetic and cross-modal perception has been often shown to be inferior in children with DCD (e.g. Mon-Williams et al. 1999). However, one should bear in mind that this frequent association of perceptual deficits and poor motor coordination does not directly imply a causal relationship (Henderson et al. 1994). Still, these findings lead to the suggestion that the perceptual processes involved in the registration, integration, and interpretation of sensory information may play a crucial role in the movement disorders of children with DCD. Unfortunately, these conclusions regarding perceptual deficits often stem from rather psychophysical tasks involving only limited motor function (e.g. Sigmundsson et al. 2003), which might obscure implications at a functional level. A way to better understand the link between putative perceptual deficiencies and the movement difficulties of children with DCD could be to test them in a more functional setting, using everyday movement skills, such as walking.

It is generally assumed that walking is controlled by a central pattern generator at the spinal level (Grillner 1981) and that higher level input from visual, proprioceptive, and vestibular channels are indispensable for establishing a stable locomotor pattern (Rossignol 1996). In one of his reviews Patla (1997) argues that the critical role of vision for locomotion lies in (1) the control of the equilibrium, (2) in adapting the basic pattern to the environmental constraints and (3) in guiding the body towards the endpoint. It is well established that the visual flow pattern generated by moving through the environment affords the necessary cues to regulate these different aspects of the locomotor pattern (Gibson 1958; Warren 1998). Previously, it was assumed that the visual control of locomotion predominantly depended on peripheral, lamellar structured flow (Schmuckler and Gibson 1989). However, more recent findings were able to qualify this notion and now it is generally assumed that both central and peripheral visual cues, i.e. global optic flow, are important (Bardy et al. 1999).

Evidence for this regulatory function of vision during locomotion was provided by studies where the visual field was manipulated. When walking subjects were exposed to a visual flow that was virtually accelerated, it was found that their walking velocity decreased in an attempt to match the walking velocity to the specified optically motion information (Bardy et al. 1992; Prokop et al. 1997). Additional support for the role of vision in tuning the walking velocity was provided in an experiment where walking subjects were deprived from visual information (Konczak 1994). Walking in an uncluttered environment without visual information appeared to be slower than with the eyes open.

Further, like in upright standing manipulation of the visual information during walking has been shown to affect balance. In a study by Stoffregen et al. (1987) it was found that children, ranging in age from 10 months to 5 years, staggered and fell more when the visual flow was perturbed by moving the room both in standing and walking. In a group of adults similar dramatic effects remained absent when they were exposed to a virtual visual flow during locomotion (Konczak 1994). However, Assaiante et al. (1989) suggested that, whilst the constraints on the control of posture are large enough, even adults strongly rely on optical information to control balance during locomotion. In an experiment where walking velocity was compared during overground walking and walking on a narrow beam under different visual conditions (from dark to high frequency stroboscopic illumination), the beneficial effect of visual cues appeared to be larger when postural constraints were more demanding (i.e. during walking on a beam).

Overall, it appears that vestibular and proprioceptive inputs can not fully compensate for the absence of vision to produce a normal gait pattern (Konczak 1994) and that this dependency on visual monitoring for the generation of a stable walking pattern is negatively correlated with developmental stage (Stoffregen et al. 1987). The imposed virtual optical flow turned out to provoke more falling and staggering in younger children (10 months to 2 years) than in older children (2 to 5 years). In a related study, Schmuckler and Gibson (1989) found that the negative postural stability effects of obstacles obstructing the walkway decreased with increasing age.

Given this primary role of vision in several aspects of the control of locomotion, it seems useful to investigate the contribution of vision to the control of the spatiotemporal pattern in children with DCD in order to better understand the nature and consequences of the frequently occurring perceptual processing problems on everyday skills. In children with DCD, it appears that when perceptuo-motor control involves several sensory modalities, vision turns out to dominate the other sensory system. This bias to visual information was shown in for example the control of posture (Wann et al. 1998). Contrary to typically developing children, the amount of postural sway during upright standing in children with DCD increased when visual cues were absent. In a recent analysis of the sensory contributions to the control of upright standing at our lab, children with DCD seem to display a decreased redundancy of the three sensory systems (vision, proprioception and vestibular system) to detect posture-relevant information. They give the impression not to 're-weight' the sensory information from the three different modalities (visiom, proprioception, and vestibular system) to the changes in environmental conditions or to compensate for sensory loss (Deconinck et al. submitted).

Increased reliance of visual feedback control was also the main characteristic of the children with DCD during fast, repetitive drawing movements (Smits-Engelsman et al. 2003). They attributed the problem of efficiently integrating online visual information during this graphical aiming task to a deficit in the open loop or feedforward control, which in turn was suggested to be caused by a poor internal representation of the movement as was put forward in studies on motor imagery by Wilson and his colleagues (Wilson et al. 2001). From this perspective, the increased dependence on visual feedback control of children with DCD was assumed to stem from the reliance on poorly developed internal models, which are suggested to represent a central, neural translation of the current state (position and velocity) of a limb (Wolpert et al. 1995).

So far, examination of the role of visual perception and control in children with DCD has been limited to rather fine motor tasks (e.g. handwriting in Smits-Engelsman et al. 2003) or skills without voluntary motor component (e.g. posture in Wann et al. 1998). In the present study, the hypothesized compromised sensorimotor relationships of children with DCD will be further investigated by examining the contribution of vision to the control of an everyday gross motor skill, i.e. walking. More in particular it will be examined and compared whether children with and without DCD show different adaptations to the spatiotemporal walking pattern when they are deprived from visual information. Because of the role of vision in the control of locomotor balance, adaptations to balance parameters such as the duration of the support phase or the width of the base of support can be expected. From the above findings that children with DCD are more dependent on visual feedback, it can be hypothesised that visual deprivation will affect the walking pattern of children with DCD to a larger extent than that of typically developing children.

METHODS

Participants

Twenty-four children between 7 and 9 years of age participated in this study: 12 children with DCD (10 boys and 2 girls) and 12 matched, typically developing children (TD). The children with DCD all attended a physiotherapist but were free from any medical conditions or symptoms of comorbid developmental disorders as assessed by a physician. They attended normal primary schools and none of them had an intelligence quotient below 85. Their mean percentile on the Movement Assessment Battery for Children (Henderson and Sugden 1992) was 5.0 (SD: 3.77, Range: 1-12; See Appendix 1c for details), with 8 children having a percentile at or below 5 while the remaining 4 had a MABC percentile between 5 and 12. The 12 typically developing children were recruited from four primary schools. They were matched on gender, age, stature, and body weight. In order to control for IQ, the children had similar marks for mathematics (Brusselmans-Dehairs et al. 2002). A physical activity questionnaire (See Appendix 2) was used to assess the movement profiles of the participants. By means of this survey it was possible to match the children on their usual degree and nature of physical activity. Detailed demographic data are presented in Table 1. The protocol of this study was in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethical Committee of the Ghent University. All children assented to participate and prior to the test parents gave their informed consent (See Appendix 3).

Table 1 Mean and standard deviations (in parentheses) of the demographic data of children with and without DCD.

	Children with DCD	Children without DCD
Sex	10 ♂ - 2 ♀	10 ♂ - 2 ♀
Age	7.8 (0.52)	7.7 (0.56)
Stature (cm)	126.8 (4.93)	127.5 (6.13)
Body Weight (kg)	25.6 (4.43)	25.6 (3.43)
MABC percentile	5.0 (3.77)	78.3 (17.28)

Materials

A walkway, 9.60 m long and 1.00 m wide, was surrounded by 8 ProReflex cameras (Qualisys, Sweden) with a sampling frequency of 240 Hz to register three-dimensional kinematics. Data capturing started after walking a distance of approximately 3.00 m and lasted about 4 s, covering a measurement volume of 3.00 m by 1.00 m. A live-sized Harry Potter puzzle was placed vertically at the end of the walkway (see Figure 1 for a view of the experimental set-up).

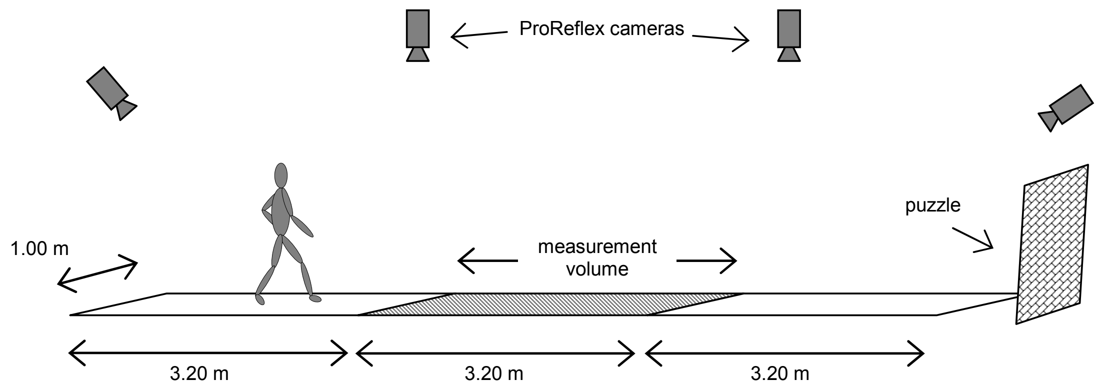


Figure 1 Side view of the experimental set-up

Reflective spherical markers were attached bilaterally to nine bony landmarks on the skin of the participants: the nail of the big toe, caput of the fifth metatarsal bone, lateral malleolus, lateral epicondyle of the femur, trochanter major of the femur, anterior superior iliac spine, acromion, lateral epicondyle of the humerus, acromion, and the processus styloideus of the ulna. In order to ensure the accurate determination of the centre of mass (CoM) two additional markers were placed on the processus of C7 and L5.

Procedure

During a short habituation period and warming-up the children were instructed to walk and run along the walkway approximately five times. Then, a demonstration of the test protocol was given by one of the experimenters. Subsequently the children walked two times along the walkway following the instructions of the experimenter. A third trial was allowed when it was clear that the children did not understand the instructions. To avoid that the children would focus too much on their walking pattern we made them believe that the real purpose of the test was to make the puzzle at the end of the walkway. The children were instructed to walk at their preferred, constant speed from the starting point up to the puzzle looking straight ahead. One of the testers was seated next to the puzzle and held a piece of the puzzle at eye level to draw the attention.

Two visual conditions, with and without normal lighting, were tested. In the condition without normal lighting the room was totally dark, with the exception of a small LED placed at eye level at the end of the walkway. The order of the two conditions was randomized, with half of the children per group starting with the normal lighting condition and the other half starting with the dark condition. Seven consecutive, neat walking trials were recorded per visual condition.

Data processing

The five trials with the best capturing quality were selected for further analysis. Raw three dimensional coordinates of toe and ankle were low-pas filtered at a cut-off frequency of 25 Hz for determination of foot strike and toe-off. These events were determined based on the velocity trajectory of the markers at the ankle and the toe, according to a validated and reliable procedure of Mickelborough et al. (2000). Subsequently, all trajectories were smoothed by means of a low-pass Butterworth filter at a cut-off frequency of 10 Hz.

The spatiotemporal variables of interest in this study were stride length, stride frequency, stride velocity, support time, swing time and double support time. In order to assess stability, step width ratio was calculated as the medio-lateral distance between the two ankle markers at their respective foot strike divided by the width of the hip.

The position of the CoM was calculated based on the 15 segment body model determined by the 20 markers. Relative segment masses and relative positions of the CoM of each segment were estimated with the regression equations for children of Jensen (1986). As a second measure of stability the amplitude of the excursion of the CoM in the medio-lateral direction was calculated.

Statistical analysis

For each dependent variable the mean of five strides, i.e. each full left stride of the five selected trials, was calculated for statistical analysis. Differences between children with and without DCD and the effect of vision were evaluated in a 2 x 2 (group x vision) ANOVA with repeated measures on the last factor. Post-hoc paired *t*-tests were used to further examine interaction effects. Alpha level for statistical significance was set at .05. Effect sizes are expressed as partial η^2.

RESULTS

Table 2 shows a summary of the results of the spatiotemporal variables. A significant group by vision interaction indicates that the stride times of children with and without DCD were differently affected by the absence of vision ($F_{1,22} = 11.599$, $p < .01$, $\eta^2 = .345$). In children with DCD the absence of normal visual information led to an increase in stride time ($t_9 = 5.196$, $p < .001$), whereas stride time was not affected in the TD-children. Further, the absence of vision resulted in shorter stride lengths for both groups ($F_{1,22} = 35.528$, $p < .001$, $\eta^2 = .618$), but the group by vision interaction indicated that the effect was again significantly larger for the children with DCD ($F_{1,22} = 8.089$, $p < .01$, $\eta^2 = .269$). Figure 2 illustrates that the former effects resulted in slower velocities when walking in the dark compared to walking with normal lighting ($F_{1,22} = 44.126$, $p < .001$, $\eta^2 = .667$). A significant group by vision interaction ($F_{1,22} = 21.022$, $p < .001$, $\eta^2 = .489$) again reveals that this condition effect could be solely attributed by the significant decrease of the walking velocity of children with DCD ($t_9 = 9.775$, $p < .001$). The walking velocity in the dark of TD-children remained virtually the same.

Table 2 Mean and standard deviations (in parentheses) of the gait variables for children with and without DCD in both conditions (with and without vision)

		Children with DCD			Children without DCD		
		vision	no vision		vision	no vision	
Stride time (ms)		837 (75.7)	897 (92.5)		843 (48.6)	840 (64.0)	**
Support time (ms)		516 (52.3)	563 (65.9)		511 (37)	507 (43.1)	**
Swing time (ms)		321 (27.8)	334 (34.5)		333 (16.6)	330 (21.7)	
Double support time (ms)		96 (16.2)	119 (23.5)		83 (12.3)	84 (15.1)	**, #
Support (%)		61.6 (1.69)	62.7 (2.01)		60.6 (1.36)	60.3 (1.72)	*
Swing (%)		38.4 (1.58)	37.3 (2.01)		39.5 (1.28)	39.3 (1.32)	**
Double support (%)		11.4 (1.30)	13.2 (1.75)		9.9 (1.30)	10.0 (1.38)	*, #
Stride length (mm)		1072 (92.8)	972 (85.5)		1097 (83.6)	1061 (79.1)	***
Step with ratio (%)		71.3 (13.8)	70.7 (9.3)		72.4 (13.16)	72.1 (13.6)	
Medio-lateral excursion (mm)		33 (7.8)	40 (9.8)		36 (6.4)	34 (5.6)	

* group by vision interaction: p < .05 ** p < .01 *** p < .001
# group effect: p < .01

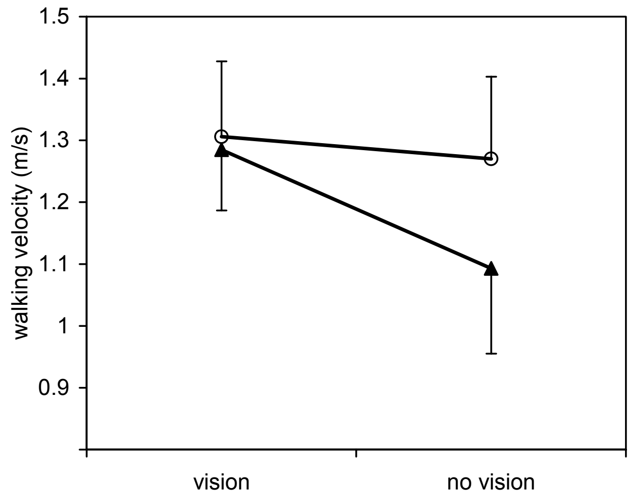


Figure 8 Mean walking velocity for both groups ▲: children with DCD, ○: children without DCD
*: group x vision interaction p < .001

The significant interaction effect for the stride time is accompanied by a similar interaction for the support time ($F_{1,22} = 22.209$, $p < .01$, $\eta^2 = .414$). This means that the increase of the stride time in children with DCD was mainly due to a significant increase of the support time ($t_9 = 6.567$, $p < .001$), which remained stable over the two conditions in the TD-children. Swing time did not appear to be affected by the absence of visual information, however a tendency to a group by vision interaction could be observed ($F_{1,22}$ = 3.807, p = .64, η^2 = .148). Together, this gave rise to a differential effect of vision on the relative support duration ($F_{1,22}$ = 6.116, p < .05, η^2 = .218), i.e. support time scaled to the total stride time, which significantly increased in children with DCD (t_9 = 4.275, p < .01) but not in the TD-children. This was accompanied by a logical decrease in relative swing duration ($F_{1,22}$ = 13.619, p < .01, η^2 = .382) in children with DCD.

