Postural and Cardiac Responses to Suprapostural Tasks Among Children with and without Developmental Coordination Disorder

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Dedication

This dissertation is dedicated to my wife, Gue-Jen (Jean) Lin; my brother, Fu-Sheng Chen; and my parents, Chih-Chung Chen and Tun-Yung Ho.

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Introduction

Developmental Coordination Disorder

The term Developmental coordination disorder (DCD) refers to developmental impairments of motor coordination and difficulties in movement skills that children exhibit, that are not derived from general intellectual, sensory or motor neurological impairment (Gubbay, 1985). The prevalence of DCD is highest among elementary school-aged children, where the problem is often disregarded, and as a consequence children with DCD are stigmatized as ‘‘clumsy’’, ‘‘physically awkward’’ or worse ‘‘lazy’’. The fifth edition of Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2010) lists the diagnosis of DCD as follows:

A. Motor performance that is substantially below expected levels, given the person's chronologic age and previous opportunities for skill acquisition. The poor motor performance may manifest as coordination problems, poor balance, clumsiness, dropping or bumping into things; marked delays in achieving developmental motor milestones (e.g., walking, crawling, sitting) or in the acquisition of basic motor skills (e.g., catching, throwing, kicking, running, jumping, hopping, cutting, coloring, printing, writing).

B. The disturbance in Criterion A, without accommodations, significantly interferes with activities of daily living or academic achievement.

C. The disturbance is not due to a general medical condition (e.g., cerebral palsy, hemiplegia, or muscular dystrophy)

The prevalence of DCD is 6% for children in the age between 5 to 11 years (American Psychiatric Association, 2000). In the research literature, estimates of prevalence vary 3%~22% (Hoare & Larkin, 1991; Wright & Sugden, 1996).

Currently, there is no gold standard to diagnose DCD (Cairney, Hay, Veldhuizen, Missiuna, & Faught, 2009). There are many assessment tools for DCD, the most commonly used is the Movement Assessment Battery for Children (MABC) (Henderson & Sugden, 1992). The present study used the MABC to sample participants in a primary school in Taiwan. Children with DCD were identified if they scored at or below the 5th percentile on the MABC performance test; TDC were identified if they scored higher than 15th percentile.

Children with DCD have difficulties with activities requiring control of body segment which impact learning and executing activities at home, school and play environment (Polatajko & Cantin, 2005). Examples of such activities of daily living include dressing and personal health care. At school, children with DCD often struggle with printing or handwriting, holding a pen or pencil, using scissors, and problems with gross motor activities such as running, jumping, and hopping during physical education class.

It has also been established that the physical health of children with DCD is affected as a result of their motor coordination difficulties. Various studies have established that children with DCD participate less in physical activity than their typically developing peers. For example, Bouffard, Watkinson, Thompson, Caugrove-Dunn, and Romanow (1996) compared the intensity of physical activity, social interaction, and equipment use during recess between the two groups. It was determined that children with DCD participated less in vigorous activity, spent more time away from the playground, and avoided using large playground equipment. Notably, the decline in physical activity is an important determinant of cardiorespiratory fitness. Faught, Hay, Cairney, & Flouris (2005) reported that less participation in physical activity is a significant mediator in the relationship between cardiorespiratory fitness and DCD, that is, children who have motor coordination problem would be likely to participate less in physical activity and thus, have decreased fitness.

Children with DCD have reported concomitant difficulties; for example, co-occurrence of motor coordination deficits, perceptual abnormalities, learning difficulties and attention problems in several studies (Gillberg & Rasmussen, 1982; Kadesjo & Gillberg, 1998; Landgren, Kjellman, & Gillberg, 1998). Studies investigating attention-deficit hyperactivity disorder (ADHD) reported that approximately 50% ADHD children also have motor problems severe enough to be diagnosed with DCD (Pitcher, Piek, & Hay, 2003). Moreover, children initially diagnosed as DCD have been found to meet moderate to severe diagnosis with ADHD as well (Kadesjo & Gillberg, 1999). Dewey, Kaplan, Crawford, and Wilson (2002) further evidenced a relatively high level of associated problems in attention for DCD children regardless of a diagnosis of ADHD. Aside from the attention problems, it has also been suggested that children with DCD may suffer impairments in cognitive function, such as working memory and short-term memory (Alloway, 2007). DCD is not merely motor coordination deficits but rather commonly associated with perceptual and cognitive problems. Those finding emphasizes the importance of conducting experiments to investigate the link between action and both perception and cognition, in addition to solely examine motor coordination for children with DCD.

Postural control of DCD

Among these associated problems of DCD, the present study focused on postural control because it is necessary for stability, balance and orientation. Stable postural control is a prerequisite for most of a child's daily living activity and academic activity (for example, writing is inefficient when postural motion is unstable). Several studies have demonstrated that children with DCD have problems maintaining upright posture. Wann, Mon-Williams, and Rushton (1998) recruited DCD children, age-matched controls, nursery aged controls and adult to examine the postural sway in response to optic flow field in a swinging room. Measurements of posture were taken from head motion using Polhemus electromagnetic position tracker. They found that when children with DCD stood upright with eye closed, they displayed significantly greater postural sway than age-matched and nursery-aged control group. In addition, Children with DCD who had static and dynamic balance problems in MABC displayed increased postural motion in swinging room. However, children with DCD who passed the static and dynamic balance assessment of MABC did not differ from age-matched counterparts. Wann et al. (1998) suggested a delay in some DCD children's capacity to develop and integrate visual and non-visual information, and were relying primarily on vision to maintain postural stability. This study used a small sample and the results must be viewed with caution.

Geuze (2003) conducted three experiments to study the motor characteristic of postural control for children at risk for DCD. Twenty-four children at risk for DCD with balance problem (DCD-BP) and 24 matched controls were recruited. In the first experiment, excursions of center of pressure (COP) were measured from force plate while children stood on one or two legs in conditions with or without vision. In the second experiment, electromagnetography (EMGs) were recorded when participants stood on one leg with eyes open. In the third experiment, a short slight force was delivered in the back in order to slightly perturb their postural motion while both excursions of COP and EMGs were measured. The results indicated that there were only subtle differences between DCD-BP and controls when stood on two legs. However, children with DCD have balance problems, showing a significant reduction in postural stability, especially in more difficult conditions such as standing on non-preferred leg with eye closed.

Finally, Tsai, Wu, and Huang (2008) recruited a larger sample of children with constrained age ranges and similar motor impairment level. Sixty-four children with DCD-BP and seventy-one non-DCD children aged between 9 to 10 years were enrolled. Excursions of COP from force plate were recorded while participants were required to stand still for 30 seconds on the dominant leg, non-dominant leg and both legs in conditions with and without vision. In consistent with previous studies, the results indicated that children with DCD manifested greater posture motion in more difficult conditions, such as one leg standing and eyes closed condition. However, in contrast to the findings from Geuze's (2003) study, Tsai and his colleagues found that children with DCD showed significant larger COP excursions when standing with two legs, either with eyes open or closed. Although the divergent study designs and broad ranges of samples make it difficult comparing the findings across studies, previous research have implicated a reduced postural control that affects postural motion for children with DCD.

Postural responses during suprapostural tasking of DCD

Our present experiments focus on the postural responses when engaged in suprapostural tasks among children with and without DCD because concurrent postural and suprapostural task is ecological valid and this scenario is so pervasive as to represent the functions of postural motion during the execution of suprapostural tasks. To date, there were only limited studies using postural and suprapostural dual-task protocol. These studies are reviewed in the following.

Laufer, Ashkenazi and Josman (2008) recruited a DCD group and a matched control group, and asked both groups to name objects showing consecutively on a computer monitor while standing quietly either on a firm or a compliant surface. Their result indicated that a concurrent cognitive task increased postural motion in both groups. However, their results may be due to confounding factors or questionable procedures. For instance, their cognitive task required subjects' vocal response during postural motion measurement. It has been suggested that the speech articulation and changes in breathing patterns during the articulation of words may inevitably increase postural sway and thus contaminate the isolated effect of the cognition task (Dault, Yardley, & Frank, 2003; Yardley, Gardner, Leadbetter, & Lavie, 1999). Moreover, Laufer et al. (2008) did not use an independent measure of subjective mental effort such that it is impossible to determine whether the tasks that they used actually were equally difficult to all participants. It is thus of importance to employ specific measures for mental efforts to equalize the difficulty of cognitive tasks across participants.

To investigate whether children with DCD and balance problem (DCD-BP) have more difficulty relative to TDC in controlling postural motion while performing cognitive task, Tsai, Pan, Cherng, and Wu (2009) manipulated cognitive difficulty, requiring children with DCD-BP and counterparts to perform five cognitive tasks during stance. The five dual tasks were oral counting, auditory verbal reaction, auditory choice, auditory memory, and articulation alone. The oral counting task required participants to count backward out loud in steps of three in a clear voice. Auditory verbal reaction task requested children to articulate quickly and accurately after a high or low-pitch tone. Auditory choice task asked subjects to hold a response button and to hit the right button after a random high tone (5000 Hz) and the left button after a random low tone (500 Hz). Auditory memory task required children to remember a list of 15 food items with one played over a stereo system every 2 second while standing; children recalled the items once after the task and the number of items correctly recalled was measured. In articulate alone task, children had to say ‘yes’ at 1 second intervals. Based on completion for central resources hypothesis, Tsai et al. predicted a reduced postural stability in the execution of cognitive task compared to quiet stance condition. However, the results were not completely consistent with their hypothesis. In fact, the opposite occurred: both DCD-BP and TDC reduced in sway area value in auditory choice task. In addition, they attempted to manipulate the levels of difficulty by using various cognitive tasks and reported that auditory memory task is harder than auditory verbal reaction and auditory choice task. However, without taking measurement of mental efforts the manipulation of varying cognitive load on static standing posture was not confirmed.

Jor'dan, Wade, Yoshida, & Stoffregen (2009) studied the postural response to a suprapostural visual task in children at risk for DCD who scored at or below the 15th percentile in the MABC. Children were asked to look at a blank white board or count designated alphabet letters on a white board while standing for 1 minute. The result indicated that the amplitude of torso motion was reduced in medial/lateral plane while DCD and TDC engage in visual search of target letter in a text compared to viewing a blank target. This result was interpreted as an expression of a functional integration between postural control and suprapostural task. However, there was no significant group effect of head and torso motion while performing a suprapostural task. Jord'dan et al. (2009) suggested that counting letters of the alphabet was insufficient to detect any group differences and larger group differences may be present if a more challenging task were to be employed. Several factors which may have affected this study result should be considered. Age distribution (8 to 11 year-old) was broad as well as sample size (6 DCD and 5 TDC) was limited. Besides, since the medical record is not available, whether DCD children co-morbid with the other developmental disorder were not confirmed. Besides, based on research associated with postural control and performance on suprapostural tasks, a distinction may be made between cognition and perception. This distinction depends on the maintenance of some type of perceptual contact with the environment; that perceptual contact is achieved and maintained via active adjustments of perceptual system. For example, reading a perceptual task and reading is successful when the reader is able to control gaze in order to clearly view the text. A memory rehearsal task is primary a cognitive task as successful performance does not require precise gaze. Research should consider the separate impact of perceptive task and cognitive task on postural motion. In the present experiments, a perceptual task was defined as a task requires perceptual contact with environment while a cognitive task was defined as a task requires process of thought but not perceptual contact with environment.

From the literature of limited dual task studies for children at the risk for DCD, it is apparent that some issues require further clarification. Notwithstanding the heterogeneity of DCD and confounding factors mentioned above, the broad motor-impairment levels (that is, borderline DCD) (Laufer et al., 2008; Jor'dan, 2008), wide age distribution and limited sample size (Jor'dan, 2008) as well as task confounding such as speech articulation have been used (Laufer et al., 2008; Tsai et al., 2009) in past studies. In order to a better understanding of postural and suprapostural characteristics in children at risk for DCD, a larger sample of children with narrow age band, a similar motor-impairment level, a resembling symptoms of inattention and hyperactivity/impulsivity as well as confounding factors (such as task requiring articulation speech) were controlled in the present study. In addition, many studies with DCD have used perceptual/cognitive tasks rather than ‘‘purely perceptual’’ or ‘‘purely cognitive’’ tasks, which may affect the responses of postural motion. Lastly, Studies using postural and suprapostural dual-task protocol usually compare postural motion in single (quiet stance) and dual-task condition. Stoffregen et al. (2007) contend that perceptual contact with the environment is pervasive; ‘quiet stance’ may be so rare as to be unrepresentative of typical postural control. If quiet stance is not representative of typical postural control, no baseline condition against which to compare stance during the performance of a suprapostural task is possible. There is little practical value in using ‘quiet stance’ as an experimental condition. The present study (1) compared two levels of task difficulty rather than quiet stance and a designated task, and (2) experimentally separated the impact of varying suprapostural task demands that require either perceptual or cognitive engagement on postural motion in children at risk for DCD.

Research Theory

The experiments reported were motivated by a interest in the relationship between suprapostural task performance and movement difficulties in children with DCD. However, the approach used in our studies differ from those of the information-processing (IP) model which had dominated research regarding to children with DCD. The information-processing viewpoint regards humans as processors of information, and it focuses on storage, coding, retrieval, and transformations of information (Schmidt & Lee, 1998). This approach uses computer processing as metaphor which includes input, a central processing unit (CPU), and output. In human information-processing system, sensory organs sense information from environment, the CNS interprets and makes decisions about what to do, and output is given in the form of movement. The term ‘information-processing’ reflects that stimulus information must be processed and cognitive operations must intervene. The stimulus around individuals is insufficient, impoverished and meaningless, and therefore, there need to have representation that the CNS will translate into useful information. In addition, the IP approach argues that perception must depend on sensation; sensation refers to the initial detection of stimuli, and perception refers to an interpretation of the things that are sensed (Solso, 1995). Perception is indirect this way. In the IP model, perceptual function is regarded as an independent stage occurring prior to movement execution, with poor perceptual processing leading to poor movement execution (Schoemaker, van der Wees, Flapper, Verheij-Jaansen, Cholten-Jaegers, & Geuze, 2001; Hill, 2005). This approach has treated stimuli as discrete variables and implicated a number of perceptual processes in children with DCD (Bairstow, & Laszlo, 1980; Lord, & Hulme, 1987; Smyth, 1994; Sigmundsson, Hansen, & Talcott, 2003; van Waelvelde, Weerdt, De Cock, & Smits-Engelman, 2004), but has failed to provide strong evidence of perceptual processes as causal factors (Henderson, Barnett, & Henderson, 1994). The current experiments investigated the relationship between suprapostural tasks performance, and postural and cardiac responses, but they were not attempts to establish degraded perceptual sensitivity as a cause of poor motor coordination.

Gibson’s ecological approach (1966) to perception and action provided the theoretical basis for our experiments. The ecological approach views animal and environment complimentary; animals perceived the world from their own capability, and environment affects the action of the animals. In this approach, perception is not based on having sensation, but on detecting information. In addition, this approach assumed that the stimulus information around individuals is sufficient, and is direct perceived, no translation or computation needed in order to interpret sensory information. Gibson (1966) argued that stimulus information can determine perception without having to enter consciousness in the form of sensation. The ecological approach emphasized the reciprocity of perception and action and their mutual influence in the emergence of adaptive behaviors (Gibson, 1986). Movements are part of a continuous perception-action loop, that is, the pick-up of information guides action, and movement, in turn, creates additional perceptual information. Successful action is thus guided by veridical perception of relevant perceptual information, and the actions of the perceiver give rise to the emergence of the optimal perceptual variables for guiding movement. Similarly, the perception of a suprapostural task has implications for action, and the action of the perceiver influences the information pick-up of a suprapostural task.

Research Motivations

The first experiment was motivated by the hypothesis of functional integration between postural and suprapostural task (Riccio & Stoffregen, 1988; Stoffregen, Pagulayan, Bardy, 2000; Stoffregen, Bardy, Bonnet, & Pagulayan, 2006; Stoffregen, Riley, Hove, Bonnet, & Bardy, 2007). They argued that postural control can be modulated, at least in part, to benefit the achievement of suprapostural activities. It suggested that posture as well as some suprapostural activities can be integrated so that concurrent performance need not result in deterioration in either and can indeed induce improved performance; for example, surgeon is successful only when head and torso sway can be stabilized so as to gaze clearly. Because in a dynamical system perspective DCD may be described as an expression of deficits associated with the ability to detect relevant perceptual information (Wade and Johnosn, 2005, p89), it is possible that children with DCD have difficulties in function integration between a perceptual task performance and control of postural motion. Jor'dan,et al. (2009) studied the postural response to a visual task in children at risk for DCD and TDC. Participants look at a blank board or search designated alphabet letters in a text stream during stance. They found both groups reduced amplitude of torso sway when engaged in searching of target letters. However, there was no significant group effect found. They suggested that a more challenging task may be more sensitive to detect group effect. Accordingly, this study manipulated the difficulty levels of a perceptual task , a signal detection task, to test their hypothesis.

The second experiment was inspired by the studies conducted by Riley, Baker & Schmit (2003) and Riley, Baker, Schmit, and Weaver (2005). They used a suprapostural cognitive task and found that postural motion was reduced as a function of task difficulty. This finding was not supported in research regarding to children with DCD. For example, Laufer et al. (2008) found postural sway and postural sway variability were always higher when children with DCD performed a cognitive task compared to no task baseline condition. Similar results were replicated in Tsai et al. (2009) study. However, this inconsistent result in regard to the effects of cognitive tasks on postural motion may be owing to a confounding effects of articulation, or questionable procedures. To seek the pure cognitive effect on postural response, we replicated Riley et al.'s (2003) study using a articulation free cognitive task, a digit memory task, to investigate whether or not the postural response is different between the two groups when engage in a cognitive task.

The third experiment was inspired by studies conducted by Porges and his colleagues. In a series of research, they reported that heart rate variability (HRV) is significantly reduced during sustained attention in adults (Porges & Raskin, 1969; Porges, 1972), children (Suess, Porges, & Plude, 1994), infants (Porges, 1974), mental retarded individuals (Porges & Humphrey, 1977), and children with ADHD (Porges, Walter, Korb, & Sprague, 1975). It is possible that HRV responses would be different between the DCD and TDC groups across task difficulty. The prediction was based on two facts: (1) Most of the children with DCD have attention problem and this associated problem would impact the regulation of HRV, and (2) Children with DCD have lower levels of physical activity and cardiorespiratory fitness which may affect the autonomic control of HRV. Accordingly, the autonomic control of HRV may differ between the two groups as a function of task difficulty.

This dissertation comprises three experiments that compared postural motion responses and cardiac responses in children with developmental coordination disorder (DCD) and typically developing children (TDC) when they engaged in suprapostural tasks. We investigated the relationship between postural activity while engaged in ongoing suprapostural tasks that requires both perceptual and cognitive effort. In addition, heart rate variability (HRV) was used as a physiological measure of the impact of suprapostural activities. These experiments sought to determine whether the postural and cardiac response would differ between the two groups.

Experiment 1 evaluated positional variability for head and torso while children performing a signal detection task. Experiment 2 evaluated positional variability for head and torso while children performing a short-term memory task. Experiment 3 evaluated cardiac response while participants engaged in those tasks used in Experiment 1 and 2. These results of the experiments are presented in the format of three articles written in journal format.

The following section describes in brief overall topics explains the motivation for studying both biomechanical and physiological responses while engaged in suprapostural tasks; and lists the research questions in the three experiments. Note that many of the topics introduced in this preliminary statement are also discussed more fully in each of the experiments (Chapters 2, 3 and 4). Chapter 2, 3 and 4 each including introduction section, there is some redundancy in this section.

Research Questions and Hypotheses

Experiment 1 sought to determine (1) does response of postural motion change across task difficulty? (2) will the response of postural motion differ between the two groups? More specifically, we investigated if the difference in postural motion between the low difficulty (LD) and high difficulty (HD) conditions would differ between the two groups when they executed a signal detection task.

Experiment 2 sought to determine if children with DCD would replicate the results in previous studies (Riley et al., 2003), that is, can they modulate their postural motion as a function of the difficulty of cognitive suprapostural tasks? In addition, with respect to children with DCD, we posed the question as to whether their response of postural motion differ from their typically developing peers when they executed a digit memory task. Last, we investigate if the variation in task difficulty would have different effect between the DCD and TDC group on postural motion.

Experiment 3 sought to determine: (1) if the cardiac response of HRV measures change across task difficulty, and (2) is the cardiac response of HRV would be different between the two groups, when they performed a signal detection task and a digit memory task with multiple levels of difficulty?

We hypothesized that children with DCD would display diminished perception-action link and cognition-action link than the TDC group. This led to the predictions that children with DCD would differ from the TDC group in (a) biomechanical response, and (b) cardiac response when performed a signal detection task and a digit memory task.

Organization of Dissertation

The results of the three experiments are presented in journal format. The first (chapter 2) presents the first experiment, the second (chapter 3) presents the second experiment, and the third (chapter 4) presents the third experiment. References, tables, and figures are presented at the end of each article (chapter 2, 3 and 4), whereas the reference for the citations in chapter 1 and chapter 5 are presented at the end of the dissertation.

Postural responses to a suprapostural visual task among children with and without Developmental Coordination Disorder

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Postural responses to a suprapostural visual task among children with and without Developmental Coordination Disorder

Introduction

Developmental coordination disorder (DCD) is characterized by poor performance in activities of daily living (ADL), and in academic achievement that requires motor coordination that is not associated with any pervasive developmental disorder, with neurological impairment, physical problems, or intellectual disabilities (American Psychiatric Association, 2000). Between the ages of 5 and 11 years the prevalence of the DCD diagnosis is between 3% and 22% (American Psychiatric Association, 2000; Hoare & Larkin, 1991; Wright & Sugden, 1996). In a 10-year follow-up study (Losse, Henderson, Elliman, Hall, Knight, & Jongmans, 1991) indicated that the majority of children with DCD still manifest motor coordination difficulties through adolescence and into adulthood. Notwithstanding the prevalence is relatively high and that those children does not outgrow their status, the etiology of DCD remains uncertain.

In children with DCD, motor skill ability is below that of age-matched typically developing children (TDC). Children with DCD demonstrate a wide spectrum of motor coordination difficulties that include unstable stance, awkward running pattern, poor handwriting, drawing, and scissoring. Previous research has reported group differences in the control of postural motion while standing on a force plate (Geuze, 2003; Przysucha & Taylor, 2004; Tsai, Wu, & Huang, 2008) or in a swinging room (Wann, Mon-Williams, & Rushton, 1998) when comparing children with DCD to TDC group.