A significant interaction effect for the double support time ($F_{1,22}$ = 6.783, p < .05, η^2 = .236) indicates that the increase of the total support time as a result of the lack of visual information in children with DCD could be primarily attributed to an extension of the double support phase. A similar group by vision interaction was found when double support time was scaled to the total stride time ($F_{1,22}$ = 7.313, p < .05, η^2 = .244). In addition, the significant group-effect for both absolute and relative double support time, points towards a general prolonged double support phase in children with DCD, in both conditions ($F_{1,22}$ = 7.945, p < .05, η^2 = .265 for the absolute values and $F_{1,22}$ = 13.958, p < .01, η^2 = .388 for the relative values).

With regard to the stability no group differences or visual condition effects were found for the step width ratio. A nearly significant group by vision interaction was found for the amplitude of CoM in the medio-lateral direction ($F_{1,22}$ = 4.007, p = .058, η^2 = .154). As a result of the lack of visual information the excursion of the CoM appears to increase for the children with DCD but not for the typically developing children.

DISCUSSION

The aim of this study was to investigate the contribution of vision to the control of walking in children with DCD. By comparing the spatiotemporal gait pattern in normal lighting and in the dark, it was found that children with DCD were significantly affected by the absence of vision. This resulted in a pattern of specific adaptations, with a lengthening of the support phase and a shortening of the stride length, ultimately causing a markedly slower walking velocity. The co-occurrence of spatiotemporal changes with a slight increase in the medio-lateral excursions of the CoM induced by the reduced visual information indicates that the gait adaptations are at least partially related to balance difficulties. In TD-children these adaptations remained absent.

The smaller steps, the longer support phase and the slower walking velocity bring about smaller destabilizing momentums (Hof et al. 2005), which alleviate the balance constraints of the task. In this respect, it is noteworthy that children with DCD display a longer double support phase than TD-children in the condition with normal lighting. This subtle difference in the temporal phasing of the walking pattern may be indicative for difficulties with the control of equilibrium even in the baseline condition (Sutherland et al. 1988). An earlier study on walking pattern of children with DCD did not find these abnormalities in the temporal phasing (Deconinck et al. submitted). However, it is likely that this lack of consistency may at least partially be attributed to the differences in task constraints, walking on a motor-driven versus overground walking. Overall, when walking in the dark children with DCD hark back to a walking strategy that ensures stability and thus safety, but it remains unclear why.

In an attempt to solve this problem, it is useful to rephrase the role of vision with regard to the control of this particular locomotion task, as argued by Patla (1997). The major functions of the visual system in the present task were (1) affording an information basis to control postural stability, (2) tuning the locomotor pattern to informational and environmental constraints, and (3) guidance of the body towards the goal. Since the walkway was a straight and uncluttered path with ample space at both sides, the constraints on the guidance-function may be considered very limited. Even in the dark condition, the small LED in the central field provided sufficient information to reach the endpoint in a safe and unconstrained manner. This local visual information however, was shown to be far less fundamental for the control of velocity and balance than global visual information, i.e. optic flow originating from the whole visual array (Bardy et al. 1992 and 1999; Warren et al. 1996). Therefore, the real challenges of the present task are related to the first and the second function of vision described above: resisting balance threats and maintaining the regular spatiotemporal locomotor rhythm, thus velocity, in the absence of vision.

In spite of the deprivation of visual information in the second, dark condition, the gait pattern of TD-children remained unchanged. The absence of balance problems of TD-children and the fact that they were able to keep up with their preferred speed in the dark, suggest that other sensory channels (such as the proprioceptive and/or the vestibular system) or higher cognitive functions were able to compensate for the loss of *visual information. Additionally, it might be that looming information or other local visual cues provided by the LED may have assisted in the control of the walking action in the dark. Children with DCD, on the contrary, did not appear to be sensitive to these local visual cues. Moreover, they could not easily shift to other sensory channels or re-weight sensory information when (peripheral) vision was removed. These deficits are thought to account for the adaptations to the gait pattern related to the control of balance and walking speed.*

Problems in re-weighting sensory information to environmental and task demands in children with DCD recently have been demonstrated with regard to static postural control (Clark 2005; Deconinck et al. submitted). A distortion of one or more sensory modalities during standing provokes an increase in the postural sway of children with DCD similar to that observed in younger, less mature children. From this perspective, the present results offer parsimoniously support for the suggestion that children with DCD have a poorly developed multisensory model that causes deficits in the re-weighting of sensory modalities. Instead, children with DCD seem to have developed other (movement-related) solutions to cope with the changing informational constraints.

Impairment or immaturity of the proprioceptive and/or vestibular sensory systems has been considered to be responsible for this deficit in re-weighting of sensory information when vision is absent. In support of this, various behavioral studies show that populations with less or decreased sensory abilities, such as children (Stoffregen et al. 1987), elderly people (Huitema et al. 2005) or Parkinson patients (Azulay et al. 1999) demonstrated increased dependency on optical flow information. However, problematic tuning of sensory information does not necessarily imply a degradation or immaturity of one of the sensory channels. It may also indicate a simple enhanced reliance on visual cues for the optimal performance of motor actions and hence a decreased amount of automaticity. Consider further the finding of Sigmundsson et al. (2003) that children with DCD have a higher motion detection threshold for visual cues in the central field, these findings might explain the fact that local visual information provided by the LED was insufficient to contribute to the control of locomotion. Therefore, children with DCD seem to rely on global, dynamic visual flow information to a greater extent than TD-children.

Smits-Engelsman et al. (2003) have linked this increased visual feedback dependency of children with DCD to the poor internal modelling hypothesis of Wilson et al. (2001). In the case of the present task, this internal representation deficit may induce problems in the cognitive mapping of the environment and the movement. If children with DCD have to rely on a poorly mapped environment this will call for more online control during execution. If this feedback information is only sparsely available, children will be forced to adopt a cautious and safe walking strategy. These suggestions, however, remain speculative and warrant further investigation.

In summary, when walking in the dark, children with DCD adopt a cautious and safe walking pattern, characterised by a slower walking velocity, resulting from shorter strides and longer double support times. In line with previous findings with regard to the control fine motor skills or posture, these adaptations reflect an increased reliance on global visual information for the control of balance and the perception of velocity during walking. In addition, these findings offer support to the notion of underlying deficits in the multisensory modeling of the perception-action relationships in children with DCD, causing problems with the process of re-weighting of sensory information.

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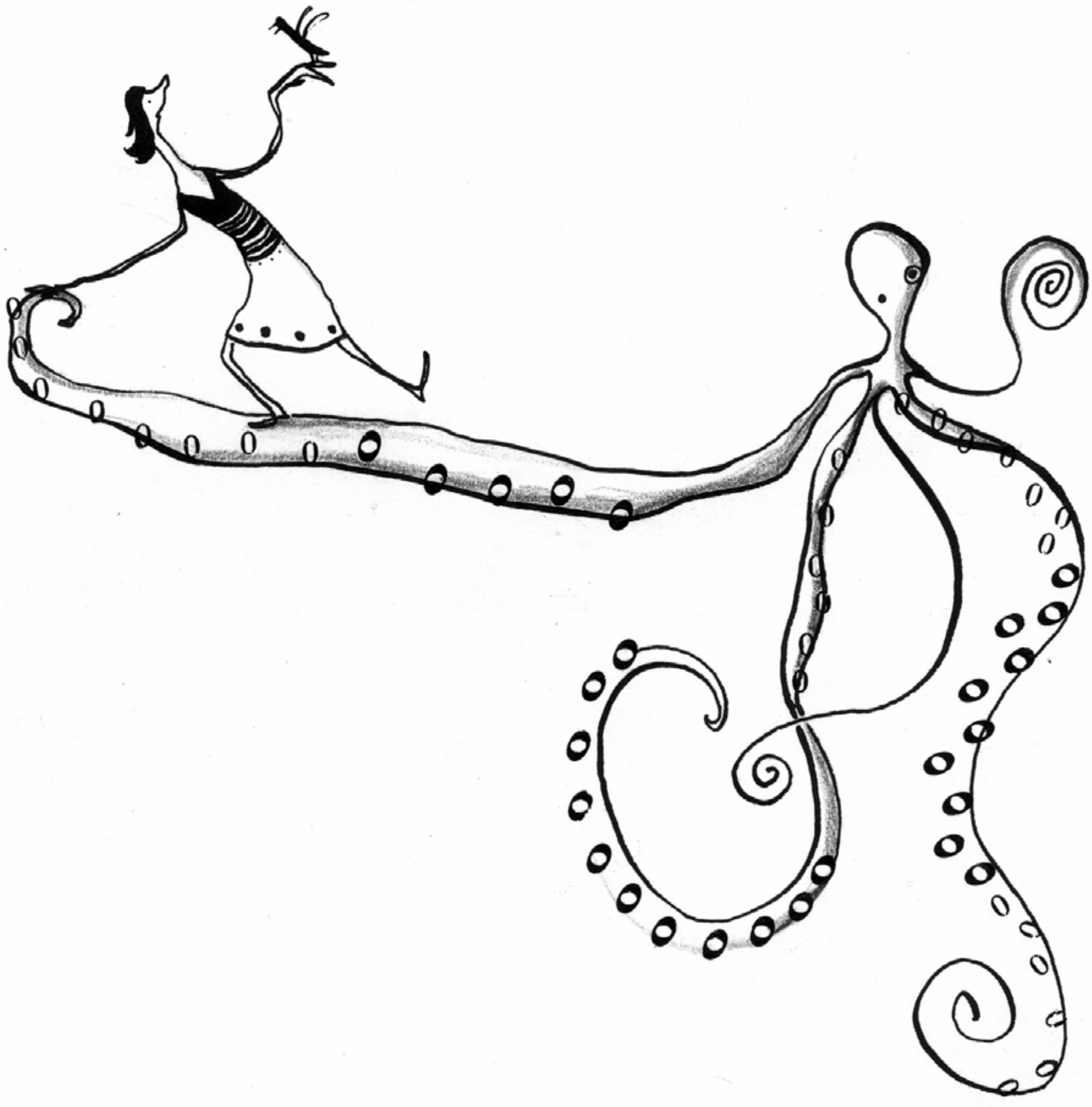
CHAPTER 5

SENSORY CONTRIBUTIONS TO BALANCE IN CHILDREN WITH DCD



ABSTRACT

In a group of 6- to 8-years-old children with Developmental Coordination Disorder (DCD) but without overt balance problems the integration of sensory information was tested and compared to that of typically developing (TD) children by means of a postural control paradigm. A Basic Balance Master force plate (NeuroCom Inc., Clackamas, OR-USA) was used to assess the mean sway velocity in four conditions (with or without visual information, on a firm or compliant surface). Children with DCD appeared to sway more than TD-children in all conditions, in spite of their similar score on the balance test items of the Movement Assessment Battery for Children. Furthermore, in contrast with the TD-children, children with DCD did not adjust the relative contribution of vision, proprioception or the vestibular system when sensory inputs were distorted. These results reveal distinct sensorimotor integration problems with regard to the control of posture in the children with DCD. These balance problems do not emerge with a traditional motor assessment battery, but they are likely hamper children with DCD in acquiring and performing basic movement skills.

FJA Deconinck, D De Clercq, R Van Coster, D Cambier, GJP Savelsbergh, and M Lenoir

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INTRODUCTION

Developmental Coordination Disorder or DCD is characterized by coordination problems in fine and gross motor skills in the absence of an overt neurological disease or mental retardation (APA, 1994). A common feature of children with DCD is poor balance. Experimental studies investigated the balance problems in more detail and resulted in the general conclusion that children with DCD show more postural sway in either one-legged (Geuze, 2003) or two-legged quiet stance (Przysucha and Taylor, 2004; Wann et al., 1998). These increased levels of postural sway in quiet stance are generally accompanied by an increased activity and co-activation of the muscles around the ankle joint (Geuze, 2003).

An intact postural control system has been shown to be of utmost importance in the development of skilled performance (Shumway-Cook and Woollacott, 1995; Johnston et al., 2002; Savelsbergh et al., 2005). This adequate control depends upon three sensory systems: the visual, the proprioceptive, and the vestibular system (Nashner et al., 1982). According to several conceptual models these three sensory inputs are dynamically regulated and integrated in adjustment to changes in the environmental conditions (Jeka et al., 2000; Peterka, 2002). This context-dependent sensory re-weighting is assumed to result in a proportionally corrective torque against the imbalance of the body, which is modeled as an inverted, inherently unstable pendulum (Peterka, 2002). The development of this re-weighting capacity in children is accompanied by a shift from primary visual dependent control at the age of 3 to a control involving visual, proprioceptive and vestibular information (Shumway-Cook and Woollacott, 1995; Forssberg and Nashner, 1982). This process results in stage-like decreases in postural sway and is suggested to result in adult-like behavior between 7-10 years of age (Shumway-Cook and Woollacott, 1995; Forssberg and Nashner, 1982).

Balance, however, is not a problem for all children with DCD. From several attempts that have been made to categorize the population into homogeneous subtypes it can be concluded that 13 to 27 % of the children with DCD actually have good balance as assessed with the balance tests included in a motor assessment battery, while they scored below normal in other areas (Hoare, 1994; Macnab et al., 2001). Still, as there are strong indications that children with DCD have difficulties in processing and mapping sensory information of different modalities (for review see Wilson and McKenzie 1998), the question arises whether the postural control system of this subtype without overt balance problems can be compared to that of typically developing children. Given the complexity of the sensory organization in the control of posture and given the importance of postural control for the development of skilled behavior, in depth assessment of postural control in children with DCD without clear, functional balance problems is important. For that purpose, the Clinical Test of Sensory Interaction on Balance (CTSIB) offers a useful paradigm where postural control in bilateral stance is investigated under different environmental circumstances (Shumway-Cook and Horak, 1986).

The aim of this study was to investigate control of posture and the contribution of the underlying sensory modalities in 6- to 8-year-old children with DCD but without overt balance problems. Therefore, the performance on a modified version of the CTSIB of children with DCD without balance problems as assessed with the Movement Assessment Battery for Children (MABC) was compared to that of typically developing children. In this modified version (mCTSIB) of the original CTSIB the sway-referenced condition is replaced by a condition with standing a compliant surface. The absence of balance problems on a motor test could simply lead to the suggestion that this subtype of children with DCD would not perform worse on the mCTSIB. This might imply that the movement disorders of this subtype are well limited to other aspects of gross and/or fine motor coordination than the control of posture and the related integration of sensory information. On the other hand, it could be argued that the normal score for balance which is based on functional balance tests included in a motor assessment battery may not a valid reflection of the integrity of the postural control system as a whole. Consequently, it may be expected that the information processing and integration problems of children with DCD as shown by Wilson and McKenzie will show up in a postural control test which does concentrate more on the sensory integration ability (Wilson and McKenzie, 1998). An inability to re-weight the sensory channels in adjustment to the environment is expected to cause increased amounts of postural sway, particularly in conditions with conflicting or distorted sensory inputs. In addition, comparison with the CTSIB-data of a 5-year-old reference group of TD-children might allow us to interpret postural control of 6- to 8-year-old children with DCD from a developmental perspective (Cambier et al. 2001).

METHODS

Participants

Ten children with DCD, all boys between 6 and 8 years old, were recruited for this study. Their mean age was 7 years and 6 months (SD: 11 mo). They all attended a physical therapist, were neurologically and mentally healthy, as assessed by a neuro-pediatrician and were free from signs of other developmental disorders. All children attended normal primary schools and scored below the 15th percentile on the Movement Assessment Battery for Children (MABC; Henderson and Sugden 1992). Their mean total impairment score on the MABC was 7.2 (SD: 4.6, range: 1-12; See Appendix 1d for details), while the scores on the cluster of static and dynamic balance (3 items) were consistently above the 15th percentile (See Materials and Procedure). Ten typically developing (TD) control children between 6 and 8 years old were recruited from primary schools (mean age: 7 years and 6 months, SD: 11 mo). They were matched with the children with DCD on sex, age, height, body weight. Furthermore, leisure time physical and sedentary activity was assessed by asking for their main sports practiced in leisure time and the hours spent in front of TV or game computer (See Appendix 2). Based on these data the children were also matched on the degree and nature of daily physical activity, in order to rule out differences related to the movement profile of the child. All TD-children scored above percentile 33 on the MABC, with a mean of 69.1 (SD: 22.3, range: 33-92). More details on both groups' characteristics of are shown in Table 1. Prior to the study, written informed consent was obtained from all parents, in accordance with the standards of the Ethical Committee of the University Hospital (See Appendix 3).

Table 8 Mean characteristics of children in each group and results of the independent-samples *t*-test.

	Children with DCD		TD-children		
Variable	*Mean*	*SD*	*Mean*	*SD*	t_{18}
Age (years)	7.7	0.8	7.5	0.9	0.18
Body length (m)	1.29	0.07	1.31	0.05	1.02
Body weight (kg)	25.7	4.1	28.0	4.3	1.22
MABC percentile	8.4	3.9	69.1	22.2	8.64*
MABC balance	0.7	0.5	0.3	0.6	0.71
Physical activity (h/week)	4.7	2.1	5.4	3.2	0.55
Sedentary activity (h/week)	9.7	4.7	10.9	4.2	0.58

* $p < .001$

Materials and Procedure

Prior the measurement of postural control the children were assessed with the MABC (Henderson and Sugden 1992). This test for motor coordination consists of eight items, divided into three clusters: manual dexterity (three items), ball skill (two items) and static + dynamic balance (three items). The sum of the individual scores on all eight items gives the total impairment score, a measure of the general motor skill. Scores higher than 8.5 (the higher the score, the worse the performance) correspond to scores below percentile 15 which was taken as a cut-off value for diagnosis of children with DCD (Geuze et al. 2001). The sum of the three items for balance (i.e. unilateral stance, jumping in squares and walking on a line) forms the sub-score for balance. A score of 3.0 corresponds to percentile 15 but as mentioned above, none of the boys participating in the present study had scores below that value.

For the assessment of the mCTSIB the Basic Balance Master system (NeuroCom Inc., Clackamas, OR-USA) was used. It is composed of a force plate connected to a computer equipped with the NeuroCom software. The force plate, 46 cm by 46 cm, consists of two footplates connected to each other by a pin joint. Four force transducers, one on every corner, measure the vertical forces exerted on the plate with a sampling frequency of 100 Hz. The NeuroCom software calculates the position of the centre of pressure (COP) and derives the position of the centre of gravity (COG) from the height of the subject, assuming that the body acts as an inverted pendulum. The modified Clinical Test for Sensory Interaction on Balance (mCTSIB) is integrated in the NeuroCom software and is an analysis tool designed to assess the amount of postural sway in bilateral stance. In this modified version the sway-referenced surface of the original CTSIB was replaced by a compliant surface. The test examines postural sway in four conditions: (1) on a firm surface with eyes open (FEO), (2) on a firm surface with eyes closed (FEC), (3) on a compliant foam surface with eyes open (FOEO), and (4) on a compliant foam surface with eyes closed (FOEC).

Three successive trials of 10 seconds (followed by a short rest period) were registered under each condition. A blindfold was used to ensure a full deprivation of vision in the eyes closed conditions. The compliant surface conditions consisted of standing on a foam cushion of 46 cm by 46 cm by 15 cm. All tests took place at the movement analysis lab of the Department of Movement and Sports Sciences. After a demonstration and explanation of the balance test, the child took place on the plate. The feet were carefully placed in the correct position as indicated on the plate to ensure a reliable calculation of the COG. Children were asked to adopt a relaxed, upright standing position and were instructed to stand as still as possible, while looking at the wall 2 m in front of them. The tester announced the initiation of the measurement and at the end of the 10 s lasting trial a bell-sound was given by the computer. During the trial no talking was allowed. In between the trials the tester encouraged the child and asked if he/she still felt comfortably.

Analysis

The first dependent variable of interest was the amount of sway of the COG, which is considered to be a general indicator of the integrity of the postural control system (Williams, 2002). The distance traveled by the COG was calculated based on the inverted pendulum model. Assuming that the body sways as an inverted pendulum the difference between COP and COG is proportional to the horizontal acceleration of the COG (Winter, 1995). Double numerical integration of the COG horizontal acceleration gives the horizontal displacement. This displacement can be converted into the angle of sway of the inverted pendulum. The NeuroCom software reported this amount of sway as the mean COG sway velocity (V). It is the total distance traveled by the COG during the trial (expressed in degrees) divided by the duration of the trial (10 s). The average COG sway velocity of the three trials per condition was statistically analyzed with the SPSS software package (version 12.0) by means of a 2 x 2 x 2 (Group x Vision x Surface) ANOVA. Prior to this analysis, intra-class correlation coefficients (Cronbach's alpha) of the sway velocities of the three trials per condition were calculated for each group separately to assess the reliability of the averages. All coefficients were higher than .90 which indicates a good reliability and justifies the use of the average values for further analysis (Portney and Watkins, 1993). Comparison of the mCTSIB results with the performance of a 5-year-old reference group was done with a one-sample *t*-test for each condition separately. The results on the mCTSIB of this reference group ($n = 41$) were obtained with similar apparatus and software and were reported previously by Cambier et al. (2001). To our knowledge, other reference data of the mCTSIB Balance Master test of older children were not available.

The contribution of the three sensory systems was investigated in more detail by means of the stabilization ratio (SR). Comparison the amount of sway in two conditions the SR offers a useful way to determine the relative contribution of the distorted sensory modality. This ratio is based on a logarithmic variance stabilizing transformation which accounts for the increase in variability of the V when the magnitude of V is larger. The Romberg-quotient, i.e. the ratio of the variable obtained in the eyes closed and the eyes open condition, traditionally used to measure the contribution vision, does not account for that increase in variability and has been demonstrated to be less reliable than the recently suggested SR (Cornilleau-Pérès et al., 2005). SR_v, the stabilization ratio for vision, was calculated as follows:

$$SR_v = 1 - \frac{\log(V_{FEO}+1)}{\log(V_{FEC}+1)}$$

In the above formula V_{FEO} stands for the mean COG sway velocity in the firm surface-eyes open condition and V_{FEC} is the mean COG sway velocity in the firm surface-eyes closed condition, which provides a measure of the contribution of vision when standing on a firm surface. In other words, SR_v gives an estimation of the extent to which the proprioceptive and the vestibular system can compensate for the loss of visual information. By replacing V_{FEO} and V_{FEC} by V_{FOEO} and V_{FOEC} respectively, SR_v or the visual contribution can be calculated when standing on a compliant, unstable surface, which is likely to compromise the input from the proprioceptive system. The contribution of proprioceptive input (SR_p) is calculated in a similar way:

$$SR_p = 1 - \frac{\log(V_{FEO}+1)}{\log(V_{FOEO}+1)}$$

SR_p gives an estimation of the contribution of proprioception to the control of posture when visual information is available. By replacing V_{FEO} and V_{FOEO} by V_{FEC} and V_{FOEC}, SR_p or the contribution of proprioception in the absence of visual information can be calculated. Group and condition effects were investigated with a 2 x 2 (Group x Condition) ANOVA for the SR of vision and proprioception separately. Post-hoc *t*-tests were used to further analyze interaction effects.

Finally, it was examined if there was a relation between the performance on a general motor test like the MABC and the performance on a specific test for postural control (mCTSIB on the Balance Master). Therefore, Spearman rho's correlation coefficients were calculated between the results on the Balance Master and the total impairment scores on the MABC. The relation between the performance on the mCTSIB and the balance performance on the MABC was examined by calculating Spearman rho's correlation between the sub-score for balance on the MABC and the amount of sway in the four conditions of the mCTSIB. The latter were also correlated with the raw scores on the item for static balance included in the MABC (i.e. maximal duration of unilateral stance).

RESULTS

Inspection of Figure 1 shows that children with DCD swayed significantly more than the TD-children ($F_{1,18}$ = 17.74, p = .001). The largest difference was situated in the FEC-condition (110 %) and in the condition where both vision and proprioception were distorted (FOEC) the difference was only 24 %. The effect of the factors vision and surface was also significant, indicating more sway without visual feedback ($F_{1,18}$ = 16.26, p < .001) and more sway in the compliant surface conditions ($F_{1,18}$ = 60.59, p < .001). A significant first order interaction was found between the factors vision and surface ($F_{1,18}$ = 40.66, p < .001), indicating that the absence of visual information affected postural control to a larger extent when standing compliant surface. The second order interaction was not significant.

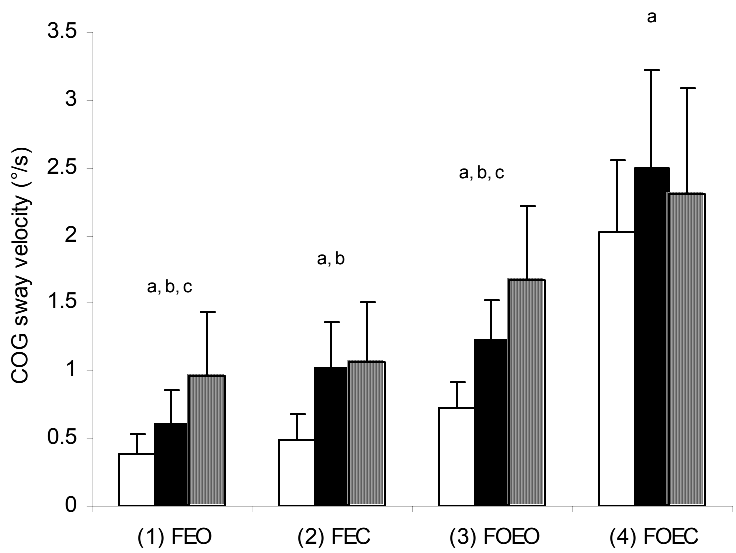

Figure 9 Mean values for COG sway velocity for all groups (TD-children: white bars, children with DCD: black bars; 5 years old reference group: shaded bars) in the four conditions (FEO: firm surface, eyes open; FEC: firm surface, eyes closed; FOEO: foam, eyes open; FOEC: foam, eyes closed).
a: difference between children with DCD and TD-children p < .05
b: difference between TD-children and the reference group p < .05
c: difference between children with DCD and the reference group p < .05

Comparison with the performance of the younger reference group revealed that TD-children performed better than the younger reference group in all but one condition, standing with the eyes closed on a compliant surface (t_9 = 12.42, p < .001 in FEO, t_9 = 9.73, p < .001 in FEC, t_9 = 15.11, p < .001 in FOEO and t_9 = 1.65, p = .13 in FOEC). Children with DCD in contrast, only performed better than the younger children in the two conditions where they could rely on visual information (t_9 = 4.48, p < .01 in FEO and t_9 = 4.66, p<.001 in FOEO). When visual information was absent, they performed at the level of the 5-year-olds (t_9 = 0.37, p = .72 in FEC, and t_9=0.96, p = .36 in FOEC).

With regard to the relative contribution of vision to the control of posture during standing, it was found that SR_v amounted to 0.32 (SD: 0.16) for children with DCD when standing on a firm surface. This indicates that the availability of visual cues reduced the logarithm of the mean sway velocity by 32%. As shown in Figure 2, the SR_v of the TD-children when standing on a firm surface amounted to 0.16 (SD: 0.08), which was fairly low compared to that of children with DCD (t_9 = 3.14, p < .01).

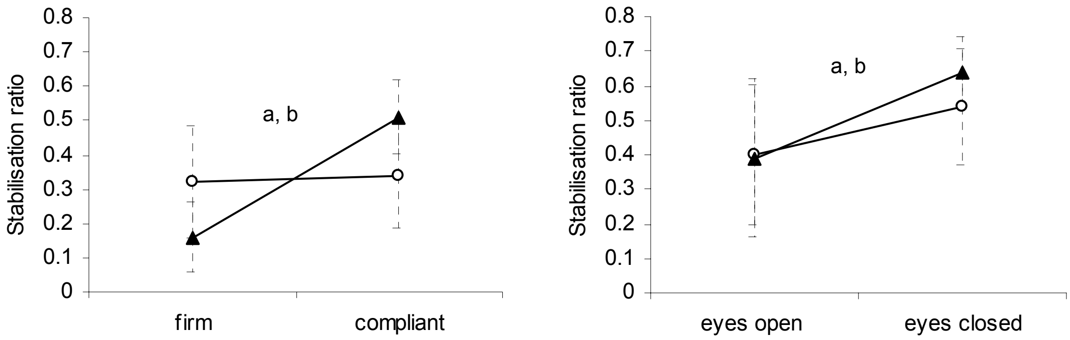

Figure 10 Stabilisation ratios (SR) for the contribution of vision (left panel) and proprioception (right panel); children with DCD are indicated with ○, TD children with ▲.
a: Group x Condition interaction p < .05
b: Condition effect p < .05

Furthermore, statistical analysis of this SR_v revealed a Group x Condition interaction effect ($F_{1,18}$ = 7.40, p < .05) indicating a differential adaptation between both groups of the contribution of vision during standing on a firm surface compared to standing on a compliant surface. Indeed, while the SR_v of children with DCD was significantly larger on a firm surface, the opposite was true for standing on a compliant surface (t_9 = 2.763, p< .01). The SR_v of the TD-children increased to 0.51 (SD: 0.11), whereas for children with DCD the contribution of vision remained virtually equal over the two conditions

($t_9 = .32$, $p = .76$). In this way, the Condition effect for SR_v ($F_{1,18} = 9.85$, $p < .01$) could be attributed to the increase of visual contribution in TD-children alone.

For SR_p, a significant interaction effect again revealed a larger increase of SR_p in the TD-children ($F_{1,18} = 5.12$, $p < .05$) when the contribution of proprioception was compared with and without visual information available. Post-hoc analysis indicated that the role of proprioception becomes more important when visual cues are absent in this group ($t_9 = 3.43$, $p < .01$), whereas this was not the case in children with DCD ($t_9 = .50$, $p = .63$).