More importantly, Geuze (2003) and Tsai et al. (2008) found that the differences in postural motion between the two groups was more noticeable in more challenging conditions (e.g. eyes closed v.s. open, and one-leg v.s. two-leg stance). Geuze and Borger (1993) and Vaessen and Kalverboer (1990) suggested that group differences in such measures may be exacerbated in dual task protocols.

In healthy adults and typically developing children, the magnitude of standing body sway is often modulated by variations in the ocular demand of suprapostural visual tasks. Stoffregen, Riley, Hove, Bonnet, and Bardy (2007b) compared body sway in healthy adults during performance of a cognitive task (mental arithmetic) and a visual perceptual task (signal detection) that were matched for subjective mental workload. They found that body sway was greater during mental arithmetic than during signal detection. By contrast, sway was not affected by variations in the difficulty of purely cognitive tasks (easy vs. hard mental arithmetic). Chang, Wade, Stoffregen, Hsu, and Pan (2010) compared sway in children with and without autism spectrum disorder (ASD). Children with ASD tended to sway more than typically developing children; however, both groups reduced their sway during performance of a demanding visual task, relative to sway during a less demanding visual task.

To date, few studies have examined relations between postural control and the performance of simultaneous non-postural tasks in children with DCD. Laufer, Ashkenazi, and Josman (2008) asked participants to vocalize items (i.e. ball and table) displayed on a screen during stance. They reported that both DCD and TDC increased postural motion while engaged in a task compared to sway during quiet stance (no task). This finding may be questionable because the task they used required a vocal response;

speech articulation tends to increase measured postural motion (Yardley, Gardner, Leadbetter, & Lavie, 1999). This issue is also problematic for other previous studies (Cherng, Liang, Chen, & Chen, 2009; Tsai, Pan, Cherng, & Wu, 2009). In the present study, we eliminated this problem by using visual tasks that did not require spoken responses.

In the present study, children with and without DCD performed easy and hard visual tasks while standing. We made several predictions. First, we predicted that overall sway would be greater in the DCD group than in the TDC group. Second, in the TDC group we predicted that sway would be reduced during performance of a more demanding visual task, relative to sway during performance of a less demanding visual task. Third, contrary to the findings of Chang et al. (2010) in children with ASD, we predicted that DCD children would not exhibit a reduced effect of visual task difficulty on postural sway.

Methods

Participants

The study protocol was approved by the University of Minnesota Institutional Review Board. All participants and their parents gave written informed consent. There were 32 children (17 boys, 15 girls) between the age of 9 and 10 years (mean= 9.40, SD= 0.50) in DCD group while 32 age-matched (mean= 9.21, SD= 0.42) counterparts (17 boys, 15 girls) in TDC group. Table 1 illustrates that no significant differences were present between the DCD and TDC group for age, height, weight, and BMI. In addition, no significant group differences were found for IQ and the attention deficit and hyperactivity disorder- Diagnostic Teacher Rating Scale (ADHD-DTRS, Dupaul, Power, AnastoPoulos, & Reid1998). All participants' IQ scores were greater than 80 and all were free from a diagnosis of ADHD.

The percentile range for total impairment score for the Movement Assessment Battery for Children (MABC, Henderson & Sugden, 1992) was 26th to 79th percentile for the TDC group and 1st to 3rd percentile for the DCD group. The MABC scores are illustrated in Table 2 and show scores for the DCD group were significantly higher than the TDC group for total impairment score, manual dexterity, ball skill, and both static and dynamic balance.

Insert Table 1 about here…

Insert Table 2 about here…

Apparatus

We monitored postural activity using a magnetic tracking system (Flock of Birds, Ascension Technologies, Inc., Burlington, VT). One sensory was attached to a helmet worn by participants. A second sensor was attached (using cloth medical tape) to the skin at the seventh cervical vertebrae (i.e., between the shoulder blades). Each sensor was sampled at 60 Hz in each of six degrees of freedom. The emitter was placed 60 cm behind on a stand at approximately the participants' waist height.

Assessments

The Movement Assessment Battery for Children (MABC) is designed to identify children with motor coordination problems. This tool is popular for evaluation and identification of the DCD in research and clinical contexts. (Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001). The MABC is appropriate for the Asian children, both of the inter-rater and intra-rater reliabilities were excellent for Chinese preschool children, with a mean intra-rater of .96 and inter-rater of .77 (Chow, Henderson, & Barnett, 2001; Miyahara, Tsujii, Hanai, Jongmans, Barett, & Henderson, Hori, Nakanishi, & Kageyama, 1998; Wright & Sugden, 1996). The current validity of the MABC was based on the Bruininks-Oseretsky Test of Motor Proficiency (Bruininks, 1978). According to the manual, children whose total impairment score are more than 13.5 (< 5th percentile) are defined as presenting coordination difficulties and less than 10 (>15 percentile) are regarded as TDC. The MABC was administered in the present study to screen participants.

The ADHD Diagnostic Teacher Rating Scale (ADHD-DTRS) is an efficient instrument for screening children with ADHD. The ADHD-DTRS has been demonstrated high inter-reliability (77-.89) and high concurrent validity from correlations with Child Behavior Checklist (Dupaul et al., 1998). ADHD-DTRS consists of 18 items. Nine items evaluated inattention and nine the hyperactivity-impulsivity domain. Six or more counted behaviors in the inattention domain indicates an inattentive subtype; six or more counted behaviors in hyperactivity/impulsivity domain indicates a hyperactive/impulsive subtype.

Signal detection display

A signal detection task served as the suprapostural visual task displayed on a 14.1 inches (12.20× 7.10 inches) laptop screen (HP, Presario V3807). The screen was placed 1 m from the toe of the participant on a table that could be adjusted to each participant's eye height (Figure 1). The visual stimuli comprised a pair of vertical lines presented at the center of the screen. Each task condition consisted of two lines separated horizontally by 1.55° of visual angle against a white background. One pair constituted the *neutral event*, and the other the *critical signal* (see Figure 2). In the low difficulty (LD) condition, *neutral event* comprised of two dark lines equal in height (1.95° of vertical visual angle) while *critical signals* were two dark lines different in height where the left line had a vertical extension of 1.95° and the right line had a vertical extension of 2.35°. The brightness contrast between dark lines and background had a ratio of 1:26. In the high difficulty (HD) condition, the *neutral event* was the same as the LD condition except that grey lines replaced dark lines, while *critical signals* were two grey lines different in height with the left line having a vertical extension of 1.95° and the right line a vertical extension of 2.12°. The brightness contrast between grey lines and background had a ratio of 1:1. Each visual stimulus (pairs of lines) appeared for approximately 444 ms with 888 ms between stimuli such that each trial lasted for 120 s epochs. Each trial consisted of 30 critical signals and 60 neutral events. The sequencing of critical signals and neutral events were presented in random order using a custom software application.

Insert Figure 1 about here…

Insert Figure 2 about here…

To investigate the relation between postural sway and suprapostural tasks, it was necessary to assess the level of difficulty of the suprapostural tasks. We used mental workload for this purpose. Mental workload refers to the amount of mental work or effort used to perform a task. There is no universally accepted definition of mental workload, and for this reason there are numerous rating scales available. Hart and Staveland (1988) defined mental workload in terms of the costs incurred in achieving a given level of performance, where both internal and external factors can contribute to mental workload.

We measured subjective mental workload using the National Aeronautics and Space Administration Task Load Index (NASA-TLX). The TLX can be quickly administered and offers a reliable index of Overall Workload. While originally developed for use with adults, it has been used to measure subjective mental workload in school-aged children (i.e. Straker, Burgess-Limerick, Pollock, Coleman, Skoss, & Maslen, 2008; Als, Jensen, & Skov, 2005). The NASA-TLX is a multidimensional rating procedure which produces an overall Workload rating based on a weighted average of six subscales: Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration. Each subscale provides differentiated contribution and sum up as a subjective overall Workload score. Following Stoffregen et al. (2007b), we used the Overall Workload rating to specify the subjective mental workload separately for the low difficulty and high difficulty tasks.

Procedure

Participants were tested in a soundproof classroom located within a primary school. Participants stood facing a laptop screen with both arms by their side. An experimenter asked each to stay relaxed and not move their arms while standing with their feet shoulder width apart. Participants were instructed to keep their feet fixed for the duration of each trial. Two conditions (LD and HD) were presented for the signal detection task. Each condition was explained to each participant; then a 1 min practice was given to each participant to ensure that each fully understood and correctly executed the task. If necessary, additional instruction and practice was provided.

Each participant performed six trials. Three trials each for the LD and HD condition. Trials were blocked by conditions and the order of blocks was randomized and counterbalanced across participants. Participants held a computer mouse (Kingston, SlimBlade^{TM} Bluetooth Presenter Mouse) in their preferred hand and pressed the left button of the computer mouse in response to a critical visual stimulus. Correct responses (button pressed corresponding to a *critical signal*) and false alarms (button pressed corresponding to a *neutral event*) were recorded. Postural motion was recorded during each trial. After each trial, participants rested (sitting on a stool) for 1 min before the next trial to minimize fatigue (Smart, Pagulayan & Stoffregen, 1998). The NASA-TLX was administered twice to each participant after each block of trials, per condition. With instructions from an experimenter, all participants rated NASA-TLX workload for the condition most recently completed. Finally, participants were asked whether they fully attended to the signal detection task or they directed their attention to postural control. Participants who failed to allocate their attention fully on the signal detection task were excluded from the analysis.

Data analysis

We evaluated visual task performance in terms of signal detection theory (Stoffregen et al., 2007b; Yu, Yank, Katsumata, Villard, Kennedy, & Stoffregen, 2010). For each subject, d’ (an index of perceptual sensitivity) was calculated by combining the rates of hits and false alarms across the trials in each condition. Each rate was normalized relative to the mean of its distribution, and d’ was defined as the difference between the normalized rates for hits and false alarms (Craig, 1984). According to Craig (1984), tasks with d’ values greater than 3.5 can be described as very easy, while tasks with d’ values between 2.5 and 3.5 can be considered moderately easy. Values below 2.5 indicate moderate to very difficult tasks.

We computed the overall Workload score from the NASA-TLX across participants for each condition. The overall score was taken as the measure of subjective mental workload.

For postural activity we focused on the positional variability of the head and torso, which we operationalized as the standard deviation of head and torso position. Standard deviation of position was computed separately for position in the anterior-posterior (AP) and mediolateral (ML) axes. Previous research regarding postural motion and suprapostural task performance has sometimes found a trials effect (i. e. Stoffregen, Bardy, Bonnet, & Pagulayan, 2006). We analyzed our data for any possible trial effects, but made no predictions about trial effects.

For each dependent variable we conducted a Group (2) × Task Difficulty (2) × Trials (3) repeated measures analyses of variance (ANOVA). An alpha level was set at .05 for all statistical tests, which were performed employing SPSS version 14.0.