The Spearman's rho correlation coefficients between the postural sway values and the scores on the MABC are presented in Table 2. A moderate but significant correlation was found between the MABC percentile and the amount of sway in the FEC and the FOEO condition. In contrast, no single significant correlation could be found between the MABC sub-score for balance and the Balance Master results, or between the score on the unilateral stance item and the Balance Master results.

Table 9 Spearman's rho correlation coefficients between the MABC scores and the amounts of postural sway in the four condtions (FEO: firm surface, eyes open; FEC: firm surface, eyes closed; FOEO: foam, eyes open; FOEC: foam, eyes closed).

	FEO	FEC	FOEO	FOEC
MABC total	-.430	.638*	.713*	-.349
MABC balance	.333	.416	.332	.187
Unilateral stance	.396	.416	.320	.159

* *p < .01*

DISCUSSION

The present study demonstrated that postural control measured by means of the mCTSIB of children with DCD in the absence of overt balance problems on a motor assessment battery differed significantly from that of typically developing children. The children with DCD displayed larger amounts of sway than their typically developing peers. This effect was large under normal environmental circumstances and under circumstances where only one sensory system was degraded, but it diminished when both the visual sensory information and the proprioception were distorted. In addition, the stabilization ratios indicate that children with DCD had more benefit from visual input when standing on a firm surface than the TD-children. However, the opposite was true when standing on a compliant surface. Also, TD-children compensated for the absence of visual cues by increasing the contribution of proprioception, in contrast to children with DCD, indicating a general re-weighting insufficiency in the latter.

The present results are in line with Wann et al. and Przysucha and Taylor who also found larger postural sway measures in children with DCD in bilateral stance (Przysucha and Taylor, 2004; Wann et al., 1998). Geuze (2003), however, only found increased measures of postural sway in children with DCD in unilateral and not in bilateral stance. The reason for this inconsistency may, at least partially, lie in the choice of the variable to characterize postural control. Maximal sway amplitude used by Geuze is rather a measure of the degree of destabilization at a specific moment (Geuze, 2003), while mean sway velocity used in the present study is more a reflection of the sway dynamics during the total duration of the stance. Being an expression of the path length covered by the CoG, this mean sway velocity has been shown to demonstrate a high reliability in several studies (e.g. Przysucha and Taylor 2004). However, because of the complexity of the CoP migration patterns some caution is warranted when interpreting postural sway measures based on a limited amount of measures (Duarte and Zatsiorsky 1999).

Further, it should be emphasized that the deviations in the control of posture of the children with DCD had no obvious implications at the functional level, as functional balance problems assessed with the three balance-items of the MABC were absent (all above the 15th percentile). Moreover, not a single fall occurred during administration of the Balance Master tests. The low correlation coefficients between the MABC balance cluster score and the COG sway velocity underpin this discrepancy. Task specificity can, at least partially, explain this paradox, but it has already been suggested that the discriminative power of the balance items of the MABC is rather low (Miyahara et al., 1998; Van Waelvelde et al., 2004). All together these findings point out that the Balance Master reveals differences in postural control at a deeper level, i.e. the level of sensory integration, than the functional level as the MABC does. In this way, they might question the validity of clear-cut subtypes, as suggested by others, since the absence of balance problems on a motor test apparently does not rule out distinct impairments at the level of postural control.

As many others have found, postural sway increased when sensory information was removed or distorted (Shumway-Cook and Woollacott, 1995; Nashner et al., 1982). With regard to the relative contribution of the individual sensory modalities, children with DCD appeared to show a greater dependency on vision in the firm surface condition, which corroborates the findings of Wann and co-workers (Wann et al., 1998). Geuze (2003) and Przysucha and Taylor (2004) however did not find evidence for a greater reliance on vision of children with DCD. Though, it should be noted that these findings were based on Romberg-quotients which have been shown to be less reliable than the stabilization ratios used in the present study (Cornilleau-Pérès et al., 2005). In addition, the fact that the children with DCD in the former studies were also selected based on their balance problems, could account for this inconsistency as well.

It turned out that TD-children benefited more from the most reliable sensory modality in a situation where one of the sensory signals was attenuated. In other words, the sensory systems that were challenged were more capable to compensate for less reliable or loss of other information in TD-children. These findings suggest a deviant weighting or integration of the three sensory modalities involved in postural control and difficulties in re-weighting of the three channels in response to the environmental changes in children with DCD. More particularly, there seems to be a problem in the inter-modality dependency which implies that when one sensory input becomes less reliable, other inputs are weighted more heavily (Oie et al., 2002). This is nicely illustrated by a comparison of the visual contribution under different surface conditions. The high increase of the stabilization ratio for vision when standing on a compliant surface in TD-children indicates an increase in the importance of visual cues when proprioceptive information is less reliable. This increase is absent in children with DCD, indicating that the ‘weight’ attributed to vision is not dependent on the reliability of the proprioceptive input. Similarly, TD-children increase the proprioceptive input in upright standing without vision, while again children with DCD seem to not to compensate for the lack of visual information. Modeling studies have shown that inadequate (re-)weighting can result in disproportionate (too much or too little) corrective torque against the sway inducing gravity-related torque (Peterka, 2002). This failure in “torque normalization” in turn, has been shown to result in increased oscillatory behavior and to be compatible with a number of pathological conditions. The present findings strongly correlate to the current models on sensory integration suggested by Jeka, Peterka and co-workers (Jeka et al., 2000; Peterka, 2002). However, future in depth analysis of the CoG signal should provide more information on the source of the change in balance control in this population. In addition, the above stated interpretations are not meant to attribute the differences or deficiencies in balance control to sensory re-weighting alone. As suggested by Oie et al. (2002) the influence of changes in control strategy may not be neglected but requires spectral analysis and comparison of experimental results to quantitative models. This strategy could imply differences in body dynamics such as an increase in stiffness as was found in some patients with vestibular loss (Peterka, 2002). Evidence for the possible involvement of increased ankle stiffness in the impaired generation of corrective torque in children with DCD has already been put forward by Geuze (2003).

From a developmental perspective, the less oscillatory behavior of TD-children speaks to the frequently suggested developmental and maturational process of sensorimotor integration for postural control (Shumway-Cook and Woollacott, 1995; Forssberg and Nashner, 1982). There, it also appeared that children younger than 7½ years seemed to be unable to balance efficiently when both visual and proprioceptive cues were degraded. Since in the present study only 5 out of 10 TD-children had reached the age of 7½, it was not unexpected that they did not perform significantly better than younger children in a condition requiring increased weighting of the vestibular channel (Peterka and Loughlin, 2004). The fact that children with DCD performed better in the eyes open condition, but dropped to a level of 5-year-old children in the eyes closed condition, again indicates the important role of vision in the control of posture in children with DCD. When available, vision can be used to slightly reduce sway compared to the younger reference group, but this compensation disappears when vision is removed.

Overall, our experimental data indicate that the feedback mechanism underlying postural control of children with DCD shows distinct impairments in the sensorimotor integration. The reduced ability to compensate or re-weight other sources of information may be specific to postural control, though is also likely to underlie problems in other skills as illustrated be the low MABC scores. Therefore, from a clinical point of view these findings point out that in diagnosing children with motor coordination problems and in developing a therapeutic plan, attention should be paid to a reliable and complete assessment of postural control, which should not only be based on the performance on a motor assessment battery. It should be acknowledged, however, that the severe selection procedure yielded a specific sample of children with DCD who experienced problems mainly in the domains of fine manipulative and ball handling skills. This calls for some caution when generalizing the findings of the present study.

In conclusion, children with DCD without distinct balance problems as assessed by the MABC exhibit more postural sway than TD-children in bilateral stance. The children with DCD seem to lack the capacity to adequately re-weight the information from different sensory sources in adjustment to the environmental circumstances. This reduced re-weighting capability indicates problems in the sensorimotor integration feedback process underlying postural control. The differences in the regulation of posture may be invisible for the eye of the clinician or may not emerge in a motor coordination test; however, they indicate a less efficient control of balance that can complicate coordination in all sorts of daily living activities. Given the importance of an intact postural control system for the execution of virtually all voluntary movements, these problems may be, at least partially, at the basis of the perceived motor problems in children with DCD. Since these findings are based on a relatively small and specific sample of children with DCD, future research is warranted in order to extend this knowledge to other types of DCD and to further disentangle the role of putative postural problems in the control of voluntary movements.

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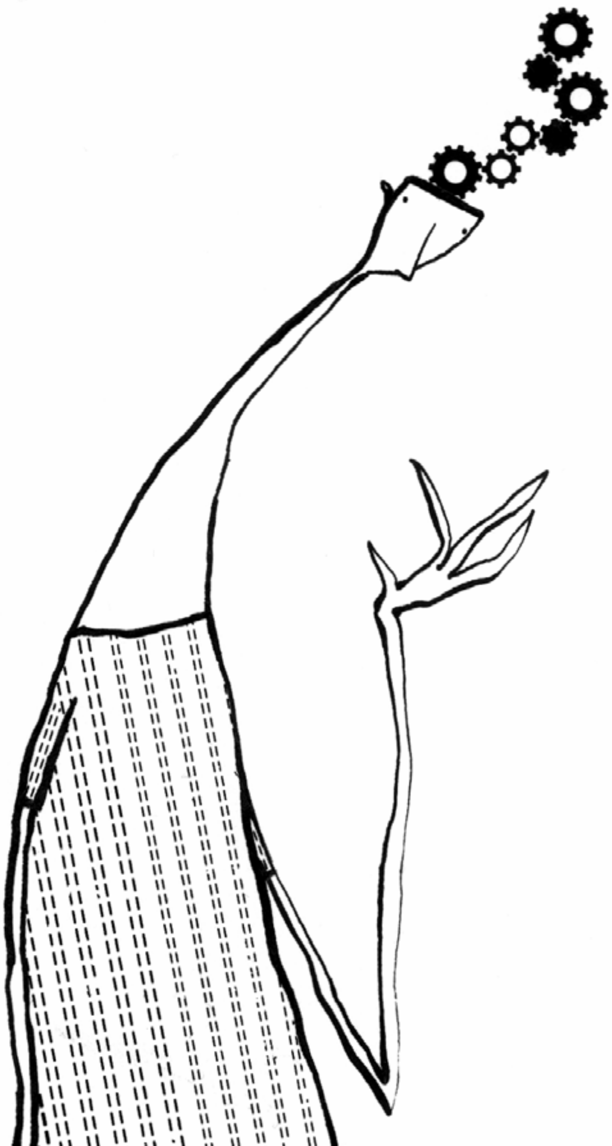
CHAPTER 6

GENERAL DISCUSSION



The studies presented in this dissertation are part of a research project that aims at providing objective, kinematic, and quantitative descriptions of a wide range of functional movement skills of children with DCD. This information enables validation and qualification of the findings from pure outcome measures and qualitative observations. In this way it is attempted to gain a better insight in the control and coordination of movements of children with DCD and to fill the gap between findings originating from information processing and motor control studies and the movement problems manifested in everyday life.

1. Summary of the research findings

A first movement skill that was investigated was catching. Interception of objects is essential to many daily activities and numerous playground activities or sports and catching provides an excellent way to study the precise control of a timed motor action in response to a visual stimulus. In the simple catching task presented in *Chapter 2*, where the focus was on the grasp phase, no differences in timing of grasp onset or hand closure were found between children with DCD and matched typically developing (TD) children without coordination difficulties. In addition, the temporal control of both groups appeared to be invariant to the variable ball velocity. However, the faster balls did cause a distinct increase of the hand closing velocity. While this adaptation occurred in the TD-children as well as in the children with DCD, group comparison revealed consistently lower maximal hand closing velocities for children with DCD in all three ball speed conditions. It was concluded that, although all children with DCD were shown to be poor catchers as assessed with the ball handling skill items of the M-ABC, this difference in performance was not due to their basic interceptive timing abilities, as evaluated in a simple setting. Instead, the lower hand closing velocities might suggest subtle deficits in the neuromuscular control, indicating that execution of this simple catching task was hampered at the efferent level, rather than at the level of information-processing.

A second important, everyday motor skill that was subject of our research was locomotion (*Chapter 3*). The purpose of this study was to investigate and compare the spatiotemporal control and kinematics of walking in children with DCD and TD-children. It was found that during walking on a treadmill, children with DCD used smaller steps and a higher step frequency to obtain a similar walking velocity as the TD-children. The absolute duration of the consecutive phases of the gait cycle (initial double support, single support, second double support, and swing) were shorter in children with DCD, but when they were scaled to the total stride time, the timing appeared to be similar. With regard to the whole body kinematics of the walking pattern, the most remarkable finding was that the trunk of the children with DCD was more flexed throughout the entire gait cycle, resulting in an increased forward inclination of the trunk. Increased flexion was also demonstrated for the knee in the initial part of the support phase. Further, children with DCD tended to place the foot flatter at initial foot strike and extend the ankle to a lesser extent just before toe-off, causing a less pronounced propulsion. These findings were discussed in the light of the immature picture of walking in children with DCD and possible underlying deficits in the proactive control of posture. An important finding with respect to the heterogeneous picture of DCD was that the pattern of the spatiotemporal and kinematic adaptations was not consistent among the children with DCD.

In an attempt to assess the importance of visual monitoring for the control of an everyday gross motor task, a consecutive study explored the role of vision in the control of locomotion in children with DCD (*Chapter 4*). A comparison of the spatiotemporal pattern during overground walking in normal lighting and in the dark revealed that for the establishment of their natural gait pattern children with DCD were more dependent on global visual flow than TD-children. While walking on a straight and uncluttered walkway with no visual cues available stride length was shorter and step frequency was higher in children with DCD, resulting in a considerably slower walking velocity. None of these adaptations occurred in TD-children. Apparently, the absence of visual cues resulted in a lack of perceptual information that could not be compensated by children with DCD and consequently resulted in adaptations with respect to the control of balance and speed. These spatiotemporal adjustments of the gait pattern during walking in the dark are in line with the atypical walking pattern of children with DCD on a treadmill. In both experiments increased task demands provoked by either manipulation of visual information or unusual walking dynamics caused by the interchange of power between the body and the treadmill resulted in a safer walking strategy. These results possibly suggest a reduced capacity to integrate and re-weight sensory information in response to the demands of the task and the environment in children with DCD.

In *Chapter 5* the focus of attention was not on a specific movement skill, but rather on one of the basic underlying components of virtually all voluntary movements:

the control of posture. Every human body is inherently unstable and an unimpaired and efficient control of posture is indispensable for optimal, skilled performance. In the preceding studies inferences to a putative inadequate control of posture in children with DCD frequently occurred and therefore in depth examination of the postural control system in children with DCD was a logical and essential step in this research project. Likewise, this study allowed for a more profound investigation of the sensory integration capacities of children with DCD. The integrity of the postural control system of children with DCD was explored by means of the assessment of the amount of postural sway under different environmental circumstances. It was shown that in bilateral upright stance, children with DCD displayed more postural sway than children without coordination difficulties in all four conditions (with or without visual information, on a firm or compliant surface). When perceptual modalities (vision, proprioception, and vestibular system) were distorted postural sway increased in both groups. Children with DCD, however, seemed depend more on visual information than TD-children. Moreover, a comparison of the stabilization ratios for the different conditions revealed that children with DCD were less capable of very precise re-weighting of multiple sensory inputs. Based on these findings, it was suggested that a poor or broadly tuned multisensory internal model is possibly a major factor in the inadequate control of posture of children with DCD. Moreover, this atypical postural control strategy may compromise the acquisition and execution of a wide range of movement skills since any voluntary movement involves by itself a postural perturbation (Latash and Anson, 1996). Strikingly, this atypical control of posture was encountered in children with DCD who did not show overt balance problems as assessed with the balance items of the M-ABC, calling for caution when interpreting balance performance based motor test batteries alone.

In summary, the preceding, exploratory studies provide a kinematical approach of some functional movement skills of children with DCD that are useful in refining the picture of their movement difficulties. In addition, they enable us to review some of the assumed underlying mechanisms from a more functional perspective than the traditional studies.

2. Aspects of information processing and motor control

2.1. Planning

From an information-processing point of view the very first act preceding the motor response implies the identification of the stimulus. Based on the interpretation of that stimulus the motor response is planned (Schmidt and Lee 1991). In this respect, two findings from the first study on catching render support for the suggestion that these information processing aspects are intact in children with DCD. First, it was found that children with DCD and TD-children initiated the grasp movement and reached maximal hand aperture, i.e. the onset of hand closure, at similar times before ball-hand contact. These similarities in temporal control indicate that the pick-up and use of information in the planning of the motor task take place in a similar way. According to Alderson et al. (1974), this strict temporal control has been argued to be the prerequisite for a successful catch and the absence of timing differences between both groups suggests that children with DCD are able to meet these important temporal constraints. Second, in line with a constant time-to-contact or tau-margin strategy (Lee and Young 1985; Savelsbergh et al. 1992) the temporal control, i.e. the occurrence of crucial temporal landmarks, remained constant over the three ball speed conditions for both children with and those without DCD. Instead, adjustments in response to the speed of the upcoming ball occurred at the level of the maximal closing velocity of the hand. In correspondence with the findings of van der Kamp (1999) a higher speed of the approaching ball caused an increase in the peak movement velocity of the hand in TD-children as well as in children with DCD. Thus, children with DCD, similar to TD-children, demonstrate a tight coupling between the identified information, present in the trajectory of the oncoming ball, and the control of the action that enables them to plan the catching movement accurately and to tune the baseline control to the informational constraints of the task. However, the lower overall hand closing velocity of children with DCD suggests a deficit in the execution of the motor action. In line with findings of Lundy-Ekman et al. (1991) and Raynor (2001), neuromuscular deficits causing increased levels of co-activation may be responsible for this decreased closing velocity of the children with DCD, although these speculations certainly warrant further investigation. Still, the main message of these results is that the rudimentary ability to plan, time and adjust a motor action in response to a visual stimulus seems to be intact in the children with DCD.

2.2. Sensory integration

The previous findings suggest that the coupling between information and movement appears to be intact in a simple, unimodal condition, i.e. when the movement to be performed does not require a large amount of degrees of freedom and is predominantly dependent on visual information. Further research however, revealed that when this visual information needs to be integrated with proprioceptive and vestibular information into a multisensory model, such as in the control of posture, problems are likely to occur. In normal upright standing on a firm surface, children with DCD display more postural sway than control-children even when the perceptual systems are not manipulated. Geuze (2003) found that this less adequate control of posture was associated with a high degree of co-contraction of the lower leg muscles, which may be assumed to compromise the regulation of the torque generation to control the unstable body. Our research however, concentrated on the sensory systems contributing to the control of posture and the findings suggest that a deficient integration of the three sensory modalities is also likely to play an important role in the problems associated with postural control of children with DCD. When perceptual information was removed or distorted, children with DCD appear to be less capable to compensate for this loss and re-weight the contribution of other sensory channels in response to the new task constraints. This decreased sensory compensation capacity is associated with an increased reliance on (reliable) online visual information. In *Chapter 3* and *4* it was shown that the reduced sensory integration capability not only compromises the adequate control of posture but can also prevent children with DCD from establishing their usual walking pattern under visual restrictions. The absence of global optical flow resulted in kinematic and spatiotemporal gait adaptations indicating that, in contrast with TD-children, the remaining sensory modalities (proprioception and the vestibular system) did not provide an appropriate perceptual base to control walking in children with DCD. Because of this integration deficit they appear to fall back on a more conservative movement control that relies on visual monitoring, a characteristic that also has been demonstrated with respect to the control of fine motor goal-directed behavior, such as the aiming studies of Rösblad and von Hofsten (1994) or the writing experiments of Smits-Engelsman and co-workers (2003).

An increased reliance on visual feedback or deficient feedforward control is suggested to be the result of a poorly developed internal model. According to Wolpert et al. (1998) an arrangement of such models, which contain a central, neural image of the sensorimotor relationships of the dynamic behavior of the motor system, plays an indispensable role in the control of voluntary movements. When an optimal representation of the current state of the body segments participating to a movement and knowledge of the sensory consequences of a motor command are available, the CNS is assumed to have the capacity to compensate for the slow and complex nature of the motor effector system by enabling movement control in a feedforward manner (see Wolpert et al. 1998 for review). The assumption of an impaired or poorly developed internal model has already been made by Kagerer and colleagues (2004) based on the results of a drawing experiment where visual feedback was manipulated. When exposed to visual feedback rotation, drawing kinematics of children with DCD appeared to be less affected than in controls, suggesting a less well-defined or noisier reference to detect performance errors. Furthermore, on removal of the distortion the TD-children displayed aftereffects, indicating that the experienced incompatibility between the novel visual space and the motor space had incited the children to update the visuomotor map or internal model. Similar aftereffects remained absent in the children with DCD supporting the notion that their initial internal model was too ‘broadly tuned’ to detect changes in the visuomotor space, or that they were not able to adjust it to the new sensorimotor relationship. From this point of view, the less adequate postural control characterized by increased amounts of sway and underlying deficits in the sensory re-weighting capacity together with an increased reliance on visual monitoring observed in *Chapter 3*, *4* and *5* render support for this less well-defined or ‘broadly-tuned’ internal sensorimotor model hypothesis in children with DCD.

2.3. Implications of poor postural control

The foregoing implies that the impact of a poorly developed sensorimotor internal modal on the movement control is task and context specific and depends on the dynamic interaction of the organismic, environmental, and task constraints that are involved (Newell 1986). Given the indispensable role of an optimal sensorimotor relationship for the control of posture (Oie et al. 2002; Peterka 2002), tasks requiring (anticipatory) postural adjustments are highly vulnerable. This can be further illustrated with the findings of a second catching experiment, not reported in this dissertation (Deconinck et al. 2004). In contrast with the good catching performance in the seated catching task of *Chapter 2*, the scores of children with DCD were well below that of TD-children in a catching experiment where children stood upright, had to locate the interception point by themselves and transport their hand to the desired point in order to catch the ball. A remarkable finding was that although temporal differences were absent in seated catching, subtle disruptions in the timing of children with DCD could be observed when standing. It appeared that the catching performance of children with DCD was, at least partially, compromised by a delayed movement onset. This jeopardizing role of a less adequate postural control on the kinematics and the success of catching is in line with recent findings of Savelsbergh et al. (2005), who found that a decrease of the postural constraints resulted in an increase of performance in bad catchers. Likewise, in the present study the increased amounts of sway as a consequence of standing upright and the destabilizing torque provoked by lifting the arm appeared to prevent children with DCD from integrating the initially accurate timing of the catch into the global control of posture. Thus, it seems that in some cases not the control of the voluntary movement itself is the major problem, but rather the related postural adjustments which in turn hamper efficient movement control. In this way, postural instability is likely to affect virtually all voluntary movements involving postural adjustments (Johnston et al. 2002). Furthermore, this postural instability might restrict the exploration of the perceptual motor workspace, which has been shown essential for the development of the sensorimotor internal model and hence for the acquisition of motor skills (Berthouze and Lungarella 2004; Vereijken et al. 1992).

3. The picture of DCD

3.1. The Movement Assessment Battery for Children (M-ABC) into perspective

An important issue of this research project is the question: Do the movement kinematics of children who perform inferiorly on a motor test (M-ABC) differ from that of children who perform well? In other words, do the movement kinematics provide a possible explanation for the poor performance, based on outcome scores? Indeed, the original purpose of this research was to examine to what extent movement trajectories of children with DCD differ from those without, and in this way to provide a kinematic validation of the M-ABC scores. It should be recognized however, that the findings on catching, walking and postural control are insufficient to discuss all aspects of (un-)skilled motor behavior. In this way the studies presented here are only an initial and incomplete step towards a comprehensive movement analysis of the skills assessed in the M-ABC. Still, our data provide supplementary insight into the motor problems of children with DCD and they put the outcome scores of the M-ABC into perspective.

First, the pendulum catching task which provides a useful paradigm to investigate the precise control of the grasping phase of a catch (Savelsbergh et al. 1991), revealed that timing errors are not likely to be responsible for the poor ball skills of children with DCD as assessed with the M-ABC. Instead, neuromuscular deficits as illustrated by the smaller grip force, expressed by hand closing velocity, or postural control problems which might cause a disruption of the perceptual-motor organization, appear to be more plausible underlying mechanisms of the inferior ball skill scores of children with DCD.

Our data further indicate that the absence of balance problems at the functional or behavioral level, as assessed by the balance items of the M-ABC, does not necessary imply an intact postural control system. Previous research has already pointed out the low discriminative power of the balance items of the M-ABC (Miyahara et al. 1998; Van Waelvelde et al. 2004). Given the negative influence of postural control problems on the acquisition and execution of a broad range of voluntary movements (e.g. catching: Savelsbergh et al. (2005) or reaching: Johnston et al. 2002) a reliable assessment of static and dynamic balance skills constitutes an indispensable part of any motor test. Our findings therefore demonstrate that the balance items of the M-ABC, at least of the first and the second age band (i.e. 4-6 and 7-8 years of age), require a revision. As supported by the results on the modified Clinical Test of Sensory Interaction on Balance (mCTSIB; see *Chapter 5*) a balance test challenging the proprioceptive and vestibular system might show more discriminative power.

Overall, the distinction made between children with DCD and rigorously matched TD-children based on the M-ABC was also reflected in the comparison of several crucial movement parameters investigated with our kinematic approach. This confirms the usefulness of the M-ABC as a tool for identifying children with atypical movement behavior. Still, the answer as to which movement variables distinguish both groups is not straightforward and principally depends on the specific requirements of the task. Additional research covering a wider range of functional everyday movements is warranted in order to provide a more comprehensive picture of the underlying movement patterns resulting in inferior performance on the M-ABC.

3.2. Abnormal, atypical, or adapted?

In an essay on the normality of movements in atypical populations Latash and Anson raise the question if the observed motor patterns, which may be rather different from those seen in healthy persons, are actually abnormal, and should be corrected (Latash and Anson 1996)? They argue that because the mechanisms of normal motor control still are generally unknown, the notion '(ab)normality' should b handled with caution and often is a misnomer. This rather philosophical discussion can possibly lead to a better understanding of the place of motor disorders such as DCD on the movement spectrum and by consequence to implications for treatment.

Without going in too much detail it seems useful to provide some background on the approach of Latash and Anson (1996). It builds on the Bernstein problem of overcoming or mastering redundant degrees of freedom (Bernstein 1967). Because the number of degrees of freedom (DOFs) of a limb, during most voluntary movements, exceeds the number of variables (dimensions) necessary to execute or describe a motor task, there are an infinite number of solutions or limb configurations to perform a particular movement. Several constraints (organismic, environmental, and task; Newell 1986) may help to reduce the number of DOFs but in most voluntary movements there is no unique solution. This implies that during the process of generation of a voluntary movement (understanding - generating time patterns - execution), the central nervous system (CNS) can choose from a set of strategies of muscle coordination to achieve a single movement outcome. This choice is suggested to be based on a set of coordinative rules, which restrict the amount of patterns of activation but do not solve the problem unambiguously, and secondary considerations or priorities of the CNS. At this time, these priorities are generally unknown, although some attempts have been made at deciphering the priorities mostly based on functions related to 'comfort' or 'efficiency' (e.g. Vanrenterghem et al. 2004).

The framework is illustrated in Figure 1. The central part of the movement spectrum represents the normally observed variability as displayed by an average population and controlled by a dynamic interaction of the CNS priorities, task, environmental, and structural constraints.

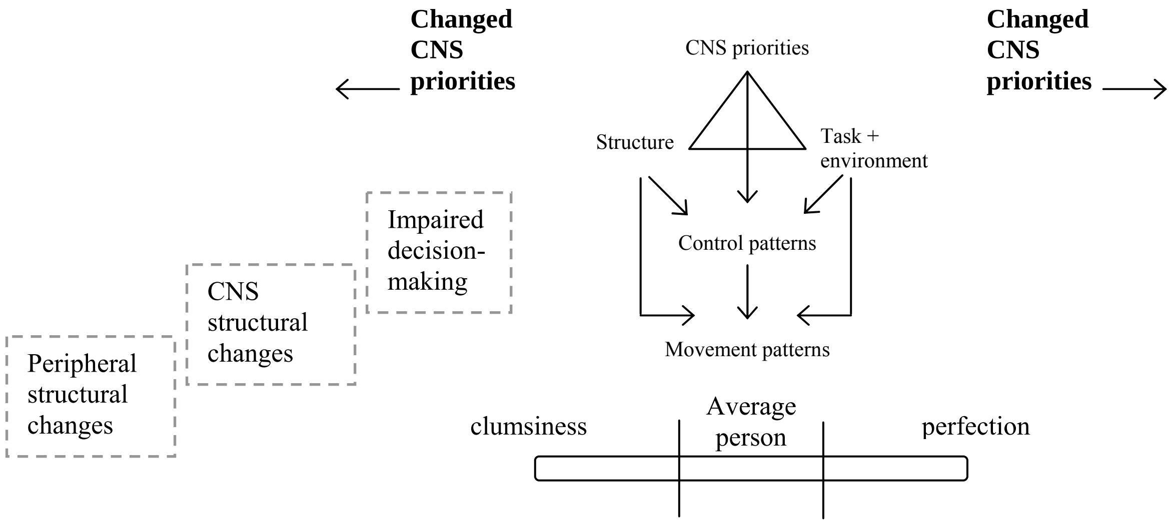


Figure 1 The spectrum of typical movement patterns. (Adapted from Latash and Anson 1996)

Within the limits of this variability the CNS priorities are basically the same, but there are situations where the CNS may prefer to reconsider its priorities. In the case of failure or change of one or more components of the motor system (such as vestibular dysfunction or limb amputation), when the task requires extreme demands (like in top performances) or when the external conditions are abnormal (e.g. a slippery floor) the CNS will be forced to abandon the common priorities and search for changed priorities that meet these different conditions. This basic assumption, namely that the CNS may solve the problem of redundancy differently for different states of the system for movement production, may result in movement patterns that differ from the 'normally observed patterns'. In this view, many of the deviating, atypical movement characteristics of children with DCD should not be considered as abnormal, but rather as adaptive and stemming from changes in the CNS priorities. It may be that the CNS of children with DCD prefers to function sub-optimally rather than risk the total failure, because of less well defined relationships in the sensorimotor model. For example, slowing down walking speed or extension of the double support phase may be a reaction to preserve stability, which may be threatened by impaired anticipatory control resulting from a poorly developed sensorimotor model.