Results

Signal detection performance

Figure 3 summarizes the data on task performance. The mean d′ was 3.90 for the LD task, and 3.10 for the HD task. This difference was significant, F (1, 62) = 6.88, $p < .05$. D-prime for the DCD group (mean = 3.20) did not differ from the TDC group (mean = 3.80), F = 3.90, ns. Craig (1984) reported that a greater d' value indicates better signal detection performance. The mean d' was significantly lower during performance of the HD relative to the LD task, confirming that the HD task was more difficult than the LD task.

While there was not an overall difference in task performance between the DCD and TDC groups, there was a significant Group × Task Difficulty interaction , F (1, 62) = 6.27, $p < .05$, which is illustrated in Figure 3b. The difference in signal detection performance between the DCD group and TDC group was greater in the HD condition than the LD condition.

Insert Figure 3 about here

Subjective mental workload

The mean (SD) Overall Workload score was 59.57 (16.32) for the LD condition, and 71.97 (13.32) for the HD condition. This difference was significant, $F(1, 62) = 3.05$, $p < .05$, confirming that children in both groups experienced the HD task as requiring more mental effort than the LD task. For the DCD group, the mean (SD) for overall workload score was 68.27 (16.33), and 63.28 (13.30) for TDC group; this difference was not significant. The task difficulty × Group interaction was not significant.

Postural activity

Contrary to our prediction, there was not a main effect of visual tasks on postural activity in either the AP or ML axes, for either the head or torso, each $F < 1.0$, ns.

Our prediction that there would be group differences in postural activity between the TDC and DCD groups was confirmed. As shown in Figure 4, the DCD group exhibited greater positional variability than the TDC group for head motion in AP, $F\ (1, 62) = 35.05$, $p < .05$; and in ML, $F\ (1, 62) = 22.68$, $p < .05$; and for torso motion in AP, $F\ (1, 62) = 36.52$, $p < .05$; and ML, $F\ (1, 62) = 15.87$, $p < .05$.

Insert Figure 4 about here

In addition, we found significant Group × Task Difficulty interactions for positional variability in the AP axis of the head, $F\ (1, 62) = 5.15$, $p < .05$, and torso, $F\ (1, 62) = 5.89$, $p < .05$; and for positional variability of the torso in the ML axis, $F\ (1, 62) = 4.59$, $p < .05$. The interaction effects revealed that the effect of visual task (HD vs. LD) on postural activity differed qualitatively for the TDC and DCD groups. As shown in Figure 5, while the TDC group reduced postural motion in the HD relative to the LD condition, the DCD group actually increased their postural motion!

Insert Figure 5 about here

Discussion

Standing children (with and without DCD) performed visual vigilance tasks that varied in difficulty. Task performance was better on the low difficulty task than on the high difficulty task for both TDC and DCD children. Consistent with this, both groups reported greater subjective mental workload during performance of the high difficulty task. Overall, the magnitude of postural activity was greater in the DCD group than in the TDC group. Both groups modulated their postural activity in response to variations in the difficulty of visual vigilance tasks, but the nature of these variations differed between the TDC and DCD groups.

Visual performance and mental workload

Visual performance was better for the low difficulty task, and worse for the high difficulty task. This result confirms that these variations in task difficulty produced reliable differences in task performance among children. The task performance data were mirrored in children’s ratings of their subjective mental workload. We did not find a difference in overall task performance between the TDC and DCD groups, that is, we did not find any evidence that TDC and DCD children differed in the overall visual and cognitive skills required for performance of these visual vigilance tasks. Similarly, the TDC and DCD groups did not differ in subjective mental workload. The absence of differences between the TDC and DCD groups in task performance and mental workload is consistent with the developmental coordination disorder is not linked to overall intelligence, cognitive ability, or visual skills.

Group differences in postural control

Overall postural activity was greater in the DCD group than in the TDC group. This finding is consistent with similar findings in previous research comparing TDC and DCD children (e.g., Geuze, 2003; Przysucha & Taylor, 2004; Tsai et al., 2008; Wann et al., 1998). As noted earlier, overall increases in the magnitude of standing body sway have been reported in children with Autism Spectrum Disorder (Chang et al., 2010), in adults with Parkinson's disease (e.g., Schmit, Riley, Dalvi, Sahay, Shear, Shockley, & Pun, 2006), and in healthy elderly adults (e.g., Prado, Duarte, & Stoffregen, 2007). Thus, the present result is consistent with the finding that many different types of clinical conditions are associated increases in the magnitude of standing body sway. In general, then, non-invasive measures of body sway may be useful for the identification of persons at risk for a variety of clinical conditions.

Group postural responses to visual tasks

We did not find overall differences in postural activity during performance of the low difficulty and high difficulty tasks. However, it is clear that children's postural activity was influenced by our variation in the difficulty of visual vigilance tasks. These effects are apparent in the significant Group × Task Difficulty interactions.

In TDC children, positional variability was reduced during performance of the high difficulty visual vigilance task, relative to sway during performance of the low difficulty task. This relation between visual task difficulty and postural activity was qualitatively similar to effects that have been observed in typically developing children (e.g., Chang et al., 2010), in healthy young adults (e.g., Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen, Bardy, Bonnet, Hove, & Oullier, 2007a, Stoffregen et al., 2007b), in healthy elderly adults (Prado et al., 2007), and in healthy adults on ships at sea (e.g., Stoffregen, Villard, & Yu, 2009; Yu et al., 2010). The decrease in postural activity with increasing visual task difficulty contrasts with previous studies in which TDC children have exhibited increased sway during performance of more difficult tasks. However, in those studies children responded to task stimulus with verbal reports (Laufer et al., 2008; Tsai et al., 2009). As noted in the Introduction, speech articulation can artifactually increased measures of standing body sway (Yardley et al., 1999).

In the DCD group, postural activity was also influenced by variation in visual task difficulty. However, the nature of the effects differed quality from the effects seen in the TDC group. In the DCD group positional variability during performance of the high difficulty visual task was greater than during performance of the low difficulty task. This effect was observed in both AP and ML axes for the torso, and in the AP axis for the head, underscoring the robustness of the effect and the fact that it was related to control of the entire body. These results are consistent with previous studies in which

DCD children exhibited increased sway during performance of more demanding tasks (e.g., Laufer et al., 2008; Tsai et al., 2009).

The qualitative difference in task-specific postural activity between TDC and DCD children is the principal result of this study. TDC and DCD children performed the same visual tasks, under the same circumstances and with the same non-speech response measures (button presses). Thus, the group-specific variations in postural activity across variations in visual task difficulty must be interpreted in terms of nature of developmental coordination disorder and its impact on relations between postural control and visual performance. At the same time, it is important to recall that the TDC and DCD groups did not differ in performance of the visual tasks, or in the subjective workload that they experienced while performing the tasks.

The present results indicated that postural motion in the TDC group was lower in the HD compared to LD condition, while DCD group increased their postural motion. Additionally, the two groups have similar signal detection performances in the LD condition, whereas the children with DCD produced lower signal detection performance than the TDC group in the HD condition. From a functional integration respective (Riccio & Stoffregen, 1988; Stoffregen et al., 2007b), the TDC group seemed capable of adaptively reducing postural motion to better perform the signal detection task. The DCD group increased their postural motion and their signal detection performance declined in the HD condition. This suggests a weakened perception-action link in children with DCD as they seem less able to reduce postural control to benefit signal detection performance in more the perceptually demanding condition.

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Table 1. Demographic data for the TDC and DCD group. The data are group means and standard deviations.

Measure	DCD (17 boys, 15 girls)	TDC (17 boys, 15 girls)
	Mean (SD)	Mean (SD)
Age (years)	9.40 (0.50)	9.21 (0.42)
Height (cm)	139.75 (7.00)	140.19 (6.42)
Weight (kg)	38.92 (11.90)	38.00 (9.00)
BMI (kg/m^2)	19.61 (4.43)	19.20 (3.83)
IQ	99.50(15.69)	101.68(15.98)
ADHD-DTRS	2.01 (1.12)	2.13 (1.17)

Table 2. The MABC scores. TOT: Total score. MD: Manual dexterity. BS: Ball skills. SDB: Static and dynamic balance. The data are group means and standard deviations.

Score	DCD (17 boys, 15 girls)	TCD (17 boys, 15 girls)
	Mean (SD)	Mean (SD)
Percentile range	1-3	26-79
TOT	19.69 (3.71)	5.45 (1.41)
MD	8.12 (2.77)	2.78 (1.47)
BS	5.66 (3.28)	0.56 (0.88)
SDB	5.85 (1.63)	2.13 (1.26)

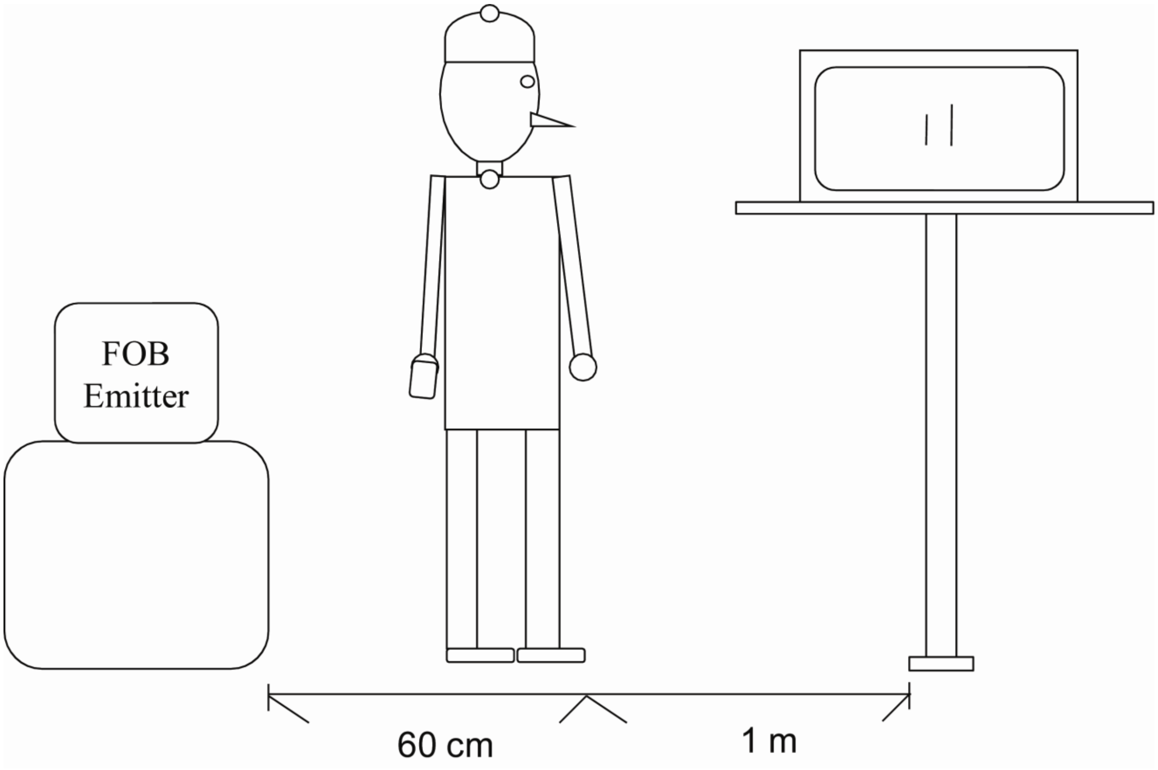

Figure 1. Experimental setup.

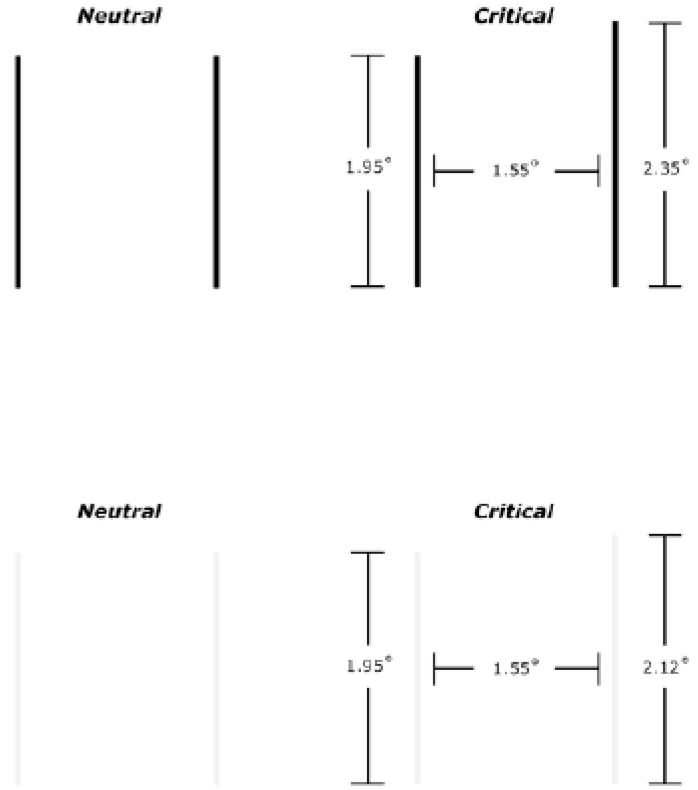

Figure 2. Signal detection task: LD and HD conditions

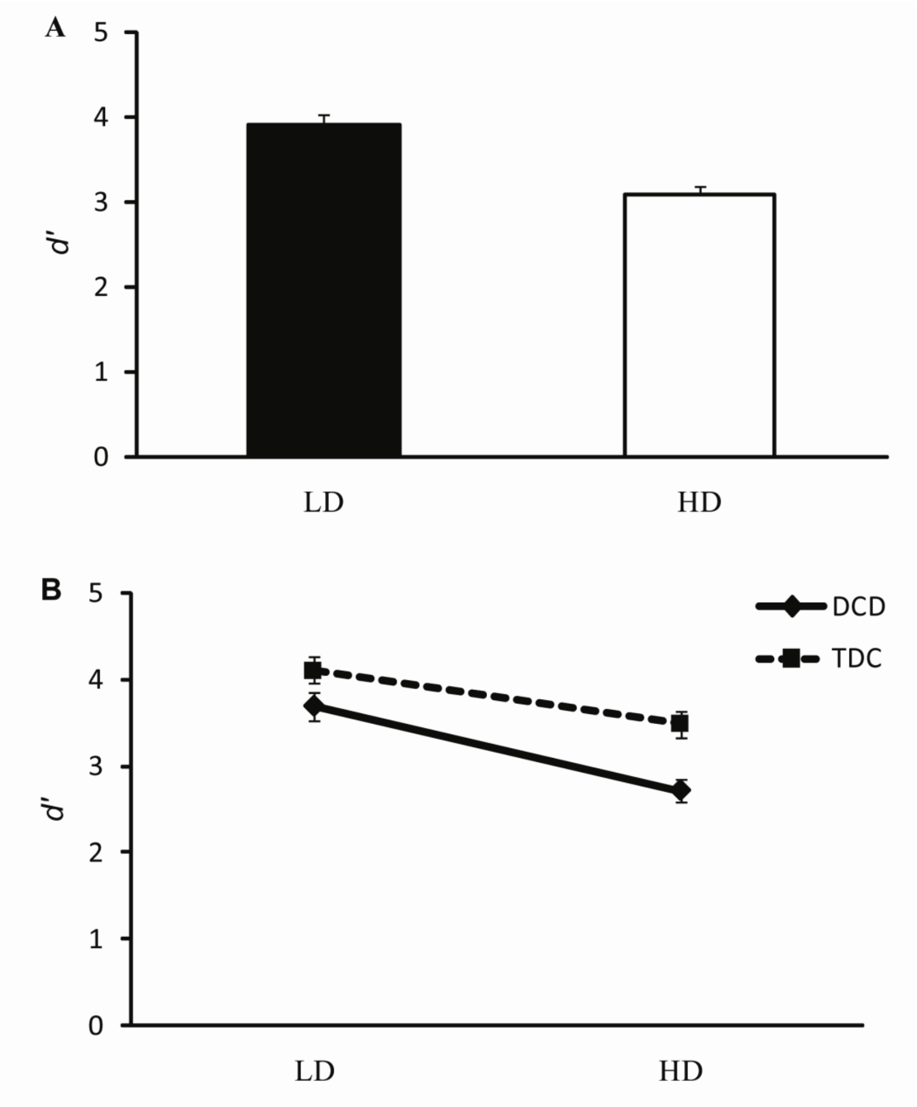

Fig. 3. Mean *d´* scores. (A) main effect of Task Difficulty (LD = low difficulty task; HD = high difficulty task). (B) Group × Task Difficulty interaction (TDC = typically developing group; DCD = developmental coordination disorder. The error bars are standard error.

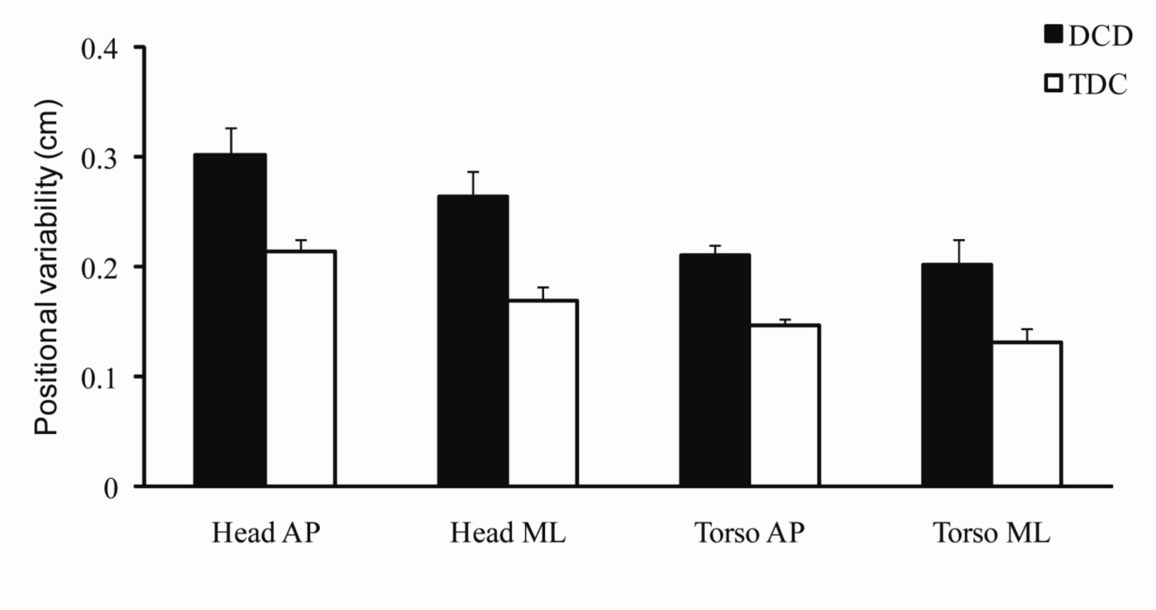

Figure 4. Mean positional variability for the head (AP and ML) and for the torso (AP), showing significant main effects of Group. The error bars are standard error.

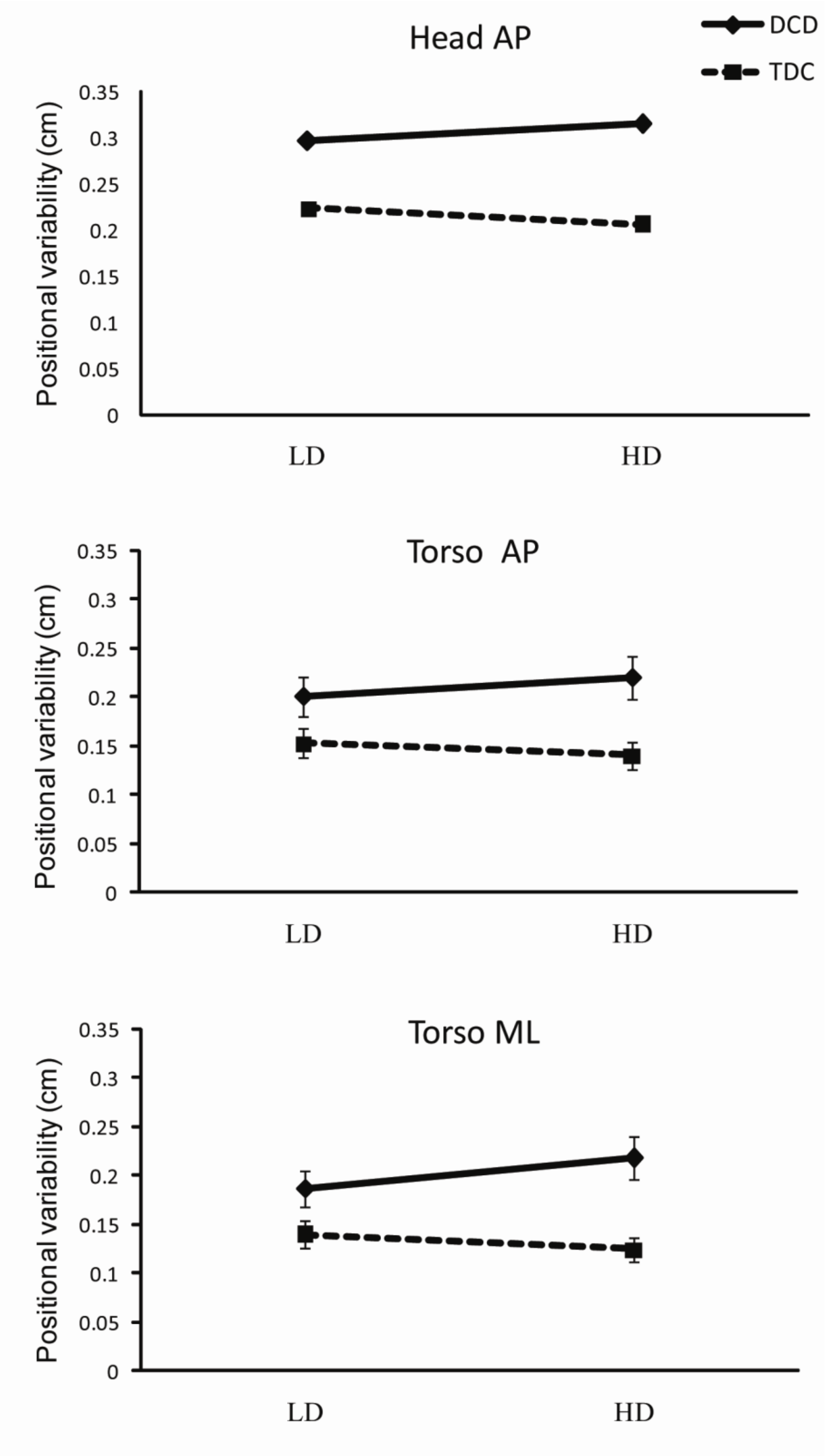

Figure 5. Mean positional variability in the AP and ML axis for the head and torso illustrating significant Group × Task Difficulty interactions. The error bars are standard error.