4. Limitations and future directions

4.1. Generalization of the results

By accurately registering and analyzing everyday movements it was attempted to provide a more comprehensive picture of the movement problems of children with DCD. In this way, this research project is one of the very few studies on DCD concentrating on the major problems of the children: motor coordination in everyday skills. The limitations of the studies presented in this dissertation are generally related to the methodological complexity associated with the measurements and the analysis of the data of this kind of movement studies. Data registration and processing of full body kinematics is time-consuming and labour-intensive and so far only a few basic movement skills of the entire, broad spectrum have been examined. At the start of this research project we chose to cover several movement skills, rather than to concentrate on one particular skill. Obviously, given the severe time constraint this has prevented us from offering an in-depth analysis of all skills that have been studied. For example, the paradigm used for catching focuses on the timing capacities and the adaptive behavior of the grasp phase, without accounting for other important aspects of the skill. Therefore, generalization of the findings discussed in this dissertation should be made with caution. This work only offers a base of knowledge to build upon and future research should attempt to complete this incomplete picture. In this respect, in-depth analysis of basic skills as well as extension of the present findings to a broader range of skills is warranted.

A second and important consequence of these methodological difficulties is the fact that all studies are limited to relatively small samples. According to Bates et al. (1992), who determined statistical power for different trial and sample sizes by means of a mathematical model, the sample and trial sizes used in the studies presented in this dissertation, are large enough to ensure a statistical power that is appropriate for the study human movement. However, bearing in mind the widely recognized heterogeneity of children with DCD, this small sample complicates the generalization of our findings to the entire population of DCD. Moreover, the severe selection procedure appears to have yielded a specific group of children with DCD that seems to perform fairly well compared to previously reported studies, which again hampers the extrapolation of our findings. In order to increase our insight into the heterogeneous picture of the disorder, future research should pay attention to this variability in performance. Larger samples will enable us to compare the movement patterns between different subtypes of children with DCD.

4.2. Suggestions for treatment

The source and at the same time the ultimate goal of research into DCD is often stimulated by the question how to treat DCD in order achieve a sustained effect of practice. Based on the results of the present research, concrete therapeutic implications would be too optimistic and unfounded; however, some clues to intervention can be made. According to the above cited approach the different movements of children with DCD in most cases are not ‘wrong’ and therefore do not directly need to be corrected to movement patterns that belong to the so-called ‘normally observed variability’. Instead of focusing on movement patterns, the treatment should concentrate on functional behavior, while exploiting the CNS adaptive abilities. Given the possible negative influence of the sensorimotor model on the motor behavior of children with DCD, the therapist could aim at strengthen the internal couplings in the sensorimotor model. For this purpose, the therapist should provide a motivational climate in which the CNS is forced to actively reconsider its reliance on feedback control and switch to a more proactive monitoring of movement execution in different tasks and environmental circumstances. Given that postural control deficits hamper the adequate and efficient acquisition of motor skills, the use of whole-body tasks should be preferred over isolated motor exercises. Furthermore, treatment not only should be directed towards ‘functionality’ but also towards coping with ‘dysfunctionality’. By offering children experiences of success and teaching them to deal with unsuccessful performance therapists can and should fulfill an important psychological role in the prevention of emotional problems.

4.3. Future perspectives

In this research, the analysis was concentrated on specific, discrete variables which are known to be reliable and crucial parameters of a particular movement. In this way, our findings are related to the control of movement skills, rather than to the coordination which has been proposed to be the function that constrains the potentially free variables into a behavioral unit (Kugler et al. 1980). A more dynamical approach, considering the entire movement trajectory and the inter-segmental relationships instead of discrete parameters, could shed a new light on the movement coordination of children with DCD and will enable the study of DCD to go beyond the pure parameterization of movements. In addition, other measurement techniques such as electromyography or neural imaging should enable us to combine knowledge stemming from behavioral motor studies with findings at a deeper level. Such a global scientific approach will serve not only to provide a better insight in the movement problems of children with DCD, but also as a window into the basic motor development as a whole. Ultimately, this knowledge should yield dividends for a purposeful, adequate and effective treatment of movement disorders in children.

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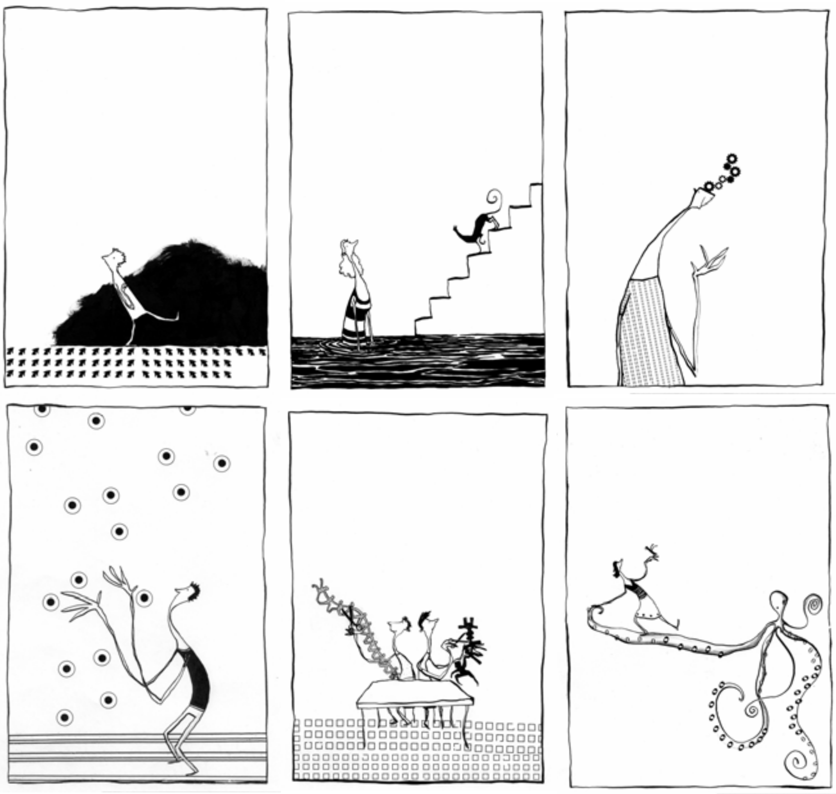
SUMMARY - SAMENVATTING



1. English summary

1.1. Background

During their development the majority of children seem to acquire and to master a broad spectrum of motor skills spontaneously. However, many children consistently show problems in performing daily motor activities in a fluent and goal-oriented way. In some occasions a medical (e.g. cerebral palsy), intellectual (e.g. down syndrome) or behavioral (e.g. autism) condition can explain these children's manifest clumsiness, but an overt condition is not always identifiable. According to DSM-IV[1], these clumsy children are diagnosed as having Developmental Coordination Disorder (DCD). Daily activities that require motor coordination are substantially below that expected given the child's chronological age and measured intelligence. This can be manifested by for instance dropping things, poor performance in sports or illegible handwriting. DSM-IV further prescribes that the coordination difficulties should significantly hamper children with academic achievement and activities of daily living and if mental retardation is present, the motor difficulties are in excess of those usually associated with it.

The population of children with DCD is very heterogeneous. Some children with DCD have motor problems that are confined to fine motor skills, such as fluently writing, tying shoe laces, or properly eating with knife and fork. Others mainly suffer from gross motor deficits manifested in for example problematic ball catching, uncoordinated locomotor skills or the inability to perform a nice soccer kick. The most severely affected children with DCD display deficits in fine as well as gross motor skills. This heterogeneity, together with the strong overlap with other developmental disorders, such as ADHD, dyslexia, or autism complicates the formal diagnosis of DCD.

Currently, little is known about the underlying mechanisms of the impairment. Although deficits in visual-spatial processing, kinesthetic perception and cross-modal perceptual integration have been identified, the findings are equivocal and often lack functional relevance. Further, children with DCD often display slower reaction and movement times together with an increased variability of performance on a wide variety of motor tasks. Several studies show that the coordination problems of children with

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[1] DSM-IV, published by the American Psychiatric Association (APA), categorizes all psychiatric diagnoses. The manual prescribes the criteria for diagnosing all mental health and developmental disorders of adults and children. [American Psychiatric Association. (1994) Diagnostic and statistical manual for mental disorders. 4th edn. Washington, DC: American Psychiatric Association.]

DCD frequently are characterized by a poor timing and force control, which seems to be associated with increased amounts of muscle co-activation. These information processing and motor control studies offer a comprehensive insight into several underlying mechanisms of motor performance. However, because the motor response in these studies is limited and often lacks functional relevance, generalization of the above findings to everyday motor tasks can be problematic. Moreover, our current knowledge about the way children with DCD move is mainly based on qualitative observation and result-scores on motor test batteries. A detailed kinematic analysis of several movement skills could provide a deeper insight into the motor behavior of children with DCD and into the pathways to motor coordination problems in everyday life.

1.2. The research

The main aim of the present research project was to provide a detailed kinematic description of a number of basic movement skills, which occupy an essential and relevant place in the everyday life of children with DCD. This accurate description of the children's motor behavior should refine the picture of their motor coordination problems. Further, this precise information about the movement trajectories of children with DCD should allow us to put their performance on a motor test battery, like the Movement Assessment Battery for Children, into a broader perspective. A second purpose was to extend current knowledge of information processing and motor control deficits of children with DCD to a functional level. Since percepuo-motor deficits have been tested almost exclusively with rather psychophysical tasks with limited emphasize on the motor component, an approach that aims at confirming these findings in a more functional setting is warranted.

Interception of objects is essential to many daily activities and numerous playground activities or sports. Therefore, catching provides an excellent example to study the precise control of a timed motor action in response to a visual stimulus. The control of the grasp phase of ball-catching was studied in an experiment where children had to intercept a ball that was attached to a pendulum. Comparison of the temporal control did not reveal differences in the timing of grasp onset or hand closure between children with DCD and matched typically developing (TD) children. Further, faster balls did cause a distinct increase of the hand closing velocity in both groups, but their temporal control appeared to be invariant to the variable ball velocity. Apparently, children with DCD and TD-children adapted to the changing task constraints in a similar way. However, group comparison revealed consistently lower maximal hand closing velocities for children with DCD in all three ball speed conditions. These results suggest that the basic interceptive timing abilities of children with DCD appeared to be intact. Therefore, it seems plausible that other aspects of the catching action, such as the control of posture or the precise location of the hand, are responsible for the poor catching performance of children with DCD, as assessed with the MABC. In addition, the lower hand closing velocities could point towards a problem in the fine neuromuscular control of the grasp action.

A second important, everyday motor skill that was subject of our research was locomotion. The purpose of this study was to investigate and compare the spatiotemporal control and kinematics of walking in children with DCD and TD-children. It was found that during walking on a treadmill, children with DCD used smaller steps and a higher step frequency to obtain a similar walking velocity as the TD-children. The absolute duration of the consecutive phases of the gait cycle were shorter in children with DCD, but when these were scaled to the total stride time, the relative timing appeared to be similar. With regard to the whole body kinematics of the walking pattern, a remarkable finding was that the trunk of the children with DCD displayed more flexion in the hip, resulting in an increased forward inclination of the trunk. Increased flexion was also demonstrated for the knee in the initial part of the support phase. Further, children with DCD tended to place the foot flatter at initial foot strike and extend the ankle to a lesser extent just before toe-off, causing a less pronounced propulsion. While not all children with DCD displayed similar adaptations to the walking pattern, these findings suggest that children with DCD have difficulties to find the optimal compromise between balance and propulsion during walking on a treadmill.

In an attempt to assess the importance of visual monitoring during the control of an everyday gross motor task, a consecutive study explored the influence of vision on the control of locomotion in children with DCD. A comparison of the spatiotemporal pattern during overground walking in normal lighting and in the dark revealed that children with DCD were more dependent on global visual flow than TD-children for the establishment of their natural gait pattern. During walking on a straight and uncluttered walkway without visual cues, stride length was shorter and step frequency was higher in children with DCD, resulting in a considerably slower walking velocity. In addition, the absence of visual information also caused a slight increase in the medio-lateral excursion of the centre of mass in children with DCD. None of these adaptations occurred in TD-children. During walking children with DCD appeared to be more dependent on visual monitoring for the control of walking speed and balance than TD-children. The absence of visual cues led up to a lack of perceptual information that could not be compensated by children with DCD, resulting in a slower and safer walking strategy. These results possibly suggest problems with the integration of sensory information and the fine-tuning of the perceptual modalities to the demands of the task and the environment.

In a last study the focus of attention was not on a specific movement skill, but rather on one of the basic underlying components of virtually all voluntary movements: the control of posture. In the preceding studies inferences to a putative inadequate control of posture in children with DCD frequently occurred and therefore in depth examination of the postural control system in children with DCD was a logical and essential step in this research project. Likewise, this study allowed us to carry out a more profound investigation of the sensory integration abilities of children with DCD. The integrity of the postural control system of children with DCD was explored by means of the assessment of the amount of postural sway during bilateral stance under different environmental circumstances (without and without visual information, on a firm and compliant surface). It was shown that children with DCD displayed more postural sway than children without coordination difficulties in all four conditions. When perceptual modalities (vision, proprioception, and the vestibular system) were distorted, postural sway increased in both groups. The children with DCD seemed to depend more on visual information than TD-children. Moreover, a comparison of the stabilization ratios in the different conditions revealed that children with DCD appeared to be less capable of very precise reweighting of multiple sensory inputs. Based on these findings, it might be suggested that a poor or broadly tuned multisensory model that generates an internal estimate of body orientation is possibly a major factor in the control of posture in children with DCD.

1.3. Conclusion

By means of a detailed, kinematic analysis of catching, walking and the control of posture, a significant step towards the refinement and extension of the picture of the coordination problems of children with DCD was taken. The basic planning and temporal control of a simple interception task appeared to be intact, while during more complex tasks, requiring the integration of multiple sensory inputs, significant adaptations to the movement pattern occur. These adaptations often point towards an increased dependency on visual control, associated with a less adequate process of reweighting of sensory information in response to the demands of the task. This rather conservative control strategy might be responsible for a less efficient control of posture and can, in turn, affect the execution of a broad range of voluntary movements.

2. Nederlandse samenvatting

2.1. Achtergrondschets

Het blijft fascinerend hoe een schijnbaar onbeholpen, bijna roerloos pasgeboren kindje geleidelijk aan uitgroeit tot een menselijk wezen dat zich stap voor stap een heel breed gamma aan bewegingsactiviteiten eigen maakt en die met een ogenschijnlijk gemak heel nauwkeurig, vloeiend en efficiënt leert uitvoeren. Net zo verbazend is het als die nauwkeurigheid, vloeiendheid en efficiëntie, schijnbaar zonder oorzaak, achterwege blijven en de bewegingen onhandige, houterige, ongecoördineerde, weinig doelgerichte acties blijven. Dat is het geval bij ongeveer 6% van de kinderen tussen 5 en 11 jaar. Deze kinderen lijden aan Developmental Coordination Disorder (DCD), een stoornis die wordt gekenmerkt door problemen met verschillende fijn- en/of grofmotorische bewegingsvaardigheden wat resulteert in moeilijkheden bij het uitvoeren van veel dagdagelijkse bewegingen. Volgens de American Psychiatric Association, die de diagnostische criteria voor DCD voorschrijft, belemmeren de bewegingsmoeilijkheden de kinderen zichtbaar om op een adequate manier deel te nemen aan het alledaagse leven en hebben ze een negatieve invloed op hun schoolprestaties. Belangrijk is dat er geen aantoonbare medische oorzaak de bewegingsproblemen van kinderen met DCD kan verklaren (zoals bij cerebral palsy of spierdystrofie) en dat de kinderen niet voldoen aan de criteria voor een pervasieve ontwikkelingsstoornis. In geval van mentale retardatie schrijft DSM-IV[2] voor dat de bewegingsproblemen van het kind ernstiger zijn dan op basis van de mentale achterstand alleen kan verwacht worden.