Postural adaptations to a suprapostural memory task among children with and without Developmental Coordination Disorder

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Postural responses to a suprapostural memory task among children with and without Developmental Coordination Disorder

Introduction

Children diagnosed with developmental coordination disorder (DCD) typically have difficulties with activities requiring perceptual-motor coordination despite the absence of a general medical condition.[1] These difficulties often affect academic achievement, learning, and activities of daily living. Researchers have reported that postural control in children with DCD differs (higher levels of postural motion) from that of typically developing children (TDC).[2,3] Theories of postural control (in both developmental and adult contexts) often focus on maintenance of the body's center of mass over the base of support, which avoids falling. It certainly is the case that the avoidance of falling is a goal of postural control. However, postural control actions may simultaneously support additional goals, both fine and gross motor skills such as surgery and catching a ball. Research has shown that postural activity can be modulated (increase or decrease) for the achievement of other behaviors.[4.5]

Research investigating the effect of cognitive demands on postural control has employed a postural and suprapostural dual-task paradigm, in which participants perform a cognitive task while maintaining upright stance or walking. Children with DCD may demonstrate more postural control difficulties in a dual-task protocol.[6] The research on the postural control of children with DCD is equivocal. Some studies report a deterioration of postural stability when executing cognitive tasks.[7,8,9] Others report reduced postural motion during an auditory choice task.[8]

The conflicting findings arise from several sources. In some studies, cognitive tasks required a verbal response,[7,8] where speech articulation can influence body sway.[10] In others, cognitive tasks required participants to press a handheld button,[8] which can influence body sway independent of cognition.[11] Third, previous studies did not measure difficulty or demand of cognitive tasks.[7,8,9] Without an independent measure of task difficulty, the manipulation of cognitive load was not confirmed. In addition, previous studies with DCD have used cognitive/perceptual tasks rather than 'purely cognitive tasks',[7,8,9] which can affect postural responses. For example, an auditory memory task required memorizing items played over a stereo system (auditory stimulation),[7] another task required objects to be named, appearing consecutively on a screen (visual stimulation).[8] Lastly, many studies have compared postural motion in single (quiet stance) and dual-task conditions. These comparisons can be a confounding factor because participants may engage in unspecified cognitive activities of unknown load, in a single task condition.[12]

To avoid these confounding factors, we modified the study protocol of Riley et al.[13], comparing postural activity of probable DCD and TDC during performance of a memory task at two levels of difficulty. We hypothesized (1) postural activity would change as a function of the difficulty level of a memory task, (2) children with probable DCD would sway more than TDC, and (3) variations in the difficulty level of a memory task would have different effects on the postural activity of probable DCD and TDC.

Methods

The study protocol was approved by the University of Minnesota Institutional Review Board. All participants gave written informed consent.

Participants

Two hundred forty-nine volunteer children from a primary school in Kaohsiung city, Taiwan, were screened. The DCD group comprised 38 children with probable DCD (21 boys, 17 girls) aged between 9 and 10 years, matched with 38 TDC (21 boys, 17 girls) serving as controls. Both groups were of normal intelligence, and had no reported specific neurological diagnoses. Table 1 presents participants' basic data; no differences between groups for age, body height, body weight, and IQ were present.

The ADHD Diagnostic Teacher Rating Scale (ADHD-DTRS)[14] was administered to test for inattention and hyperactive/impulsive symptoms. The ADHD-DTRS consists of 18 items, 9 for inattention and 9 for hyperactivity/impulsivity. Six or more counted inattention behaviors is an indication of an inattentive subtype ADHD. Six or more counted behaviors in hyperactivity/impulsivity indicate a hyperactive/impulsive subtype ADHD. The ADHD-DTRS data presented in Table 1, show none of the participants were co-morbid with ADHD.

The Movement Assessment Battery for Children (MABC) identifies children with DCD.[15] An experienced team of evaluators screened the participants using the MABC. Children who scored 13.5 or greater (below the 5th percentile) were assigned to the DCD group, and those with a score of 10 or less (above the 15th percentile) were assigned to the TDC group. Table 1 summarizes the MABC data; the DCD group had significantly higher scores than the TDC group in total impairment score, and all sub-domains scores.

Table 1

Apparatus

Data on head and torso were collected using a six-degree-of-freedom Flock of Birds (FOB) (Ascension Technologies, Inc., Burlington, VT) magnetic tracking system with a sampling rate set at 60 Hz. Participants wore a bicycle helmet to record head position via a sensor taped to the helmet. Torso position was recorded via a second sensor attached at the 7th cervical vertebrae. The emitter was located 60 cm behind the participants, on a stand, at waist-height for each participant.

Assessment of subjective mental workload

Workload was defined as a construct that represents the costs incurred by the human operator as a consequence of achieving a given level of performance.[16] The National Aeronautics and Space Administration Task Load Index[16] (NASA-TLX) assessed subjective mental workload. The NASA-TLX is a multidimensional rating scale that yields an overall workload rating based on a weighted average of six subscales: Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration. Workload ratings range from 0 to 100 with a high rating indicating greater workload. Following Stoffregen et al.,[4] we used the overall workload rating to score the subjective mental workload for each task condition.

Procedure

Prior to beginning the study, each participant was tested as a Digit Memory Test[13], to determine the maximum digit span that they could correctly retain for 10 seconds. The maximum number of recalled digits was used for the high difficulty (HD) condition, and the low difficulty (LD) condition was 50% of the HD condition. Participants were instructed to stand relaxed while performing with their hands at their sides. If the HD condition was an odd number the LD was determined by rounding down. Random digit strings were generated using Microsoft Excel.

Participants performed three trials for each task difficulty condition, for a total of six trials. Trials in the LD and HD conditions were blocked, with half the group receiving LD first, and half HD first. The task and procedure were explained to each participant. Participants practiced for 1 minute, or longer if necessary. The digit sting was displayed in black 54-point Arial font against a white background, presented via Powerpoint, on a 14.1 inches screen on a height-adjustable table placed 1 meter from the participants. The top of the screen was at eye level. The digit string was displayed for 10 seconds, participants were instructed to remember and mentally rehearse the digit string. The disappearance of the display triggered a 120 seconds mental rehearsal period, during which participants were instructed to rehearse while maintaining their gaze within the boundaries of the blank screen. Postural activity was measured during 120 seconds rehearsal period, thus, avoiding any contamination of the postural activity data by speech. Following the 120 seconds rehearsal period, participants reported the numbers of digits they could remember, and a percent correct score was computed. Participants rested between trials to minimize any possible fatigue. The NASA-TLX test was administered both at the completion of the HD trials, and the LD trials.

Data analysis

Percent correct score was recorded as the memory task performance. The overall workload rating was computed across participants for each condition. The positional variability of the head and torso was expressed as the standard deviation of position for each trial. Head and torso data were analyzed separately for both the anterio-posterior (AP) and medio-lateral (ML) directions. Data were analyzed for possible trial effects, but no predictions were made.[17] The data for memory task performance, NASA-TLX score, and positional variability were analyzed using Group (2) × Task Difficulty (2) × Trial (3) repeated-measures ANOVA. Alpha level was set at .05 for all statistical tests, which were performed using SPSS version 14.0.

Results

Memory task performance

The DCD group recorded 3 errors in the LD condition and 34 in the HD condition. The TDC group recorded 3 errors in the LD condition and 30 in the HD condition. The percent correct for the DCD group was 83.77% and 85.53% for the TDC group. The percent correct for the LD condition was 97.37% and 71.93% for the HD condition. A repeated-measures ANOVA yielded a significant main effect for Task Difficulty, F (1, 74) = 48.40, $p < .05$. No other significant effects were found.

Subjective Mental Workload

The mean and standard deviation (SD) overall workload scores were 66.05 (15.77) for the DCD group and 63.46 (14.93) for the TDC group; these means did not differ significantly. The mean and SD overall workload scores summed across groups were 58.15 (13.92) for LD condition and 71.36 (16.78) for HD condition, this difference was significant, F(1, 74)= 4.05, $p < .05$.

For the DCD group the mean and SD was 73.00 (16.5) for the HD condition and 59.20 (15.03) for the LD condition. This difference was significant, F (1, 74) = 4.41, $p < .05$. For the TDC group, the mean and SD was 70.29 (16.57) for the HD condition and 57.32 (12.95) for the LD condition. This difference was also significant, F(1, 74) = 4.22, $p < .05$. These results demonstrate that the task difficulty manipulation was effective for both groups, requiring an increased workload effort from the LD to HD condition.

Postural activity

The positional variability for the head and torso motion was separately analyzed in both the AP and ML direction. The main effect of Task Difficulty was significant for head motion in the AP axis, F (1, 74) = 8.77, $p < .05$, and in the ML axis, F (1, 74) = 13.87, $p < .05$. Similar effects were found for torso variability (AP axis: F (1, 74) =

39.02, p < .05; ML axis: F (1, 74) = 10.45, p < .05). These effects are illustrated in Figure 1.

Figure 1

The main effect of Group was significant for head motion in the AP axis, F (1, 74) = 21.96, p < .05, and in the ML axis F(1, 74) = 5.13, p < .05. For torso motion, the main effect of Group was significant in the AP axis, F (1, 74) = 12.44, p < .05, but not the ML axis, F (1, 74) = 3.28, ns. These effects are illustrated in Figure 2.

Figure 2

In the ML axis, a Task Difficulty × Group interaction was significant for head motion, F (1, 74) = 5.56, p < .05, and for torso, F (1, 74) = 4.72, p < .05. As illustrated in Figure 3, task difficulty effect was greater for the TDC group than the DCD group, indicating that the TDC group modulated their postural motion as a function task difficulty, but the DCD group did not. No other significant effects were detected.

Figures 3

Discussion

Postural motion was reduced during performance in the more difficult (HD) condition compared to the easier (LD) condition, consistent with earlier results.[13] Children with probable DCD tended to sway more than TDC, confirming previous reports.[3,6] A significant Group by Task Difficulty interaction, however, indicated that while the TDC modulated their postural activity in response to memory task difficulty, the DCD group did not, these results are discussed below.

Task Difficulty Effect

Our first hypothesis that manipulation of task difficulty would significantly influence postural motion was supported; as task difficulty increased as postural motion decreased. Overall postural motion was significantly reduced in the HD condition compared to the LD condition. These findings are consistent with Riley et al.'s study,[12] but different from reports by Laufer et al.,[7] and Tsai et al.[8] who reported an increase in postural motion. One possible explanation between the present results and these studies[7,8] may be task related. Laufer et al.[7] required participants to speak their responses which can affect postural motion.[10] Tsai et al.[8] employed several tasks that asked participants to count, recall, articulate, manually response, all of which are not pure cognitive tasks and can not be compared to the protocol employed in the present study.

A second possible explanation might be the age factor. Laufer et al.[7] recruited 4-to-6 year-olds. By age nine children have likely developed adult level postural stability,[18] postural motion should therefore be less variable. The present study used participants aged between 9 and 10 years.

Third, a methodological difference may be the task manipulation. Laufer et al.[7] and Tsai et al.[8] compared postural motion during quiet stance (no specified task), and a cognitive task condition, we compared two specific levels of task difficulty. These earlier studies were based on a resources competition hypothesis (RCH),[5] which assumes available central resources limit, and when task demands surpass the available resources, performance will deteriorate. This hypothesis predicts that performance suffers only in a difficult task condition, because of the increased demand. Our study reports reduced postural motion during the HD compared to the LD condition; thus our results cannot be interpreted in terms of the RCH. In addition, the RCH assumes that maintaining upright stance is the sole activity during quiet stance.[5] Control over what participants maybe thinking in such a baseline condition is not possible,[12] we did not use a quiet stance condition.

Both groups of children recorded their lowest postural motion and lowest task performance (percent correct) in the HD condition. Riley et al.[13] suggested that participants might sacrifice cognitive performance for the sake of postural stability. To determine if this was valid, we analyzed the positional variability, excluding the trials on which participants produced errors of recall. The positional variability data was identical when we omitted the error trials, making Riley et al.'s[13] hypothesis not tenable for the present study.

Group Effect

Our second hypothesis predicting a group effect for levels of postural motion was confirmed; children with probable DCD had significantly higher levels of postural motion, than the TDC. Several studies have demonstrated that children with DCD have difficulty maintaining postural stability.[2,3] In short, the overall higher level of postural motion exhibited by probable DCD children suggests a reduced ability to modulate postural motion when engaged in cognitive activity.

A second factor contributing to group differences was task duration. Children with DCD fatigue more easily than TDC,[19] and the present study required participants to maintain their stance for longer periods of time than previous studies.[2,3] A longer stance period demands greater endurance and a fatigue effect in DCD children may account for higher levels of postural motion, but no Group by Trial effect was found.

Group x Task Difficulty interaction effect

Our third hypothesis predicting a Group by Task Difficulty interaction was confirmed. While TDC reduced their postural motion from the LD to HD condition, postural motion was essentially the same for both levels of task difficulty for the DCD group. Wulf et al.[20] proposed a 'constrained-action hypothesis' to account for the relationship between postural control and a suprapostural task. This hypothesis proposes that when attention is directed to a suprapostural task, attention is drawn away from postural control (focusing on the performer's movements), making such control essentially automatic and more efficient. One explanation for the present interaction effect may be that TDC are more sensitive to high cognitive load which draws attention away from postural control, producing a larger reduction in postural motion in the HD condition. This explanation is unlikely, however, as both groups of participants were free of any ADHD issues.

Riley et al.[21] proposed a ‘cognitive load hypothesis’ whereby the organization of postural synergies are constrained by the demand of cognitive tasks. The cognitive load hypothesis could account for both an increase and decrease in postural stability while engaged in a cognitive task. The present study demonstrates that the DCD group do not reduce their postural motion when switching from the LD to HD condition, compared to the TDC group. Our results support the proposition that children with probable DCD exhibit different postural characteristics in response to an increased cognitive demand.

Ricco and Stoffregen,[22] and Stoffregen et al.[4,17] provide substantial support for the functional integration of posture and a suprapostural task. They support the claim that the organism’s action is controlled with reference to the consequences of the behavioral goal. Posture is controlled not for its own sake, but for achieving a specified goal, and as a consequence posture is modulated to facilitate the achievement of the task goal. Similarly, an ‘adaptive resource-sharing model’ also predicts that postural control can facilitate the performance of suprapostural tasks under relatively unchallenging (low resource) balance conditions, if resources are available. Postural motion will increase if the resource capacity is exceeded, e.g. if the balance condition becomes too challenging. In the present study, participants stood on an even surface with minimal postural challenge. Accordingly, we interpret the present interaction effect as a difference in the strength of the link between postural motion and task engagement. The strength of this link appears diminished in DCD children compared to TDC.[24] However, the functional integration perspective and the adaptive resource-sharing model predict decreased motion only when such a decrease is directly beneficial, as in visual tasks that require ocular stability as in the Stoffregen et al.'s studies.[4,17] All of the studies referenced employed perceptual tasks, whereas the present study used a cognitive (memory recall) task—which has a less obvious (and less studied) relationship to postural motion.

The most important result in this study was that while TDC reduced their postural motion when engaged in a memory task with both high and low cognitive load, children with probable DCD did not. The relationship between postural control and a memory task is complex and less well understood. A new approach is required to explore the relationship between postural control and cognition. A limitation of the present study is that we recruited the DCD group within a narrow age band, similar levels of motor-impairment, and all free from a diagnosis of ADHD. Future studies employing DCD with broad age bands and various motor characteristics are needed to substantiate the present findings.

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Table 1. Basic data, the ADHD-DTRS and the MABC scores (TOT: total impairment score, MD: manual dexterity, BS: ball skills, SDB: static and dynamic balance, PR: MABC percentile range) for the DCD and TDC group. The data are group means and standard deviations (SD).

Measure	DCD (21 boys, 17 girls)	TDC (21 boys, 17 girls)
	Mean (SD)	Mean (SD)
Age (years)	9.37 (0.49)	9.21 (0.41)
Height (cm)	139.11 (6.66)	140.11 (6.40)
Weight (kg)	37.92 (11.31)	38.07 (9.34)
IQ	100.57(15.38)	101.23(14.87)
ADHD-DTRS	2.12 (1.23)	2.28 (1.36)
TOT	20.25 (4.13)	5.59 (1.42)
MD	8.30 (2.78)	2.89 (1.46)
BS	5.94 (3.26)	0.55 (0.86)
SDB	5.95 (1.60)	2.17 (1.30)
PR	1-3	26-79

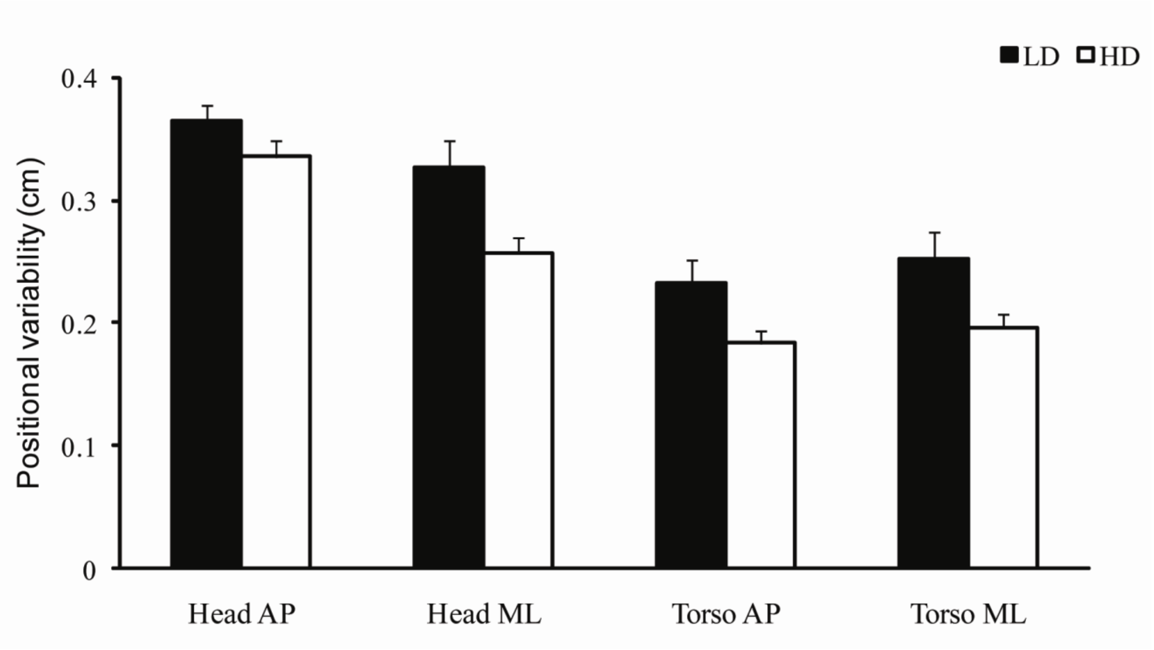

Figure 1. Mean positional variability for the low difficulty (LD) and high difficulty (HD) conditions, showing significant main effects of Task Difficulty. The error bars represent standard error.

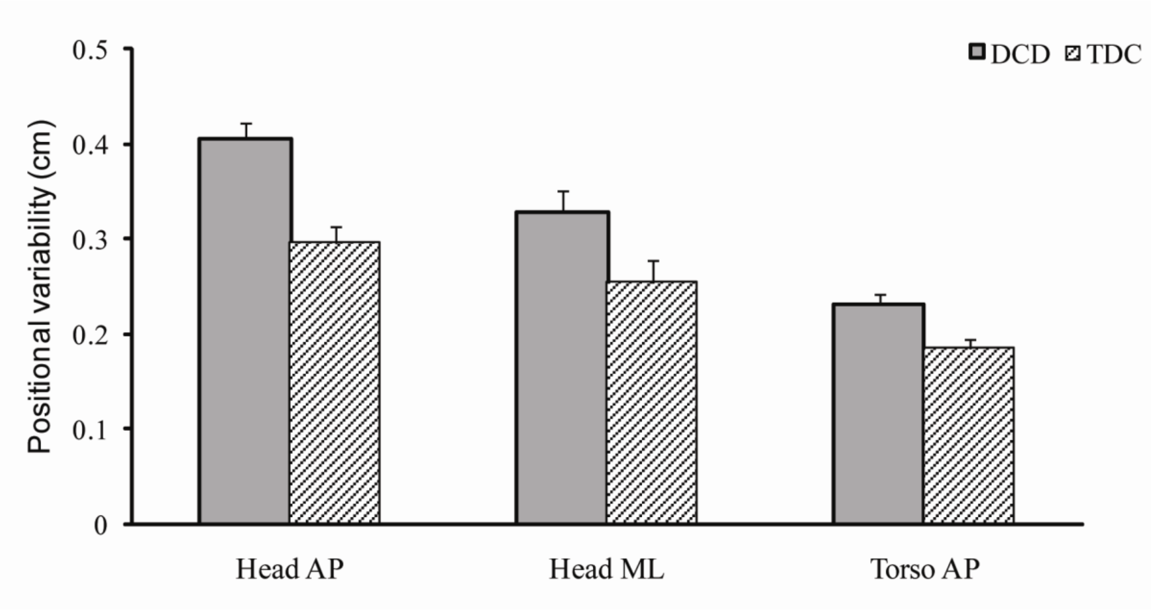

Figure 2. Mean positional variability for the DCD and the TDC groups, showing significant main effects of Group. The error bars are standard error.