[2] DSM-IV is een diagnostisch handboek uitgegeven door de American Psychiatric Association. Het boek bevat uitgebreide richtlijnen voor het stellen van diagnoses met betrekking tot psychische aandoeningen of ontwikkelingsstoornissen. [American Psychiatric Association. (1994) *Diagnostic and statistical manual for mental disorders*. 4th edn. Washinton, DC: American Psychiatric Association.]

De stoornis kan zich heel verschillend manifesteren. Het typische kind met DCD bestaat niet; sommigen hebben enkel fijnmotorische problemen zoals bij het schrijven of eten met mes en vork, anderen hebben meer problemen met de grove motoriek en hebben moeite bij het vangen van een bal. In het slechtste geval heeft het kind problemen met zowel fijn- als grofmotorische vaardigheden. Dit sterk variërende beeld, samen met de frequent voorkomende comorbiditeit met andere ontwikkelingsstoornissen zoals ADHD of autisme en het gebrek aan kennis betreffende de onderliggende mechanismen, bemoeilijkt de diagnose.
Inzake de onderliggende mechanismen tast de wetenschap voorlopig in het duister. Onderzoek van de informatieverwerkingsprocessen aan de basis van beweging bracht aan het licht dat kinderen met DCD vooral problemen hebben het verwerken, integreren en gebruiken van visuo-spatiële informatie. Daarnaast blijken ze ook minder goed te presteren in taken die kinesthetische perceptie of perceptuele integratie vergen. Vaak vertonen kinderen met DCD relatief trage reactie- en bewegingstijden en hebben ze het moeilijk om kracht accuraat te doseren. Elektromyografie wees uit dat de bewegingscontrole in veel gevallen gepaard gaat met een verhoogde mate van co-activatie van verschillende spieren. De meeste van deze bevindingen zijn echter gebaseerd op experimenten waarbij de bewegingscomponent zeer gering was. Om na te gaan in welke mate deze resultaten een impact hebben op de functionele bewegingsproblemen van kinderen met DCD, is een gedetailleerde analyse van het volledige bewegingsverloop van meer alledaagse bewegingen noodzakelijk. Bovendien kan een beter inzicht in de bewegingsproblematiek van kinderen met DCD, dat tot nu toe vooral gebaseerd is op kwalitatieve observatie of scores op een motoriek-test, bijdragen tot het verfijnen van het beeld van de stoornis.

2.2. Het onderzoek

Het doel van het onderzoek was tweevoudig. In eerste instantie werd getracht aan de hand van een gedetailleerde kinematische analyse van een aantal functionele bewegingsvaardigheden een nauwkeurig beeld te krijgen van de bewegingsproblemen van kinderen met DCD. Deze informatie maakte het ook mogelijk om de outputscores op een motoriektest zoals de Movement Assessment Battery for Children (MABC) te valideren en in een breder perspectief te plaatsen. Daarnaast wilden we een beter inzicht verwerven in de mogelijke onderliggende tekortkomingen op het gebied van perceptie en motorische controle tijdens functionele bewegingsvaardigheden.

Een eerste studie onderzocht de controle van een eenvoudige vangtaak. Een vergelijking van de temporele controle van de grijpfase, toonde aan dat het tijdstip van twee cruciale momenten in de vangbeweging, namelijk het begin van de beweging (d.i. handopening) en het begin van de handsluiting, niet verschilde tussen kinderen met DCD en de controlekinderen. Wanneer de bal gerandomiseerd aan drie verschillende balsnelheden op de kinderen afkwam, bleken zowel de kinderen met als de kinderen zonder DCD deze temporele controle constant te houden over de drie snelheidscondities. Deze constante tijd-tot-contact strategie is één van de basisprincipes van veel interceptietaken en ze toont aan dat in beide groepen de opname en het gebruik van visuele informatie voor het vangen van een bal gelijkaardig verloopt. De adaptatie van de controle van de beweging aan de verschillende balsnelheden gebeurde door beide groepen op het niveau van de sluitingssnelheid van de hand. In overeenstemming met vroegere bevindingen verhoogden zowel de kinderen met DCD als de controlekinderen de handsluitingssnelheid als de bal sneller op hen afkomt. Het lijkt er dus op dat, bij een eenvoudige interceptietaak, de elementaire vaardigheid om een beweging accuraat te plannen en aan te passen aan een externe visuele stimulus intact is bij kinderen met DCD. De consistent lagere sluitingssnelheid van de hand bij kinderen met DCD, over alle condities heen, duidt echter op een probleem dat waarschijnlijk meer gesitueerd is op efferent niveau.

In een tweede onderzoek werd nagegaan of het stappatroon van kinderen met DCD verschilde van dat van controlekinderen. Bij het stappen op een loopband gebruikten kinderen met DCD kleinere stappen en een hogere stapfrequentie om eenzelfde (opgelegde) stapsnelheid als de controlekinderen te bekomen. De relatieve tijdsindeling van de stapcyclus was voor beide groepen gelijk. Op vlak van lichaamsconfiguratie bleek dat de romp van kinderen met DCD zich meer in flexie bevond gedurende de volledige stapcyclus. Hun knie was tijdens het eerste deel van de steunfase sterker gebogen, wat aanleiding gaf tot een initieel voetcontact waarbij de voet de grond vlakker raakte. Tijdens de afstoot strekten kinderen met DCD hun enkel minder uit dan de controlekinderen. Hoewel niet alle kinderen met DCD alle hierboven beschreven aanpassingen vertoonden, wijzen de resultaten erop dat kinderen met DCD moeite hebben met het vinden van het ideale compromis tussen evenwicht en propulsie bij het stappen op de loopband.

Een vervolgstudie op het stappen ging dieper in op de invloed van visuele informatie op de controle van het evenwicht tijdens het stappen. De kinderen stapten aan voorkeurssnelheid op een rechte, harde en effen loopweg in een conditie met normale lichtsterkte, dus normale visuele informatie en in het donker, zonder visuele informatie. In de baseline conditie was het spatio-temporele stappatroon van kinderen met DCD gelijkaardig aan dat van de controlekinderen, met uitzondering van een langere dubbele steunfase. Bij het stappen in het donker bleek het stappatroon van kinderen met DCD in tegenstelling tot dat van de kinderen zonder DCD sterk onderhevig aan aanpassingen. Het wegvallen van visuele informatie ging bij de kinderen met coördinatiestoornissen gepaard met een lagere stapfrequentie en een kortere staplengte, wat uiteindelijk resulteerde in een significante daling van de snelheid. Daarnaast nam ook de medio-laterale excursie van het lichaamszwaartepunt toe, wat kan duiden op een minder stabiele gang. Kinderen met DCD blijken dus tijdens het stappen sterker afhankelijk van de visus dan controlekinderen voor de controle van snelheid en balans. Mogelijks wijst dit op problemen bij het integreren van de verschillende sensorische informatiestromen (visus, proprioceptie en vestibulair systeem) en het afstemmen van de perceptuele informatie op de vereisten van de taak en de omgevingsomstandigheden.

Posturale controle is een basiscomponent van vrijwel alle spontane bewegingen die sterk afhankelijk is van de adequate integratie van visuele, proprioceptieve en vestibulaire informatie. Uit verschillende studies, uitgevoerd in het kader van dit onderzoeksproject, bleek dat de verschillen in of de aanpassingen aan het bewegingspatroon (van onder meer stappen en vangen) van kinderen met DCD vaak in verband gebracht konden worden met een minder optimale controle van het evenwicht. Een diepgaand onderzoek van de posturale controle en de daarmee gepaard gaande integratie van visuele, proprioceptieve en vestibulaire informatie, was daarom een logische en essentiële stap in het onderzoek van de bewegingsproblemen van kinderen met DCD. De integriteit van het systeem voor posturale controle werd onderzocht aan de hand van de postural sway in een eenvoudige evenwichtstaak, waarbij de proefpersonen in een normale, bilaterale, rechtopstaande houding op een krachtplaat stonden. Visus, proprioceptie en vestibulair systeem werden achtereenvolgens verstoord door middel van een blinddoek en/of een zacht kussen als ondergrond. In alle vier de condities die op die manier gecreëerd werden (met zicht + harde ondergrond; zonder zicht + harde ondergrond; met zicht + zachte ondergrond; zonder zicht + zachte ondergrond) vertoonden de kinderen met DCD meer postural sway dan de controlekinderen wat dus wijst op een minder adequate posturale controle, mogelijks door toedoen van een minder efficiënte integratie van de sensorische kanalen. Uit de verschillende manipulaties van die sensorische informatiebronnen bleek dat kinderen met DCD sterker afhankelijk waren van visuele informatie en minder gemakkelijk overschakelden naar andere sensorische bronnen als aanpassingen aan de vereisten van de taak of de omgevingsomstandigheden. Het lijkt erop dat het intern sensorimotorisch model, dat een neurale representatie van de onderlinge relaties tussen perceptie en actie bevat, bij kinderen met DCD minder sterk is ontwikkeld.

2.3. Conclusie

Een gedetailleerde, kinematische analyse van een aantal functionele bewegingsvaardigheden kon het beeld en de kennis betreffende de bewegingsproblemen van kinderen met DCD uitbreiden en verfijnen. De planning en temporele controle van een eenvoudige, discrete interceptietaak lijkt intact. Complexere taken, met een posturale component, waarbij de motorische respons moet afgestemd worden op sensorische informatie afkomstig van diverse kanalen, worden belemmerd door een minder efficiëntie integratie van de informatie en afstemming ervan op de specifieke vereisten van de taak en de omgeving. Die problemen met de integratie van de sensorische integratie resulteren in eerste instantie in een minder adequate posturale controle. Die minder efficiënte controle lijkt op zijn beurt de controle van tal van andere bewegingsvaardigheden te beïnvloeden en te dwingen tot (taakspecifieke) aanpassingen van het bewegingspatroon.

APPENDICES

Appendix Ia - MABC-details for the children with DCD of study 1 (ball catching)

subject	sex	age	Fine motor skills		Ball handling skills		Static and dynamic balance		Total impairment score	
			raw	p	raw	p	raw	p	raw	p
1	♂	6.98	4	p15	6.5	< p5	0	> p15	10.5	10
2	♂	6.43	5	< p15	5	p5	0.5	> p15	10.5	10
3	♂	8.49	6.5	< p5	4.5	< p15	0.5	> p15	11.5	7
4	♂	8.36	14	< p5	9.5	< p5	1	> p15	24.5	1
5	♂	7.82	10	< p5	3	p15	0	> p15	13	5
6	♂	6.77	4	p15	4	< p15	1.5	> p15	9.5	12
7	♂	6.46	8	< p5	5	p5	6.5	< p15	19.5	2
8	♂	7.16	5	< p15	4	< p15	0.5	> p15	9.5	12
9	♂	8.58	5	< p5	4	< p15	0.5	> p15	9.5	12
Mean		7.5	6.8		5.1		1.22		13.1	7.9
SD		0.85	3.34		1.93		2.03		5.31	4.34

Appendix Ib - MABC-details for the children with DCD of study 2 (treadmill walking)

subject	sex	age	Fine motor skills		Ball handling skills		Static and dynamic balance		Total impairment score	
			raw	p	raw	p	raw	p	raw	p
1	♂	6.98	4	p15	6.5	< p5	0	> p15	10.5	10
2	♂	6.43	4	p15	4	< p15	2.5	> p15	10.5	10
3	♂	8.49	5.5	< p15	3.5	< p15	2.5	> p15	11.5	7
4	♂	8.36	14	< p5	8	< p5	2.5	> p15	24.5	1
5	♂	7.82	10	< p5	3	p15	0	> p15	13	5
6	♂	6.77	4	p15	4	< p15	1.5	> p15	9.5	12
7	♀	8.13	7	< p5	7.5	< p5	1.5	> p15	16	2
8	♂	6.46	8	< p5	5	< p15	6.5	< p15	19.5	2
9	♂	7.16	5	< p15	4	< p15	0.5	> p15	9.5	12
10	♂	8.58	5	< p5	3	p15	1.5	> p15	9.5	12
Mean		7.4	6.7		4.9		1.9		13.4	7.3
SD		0.86	3.25		1.84		1.88		5.09	4.50

Appendix Ic - MABC-details for the children with DCD of study 3 (walking overground)

subject	sex	age	Fine motor skills		Ball handling skills		Static and dynamic balance		Total impairment score	
			raw	p	raw	p	raw	p	raw	p
1	♂	8.10	9.5	< p5	8	< p5	6	p5	23.5	1
2	♀	8.69	3.5	> p15	3.5	< p15	3.5	> p15	10.5	10
3	♂	7.41	10	< p5	7.5	< p5	5.5	< p15	23	1
4	♂	7.29	7	< p15	6	< p5	9	< p5	22	1
5	♂	7.48	3.5	> p15	5	p5	4	p15	12.5	5
6	♂	6.94	4	p15	3.5	< p15	5	< p15	12.5	5
7	♂	8.00	4.5	< p15	5	p5	0.5	> p15	10	11
8	♂	8.29	4	p15	6	< p5	6	p5	16	2
9	♀	7.63	16	< p5	6	< p5	10	< p5	32	1
10	♂	7.12	4	p15	5	p5	0.5	< p15	9.5	12
11	♂	8.04	6	< p15	3	p15	2.5	> p15	11.5	7
12	♂	8.00	10	< p5	2.5	> p15	1.5	> p15	14	4
Mean		7.75	6.8		5.1		4.5		16.4	5.0
SD		0.52	3.86		1.73		3.07		7.07	3.77

Appendix Id - MABC-details for the children with DCD of study 4 (postural control – balance master)

subject	sex	age	Fine motor skills		Ball handling skills		Static and dynamic balance		Total impairment score	
			raw	p	raw	p	raw	p	raw	p
1	♂	6.98	4	p15	6.5	< p5	0	> p15	10.5	10
2	♂	6.43	5	< p15	5	p5	0.5	> p15	10.5	10
3	♂	8.49	6.5	< p5	4.5	< p15	0.5	> p15	11.5	7
4	♂	8.36	14	< p5	9.5	< p5	1	> p15	24.5	1
5	♂	7.82	10	< p5	3	p15	0	> p15	13	5
6	♂	6.77	4	p15	4	< p15	1.5	> p15	9.5	12
7	♂	8.00	10	< p5	2.5	>p15	1.5	> p15	14	4
8	♂	7.16	5	< p15	4	< p15	0.5	> p15	9.5	12
9	♂	8.58	5	< p5	4	< p15	0.5	> p15	9.5	12
10	♂	8.00	4.5	< p15	5	p5	0.5	> p15	10	11
Mean		7.7	6.8		4.8		0.7		12.3	8.4
SD		0.78	3.38		1.99		0.5		4.57	3.9

Dit is de vragenlijst van…

Voornaam:……………………………………………………………………………………………………

Familienaam:…………………………………………………………………………………………………

Adres:……

………

Telefoonnummer:……………………………………………………………………………………………

Geboortedatum:……………………………………………………………………………………………

School:………………………………………………………………………………………………………

Klas:………

Beste ouders,

Deze vragenlijst bevat vier delen.

- ❖ Een deel over het kind en het gezin
- ❖ Een deel over de school en de sport op school
- ❖ Een deel over sport en beweging in de vrije tijd
- ❖ Een deel over de gezondheid

Het is de bedoeling dat jullie dit samen (ouders + kinderen) eerlijk invullen. Als je dit nauwkeurig doet neemt dit niet meer dan een halfuur in beslag.

Nogmaals bedankt!!

Frederik Deconinck
prof. dr. Matthieu Lenoir

Over jezelf en je gezin

1. **Ben je een jongen of een meisje?** (kleur het juiste bolletje)
   O jongen
   O meisje

2. **Hoe groot ben je nu?** .... centimeter

3. **Hoeveel weeg je nu?** .... kilogram

4. **Welke nationaliteit heb je?** (kleur het juiste bolletje)
   O Belg
   O Andere Europese nationaliteit
   O niet-Europese nationaliteit

5. **In welke provincie woon je? (kleur het juiste bolletje)**
   O Antwerpen
   O Oost-Vlaanderen
   O Vlaams-Brabant
   O West-Vlaanderen

6. **In welke stad of dorp woon je?** …………………………..

7. **Tot welke soort behoort je gemeente?** (kleur het juiste bolletje)
   O Dorp of kleine gemeente (minder dan 2.000 inwoners)
   O Grote gemeente of voorstad (2.000 tot 20.000 inwoners)
   O Kleine stad (20.000 tot 100.000 inwoners)
   O Grote stad (meer dan 100.000 inwoners)
   O Ik weet het niet

8. **Hoeveel broers en/of zussen heb je?** (kleur het juiste bolletje)

O Geen	O 6
O 1	O 7
O 2	O 8
O 3	O 9
O 4	O 10
O 5	O meer dan 10

9. **Wat is het beroep van je vader?** (kleur het juiste bolletje)

O Arbeider
O Bediende
O Kaderpersoneel
O Onderwijs
O Vrij beroep
O Zaakvoerder van een bedrijf
O Zelfstandige
O Verpleger
O Werkloos
O Gepensioneerde
O Huisman, werkt bewust niet
O Mijn vader is overleden
O Ik weet het niet
O Iets anders:………………..

10. **Wat is het beroep van je moeder?** (Kleur het juiste bolletje)

O Arbeidster
O Bediende
O Kaderpersoneel
O Onderwijs
O Vrij beroep
O Zaakvoerster van een bedrijf
O Zelfstandige
O Verpleegster
O Werkloos
O Gepensioneerde
O Huisvrouw, werkt bewust niet
O Mijn moeder is overleden
O Ik weet het niet
O Iets anders:………………………

Over de school en de sport op school

10. **Hoeveel punten had je op je laatste rapport?**
(niet van toepassing voor kinderen uit de derde kleuterklas!)

Voor rekenen:………… op …………….

Voor taal:……………… op …………….

Voor turnen:……………op ……………

In het totaal:……………op ……………

11. **Hoe verplaats je je meestal van en naar school?**
(je mag meerdere mogelijkheden aankruisen)

O **met de fiets**
Hoelang (per dag) rij je gemiddeld van en naar de school? (heen en terug samengeteld)

.... minuten

O **te voet**
Hoelang (per dag) stap je gemiddeld van en naar de school? (heen en terug samengeteld)

.... minuten

O **met de auto, trein, bus of motorfiets**
Hoelang (per dag) rij je gemiddeld van en naar de school? (heen en terug samengeteld)

.... minuten

O **met de step, autopet, rollerblades, skeelers, ...**
Hoelang (per dag) rij je gemiddeld van en naar de school? (heen en terug samengeteld)

.... minuten

12. **Hoeveel uur lichamelijke opvoeding of sport krijg je tijdens de week op school?**

Turnen of gym
O geen
O een half lesuur
O 1 lesuur
O 2 lesuren
O iets anders:……….

Zwemmen
O geen
O 1 lesuur per week
O 1 lesuur om de 14 dagen
O 1 lesuur per maand
O iets anders:……………

13. **Wat doe je meestal tijdens de speeltijd en de middagpauze?**
(kleur het juiste bolletje)

<u>tijdens de speeltijd</u>:
O zitten
O staan
O wandelen
O sporten of actief spelen

<u>tijdens de middagpauze</u>:
O zitten
O staan
O wandelen
O sporten of actief spelen

14. **Op welke momenten kan je aan sport of beweging doen op school als je de turnles niet meerekent?**
(Je mag meerdere antwoorden kleuren.)

O tijdens de middagpauze en de speeltijd
O na schooltijd, tijdens de naschoolse opvang of studie
O op woensdagnamiddag
O bij klas- en schooltornooien
O op geen enkel moment □ **ga nu naar vraag 20**
O andere: ....

15. **Neem je aan één van deze activiteiten deel?** (kleur het juiste bolletje)

O ja
O nee □ **ga nu naar vraag 20**

16. **Aan welke activiteit(en) neem je deel?** (kleur het juiste bolletje)
(Je mag meerdere antwoorden kleuren.)

O sport tijdens de middagpauze of de speeltijd
O sport na schooltijd, tijdens de naschoolse opvang of studie
O sport op woensdagnamiddag
O klas- en schooltornooien

19. **Hoeveel tijd besteed je aan al deze sportactiviteiten?**
(kleur het juiste bolletje)

O af en toe
O 1 uur per maand
O 2 uur per maand
O 3 uur per maand
O 1 uur per week
O 2 uur per week
O 3 uur per week
O 4 uur per week
O meer dan 4 uren per week

Over sport en beweging in je vrije tijd

Bij de volgende vragen neem je een gemiddelde week (7 dagen) in gedachten

20. **Hoe verplaats je je meestal in je vrije tijd?**
bijvoorbeeld: *Hoe ga je naar de sportclub, de bakker of de winkel?*
Hoe ga je op bezoek bij familie?

- **De verplaatsing *van en naar school* mag je er niet bijrekenen**
- **Als je *fietsen en wandelen* als sport invult (zie 24), mag je dit er ook niet bijrekenen**

TIJDENS DE **WEEK**
Je mag meer dan 1 antwoord aankruisen!!

	nooit	**zelden** (af en toe eens 1 dag per week)	**soms** (paar dagen per week)	**dikwijls** (bijna iedere dag)	**altijd** (iedere dag)
Met de fiets	O	O	O	O	O
Te voet	O	O	O	O	O
Met de auto, tram, bus of motorfiets	O	O	O	O	O
Met de step, autopet of rollerblades	O	O	O	O	O

TIJDENS HET **WEEKEND**
Je mag meer dan 1 antwoord aankruisen!!

	nooit	**zelden** (af en toe eens 1 dag per week)	**soms** (paar dagen per week)	**dikwijls** (bijna iedere dag)	**altijd** (iedere dag)
Met de fiets	O	O	O	O	O
Te voet	O	O	O	O	O
Met de auto, tram, bus of motorfiets	O	O	O	O	O
Met de step, autopet of rollerblades	O	O	O	O	O

21. **Gedurende een normale week, hoeveel uur per dag kijk je gemiddeld televisie, video of speel je spelletjes op de computer, game boy, playstation?**
˜ Computerlessen in de school mag je er niet bijrekenen˜

tijdens de week (maandag-vrijdag)	tijdens het weekend (zaterdag en zondag)
O Geen	O Geen
O 0,5 uur	O 0,5 uur
O 1 uur	O 1 uur
O 2 uur	O 2 uur
O 3 uur	O 3 uur
O 4 uur	O 4 uur
O 5 uur	O 5 uur
O 6 uur of meer	O 6 uur of meer

22. **Hoeveel keer per week doe je aan intense fysieke activiteit gedurende minimum 20 minuten aan één stuk?**

Intense fysieke activiteiten zijn activiteiten waarbij je zweet en waarbij je ademhaling sneller verloopt, zoals bij zware lichaamsinspanning en bij sporten.

O geen enkele keer	O 5 keer per week
O 1 keer per week	O 6 keer per week
O 2 keer per week	O 7 keer per week
O 3 keer per week	O meer dan 7 keer per week
O 4 keer per week	

23. **Hoeveel dagen in een normale week doe je aan matige fysieke activiteit gedurende minstens 60 minuten aan één stuk per dag?**

Matige fysieke activiteiten zijn activiteiten waarbij je ademhaling iets sneller verloopt dan normaal.

O geen enkele dag	O 4 dagen per week
O 1 dag per week	O 5 dagen per week
O 2 dagen per week	O 6 dagen per week
O 3 dagen per week	O 7 dagen per week

24. **Geef de drie belangrijkste sporten die je tijdens je vrije tijd het meest beoefent.**
Let op: de les lichamelijke opvoeding en schoolsport tellen niet mee

Mijn eerste sport

O ik beoefen geen sport **ga nu naar vraag 25**

O mijn eerste sport is: ....

	Hoe regelmatig beoefen je deze sport? Slechts 1 bolletje kleuren	Hoeveel tijd (uren) besteed je aan deze sport?
O	af en toe	.... uren per jaar
O	1 week per jaar	.... uren per jaar
O	2 weken per jaar	
O	3 weken per jaar	
O	4 weken per jaar	
O	1 keer per maand	.... uren per maand
O	2 keer per maand	
O	3 keer per maand	
O	1 keer per week	.... uren per week
O	2 keer per week	
O	3 keer per week	
O	4 keer per week	
O	5 keer per week	
O	6 keer per week	
O	7 keer per week	
O	meer dan 7 keer per week	

Doe je deze sport in een club?
O ja
O neen

Doe je mee aan competitie (wedstrijden)?
O ja
O neen

Mijn tweede sport

O ik beoefen geen tweede sport **ga nu naar vraag 25**

O mijn tweede sport is: ....

	Hoe regelmatig beoefen je deze sport? Slechts 1 bolletje kleuren	Hoeveel tijd (uren) besteed je aan deze sport?
O	af en toe	.... uren per jaar
O	1 week per jaar	.... uren per jaar
O	2 weken per jaar	
O	3 weken per jaar	
O	4 weken per jaar	
O	1 keer per maand	.... uren per maand
O	2 keer per maand	
O	3 keer per maand	
O	1 keer per week	.... uren per week
O	2 keer per week	
O	3 keer per week	
O	4 keer per week	
O	5 keer per week	
O	6 keer per week	
O	7 keer per week	
O	meer dan 7 keer per week	

Doe je deze sport in een club?

O ja

O neen

Doe je mee aan competitie (wedstrijden)?

O ja

O neen

Mijn derde sport

O ik beoefen geen derde sport **ga nu naar vraag 25**

O mijn derde sport is: ....

Hoe regelmatig beoefen je deze sport? Slechts 1 bolletje kleuren	Hoeveel tijd (uren) besteed je aan deze sport?
O af en toe	.... uren per jaar
O 1 week per jaar O 2 weken per jaar O 3 weken per jaar O 4 weken per jaar	.... uren per jaar
O 1 keer per maand O 2 keer per maand O 3 keer per maand	.... uren per maand
O 1 keer per week O 2 keer per week O 3 keer per week O 4 keer per week O 5 keer per week O 6 keer per week O 7 keer per week O meer dan 7 keer per week	.... uren per week

Doe je deze sport in een club?
- O ja
- O neen

Doe je mee aan competitie (wedstrijden)?
- O ja
- O neen

🌡 Over jouw gezondheid ☯
In te vullen door mama of papa.

25. **Was de zwangerschapsduur normaal?** (d.i. tussen 37 en 42 weken)
O ja
O nee, het kind werd vóór de 37^{e} week geboren.
O nee, het kind werd te laat geboren.

26. **Wat was het exacte geboortegewicht?** ……………………..gram

27. **Maakte uw zoon/dochter ooit een ernstige ziekte door?**
O ja
O neen

Zo ja,
welke?………………………………………………………………………………..

28. **Had uw zoon/dochter ooit last van stuipen?**
O ja
O neen

29. **Verliest uw zoon/dochter vaak het bewustzijn?**
O vaak
O soms
O al een paar keer
O nog nooit

30. **Werd uw zoon/dochter ooit opgenomen in het ziekenhuis?**
O ja
O neen

Zo ja,
oorzaak?……………………………………………………………………………..

leeftijd?……………………………………………………………………………

opnameduur?………………………………………………………………………...

31. **Werd er ooit 1 van de volgende ontwikkelingsstoornissen vastgesteld bij uw zoon/dochter?**(Maak het bolletje zwart, meerdere antwoorden zijn mogelijk)

O autisme-spectrumstoornis
O aandachtsstoornis (ADD)
O hyperkinetische stoornis
O ADHD
O hechtingsstoornis
O Asperger syndroom
O leerstoornis (NLD)
O ontwikkelingsdyspraxie of ontwikkelingscoördinatiestoornis of developmental coordination disorder (DCD)
O iets anders:…………………………

Bedankt voor je medewerking

Toestemmingsformulier voor de ouders of voogd

In te vullen door beide ouders[3]

Hierbij geven……………………………………………………………………………………..

en …………………………………………………………………………………………………

ouders van …………………………………………………………………………………………

uit vrije wil de toestemming aan de onderzoeksgroep van de Universiteit Gent, onder leiding van Prof. Dr. M. Lenoir, volgende test bij hun kind uit te voeren:

1. Child Behavior Checklist (gedragstest), indien niet voorhanden
2. Movement Assessment Battery for Children (motoriektest)
3. Antropometrische metingen (lengtemetingen en registratie van het lichaamsgewicht)
4. Niet-invasieve bewegingsanalytische tests (beeldopnames van stappen/lopen, verticale hoogtesprong, posturaal evenwicht of éénhandig balvangen en –werpen)

Wij hebben de onderzoeker op de hoogte gesteld van de medische voorgeschiedenis van het kind.
Wij hebben kennis genomen van het verloop van het onderzoek en de verschillende tests die uitgevoerd zullen worden.
Wij weten dat we op ieder ogenblik vragen mogen stellen over het onderzoek en dat we het recht hebben de deelname van ons kind aan de studie te onderbreken.
Wij weten dat de gegevens (inclusief beeldopnames) enkel voor wetenschappelijke doeleinden gebruikt zullen worden en dat wij op elk moment het recht hebben op inzage in deze gegevens.

Handtekening van beide ouders:

…………………………………………   …………………………………………

Datum:…………………….

[3] Toestemming van één ouder volstaat enkel wanneer de andere ouder redelijkerwijze niet kan worden bereikt, in de onmogelijkheid verkeert om zijn toestemming te kennen te geven of ontzet is uit het ouderlijk gezag. Als het kind geen ouders (meer) heeft of beiden in de onmogelijkheid verkeren hun wil te kennen te geven of beiden ontzet zijn uit het ouderlijk gezag dan is de toestemming van de voogd noodzakelijk.

ADMINISTRATIEVE GEGEVENS

Gelieve dit formulier terug te sturen naar:

Universiteit Gent
Vakgroep Bewegings- en Sportwetenschappen
t.a.v. Frederik Deconinck
Watersportlaan 2
9000 Gent

Voornaam en naam van de deelnemer:

…………………………………………………………………………………………………

Geboortedatum:……………………….

Voornaam en naam van beide ouders:

…………………………………………………………………………………………………

…………………………………………………………………………………………………

Adres: ……………………………………………………………………………………........

……………………………………………………………………………………........

Telefoonnummer:……………………………

E-

mail:………………………………………………………………………………………………

Bij voorkeur te bereiken op volgende tijdstippen:

…………………………………………..……………………………………………………………

…...……………………………………………………………………………………………

Naam van de kinesist(e) of revalidatiecentrum:………………………………………………

Naam van de huisarts of pediater:……………………………………………………………

Adres:………………………………………………………………………………………………

…………………………………………………………………………………………………

Telefoonnummer:…………………………………