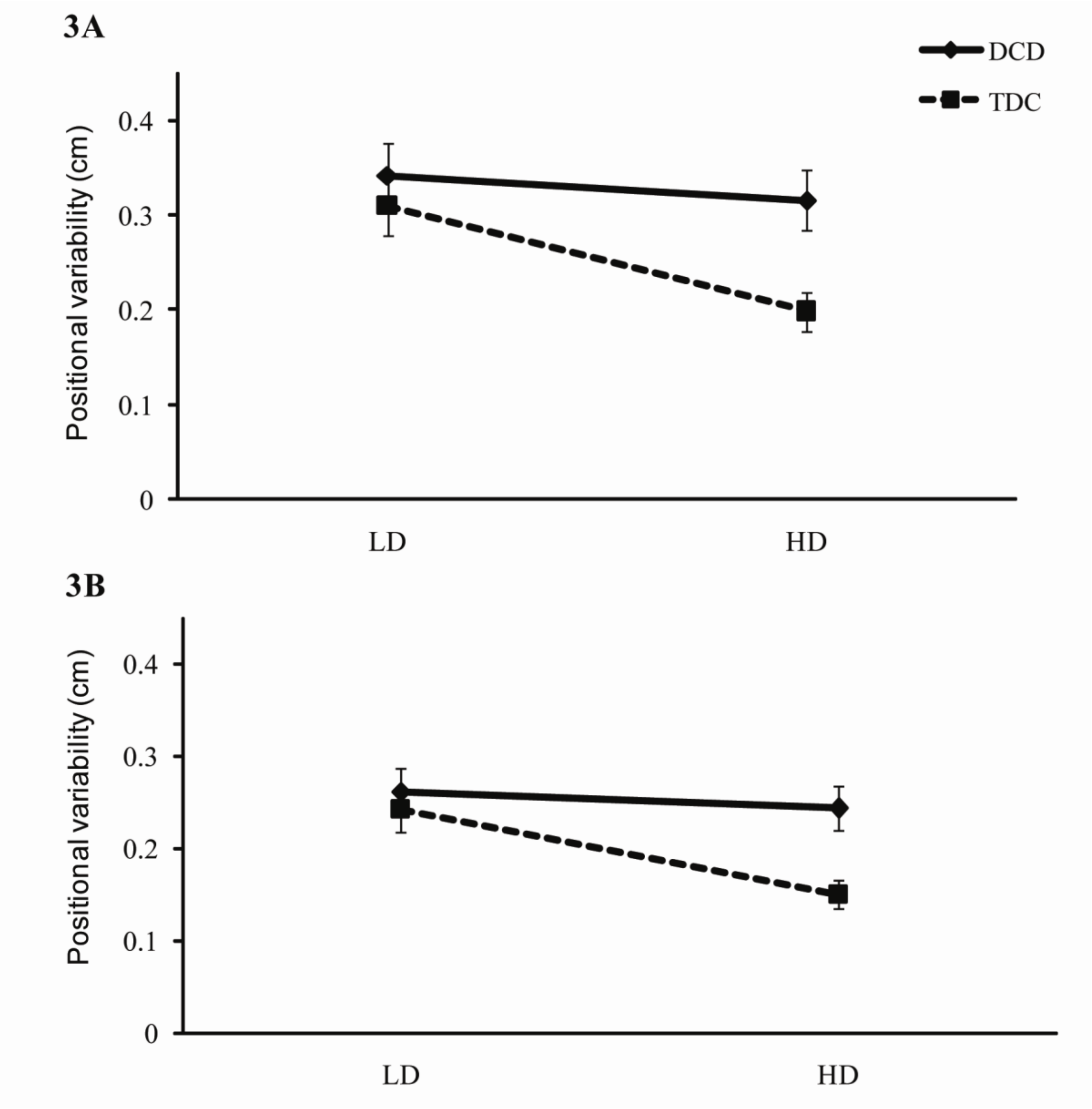

Figure 3. Mean positional variability in the ML axis for the head (A) and torso (B), showing significant Group x Task Difficulty interactions. The error bars are standard error.

Autonomic responses while engaged in attention-demanding tasks of children with and without Developmental Coordination Disorder

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Introduction

Psychological states and processes are known to profoundly influence the autonomic nervous control of the cardiovascular system. For decades the link between attentional, cognitive, and emotional processes, and changes in the autonomic nervous system (ANS) have drawn increasing interest [34, 35]. Cardiac function is extremely sensitive to autonomic influence; for example, heart rate variability (HRV), a measure of beat-to-beat variation, is a valid indicator of the functional state of the cardiorespiratory control system. HRV is increasingly being employed as a noninvasive and sensitive measure to detect the autonomic regulation/dysregulation which provides insights into the autonomic control of the heart [38]. Consequently, the analysis of HRV can be used to study the autonomic control of cardiac sympathetic and parasympathetic interaction.

Developmental Coordination Disorder (DCD) is a term that describes children who manifest coordination and control problems with their movement skills, not primarily due to a general medical condition or pervasive developmental disorder [3]. A key feature of DCD are difficulties performing activities of daily living (ADL) and academic achievement which demands motor coordination. The disorder can, however, lead to the other problems. A previous study [9] reported that children with DCD and those at risk for DCD record significantly poorer scores on measures of attention than typical developing children (TDC). This suggests that children diagnosed with DCD may have a problem with attentional effort. Several studies have shown that an increase in mental workload and attention produces a reduction in HRV [23, 34]. Richards and Casey [27] reported a decline in HRV during attention stimulus, and a return to pre-stimulus levels after the attention stimulus disappears, even in young infants. This autonomic regulation of the HRV seems impaired in children with attention deficit problems (i.e. attention deficit and hyperactivity disorder, ADHD) [11]. It is likely that the autonomic profiles in the HRV measures may differ between the DCD and TDC groups.

Children with DCD participate less in physical activity than their typical developing counterparts, and several studies have reported lower levels of cardiorespiratory fitness for children with DCD [5, 39]. Both cardiorespiratory fitness and physical activity are two factors identifies as associated with autonomic function in children. High levels of both positively affect HRV, that is, children who participate more in physical activity generate high levels of HRV, compared to their inactive peers [12]. Accordingly, DCD children's autonomic control of HRV may differ from their TDC peers due to differences in habitual physical activity and cardiopulmonary fitness.

The present study sought to determine if this hypothesized difference in HRV measures in children with DCD would be supported when the children with and without DCD are engaged in attention-demanding tasks at various levels of difficulty. We employed two tasks— a signal detection task, and a digit memory recall task, each with two levels of difficulty, low (LD) and high difficulty (HD), in two separate experiments. Specifically hypothesized that:

1. Group differences in HRV would be present between children with DCD and their

TDC peers.

2. The HRV measures will change as a function of the difficulty levels of the attention-demanding tasks.

Methods

Participants

The research project was approved by the University of Minnesota Institutional Review Board. Sixty volunteer children (30 DCD and 30 TDC) from a Primary School in Kaohsiung, Taiwan, participated in this study. Written consent for all participants were secured. The Movement Assessment Battery for Children [16] was used to assign participants to the DCD group (below the 5th percentile); and to the TDC group (total impairment scores of MABC were less than 10, above the 15th percentile. Since it is known that the HRV depends on age and is higher in males than in females, we controlled gender and age such that all participants were in the same age bands (9 to 10 years) and the gender ratio (male: female= 1:1) was the same for both groups. Table 1 presented that there were no differences between groups in basic data such as age, body height, body weight, and body mass index. Also, no significant group differences were found for IQ and the ADHD- Diagnostic Teacher Rating Scale (ADHD-DTRS) [10], thus all participants were with normal intelligence and were free from a diagnosis of ADHD. Significant differences between the DCD and TDC group were found in the MABC total impairment scores.

Tasks

1. The visual signal detection task

A signal detection task was used as the attention-demanding task in the first experiment. Tasks relating to vigilance have been thought to provide a fundamental example of ‘sustained attention’, which signifies an individual’s capacity to keep their focus and remain alert to stimuli over a prolonged periods of time [17]. A signal detection task was used in the first experiment because (1) it requires no verbal response, which has been reported to increase RSA and affect the response of the HRV [32]; and (2) it demands sustained visual attention. The signal detection task comprised pairs of vertical lines generated by a custom application presented on a 14.1 inch laptop screen placed 1 meter from the participant (Figure 1a). Each pairs of vertical lines were parallel to each other, apart horizontally by 1.09° of visual angle, displayed against a white background. In the LD condition (Figure 2, upper part), the neutral events were two vertical lines identical in length with 1.26° of vertical extent, and critical signals were two vertical lines different in length with 1.26° and 1.50° of vertical extent for left and right lines separately while the contrast ratio between black lines and white background was approximately 1 : 26. In the HD condition (Figure 2, lower part), the neutral event were two vertical line in the same length with 1.26° of vertical extent and critical signals were comprised of two different length vertical lines with 1.26° and 1.38° of vertical extent for left and right lines separately while the contrast ratio between grey lines and white background was approximately 1 : 1. Presentation of the visual stimuli (pairs of lines) lasted 444.44 ms, with a inter-stimulus interval (showing a blank white screen) lasted 888.88 ms. There were a total of 90 signals, 60 neutral and

30 critical signals, for each 120-seconds trial. Participants held a computer mouse and were asked to click it in response to a critical signal while cardiac responses were continuously recorded.

Figure 1 about here

Figure 2 about here

2. The digit memory task

A digit memory task was the task used in the second experiment and required no verbal response. In addition, the digit memory task was naturally different from the signal detection task. Participants were pre-tested on the Digit Memory Test [37] in order to obtain an individual maximum number of digits each was able to recall correctly in 10-seconds. This maximum number served as HD condition. The LD condition was 50% of the HD numbers. If the maximum number (HD) was odd, the number was rounded down for the LD condition. The digit spans were created by the function of random number in Microsoft Excel. Each digit string was presented on a 14.1 inch laptop screen for 10-seconds placed one meter ahead of participant (Figure 1b). Participants were asked to remember and mentally rehearse the digit string during quiet stance until the digits disappeared and a white screen showed up. At that moment, the 120-seconds cardiac measure period began and participants continued to mentally rehearse the previously exhibited digit string. Participants were asked to recall the digit string after the 120-seconds period.

NASA-TLX

In order to determine the difficulty score of the signal detection task, we used the National Aeronautics and Space Administration Task Load Index (NASA-TLX) [15] to assess the subjective mental workload. The NASA-TLX is a widely used tool for school-aged children [2]. The NASA-TLX produces an overall Workload rating based on a weighted average of six subscales: mental demand, physical demand, temporal demand, own performance, effort, and frustration. The overall Workload rating was between 0 and 100, higher rating represents higher workload. Following Stoffregen et al. [33], we used overall Workload rating as subjective mental workload for each task condition.

Cardiac measures

Beat to beat HR was recorded via a Polar Heart Rate Monitor (Porlar RS800, Kempele, Finland), with a sampling rate of 1000 Hz. The Polar instrument (low temporal resolution device) has excellent reliability ($r > .99$) in time domain, frequency domain and some non-linear HRV measures with three-lead system (BIOPAC Systems Inc., CA). (high temporal resolution device) [6]. The transmitter was worn by each participant via a chest-strap and a receiver/stored watch was taped to the wrist of an experimenter. Children wore the transmitter during both quiet stance (baseline state 120-seconds), and during task execution (120-seconds).

Cardiac measures were analyzed using Kubios software 2.0 (Finland: Department of Physics, University of Kuopio). The HR was derived by averaging across 120-seconds period. HRV was analyzed using a frequency domain approach and heart rate sample entropy (SampEn).

For the frequency domain analysis, fast Fourier transformations (FFT) was used to calculate the power spectral density of the RR series. This analysis provides insights into the presence of any underlying intrinsic rhythms with respect to HR regulation. This analysis is typically divided into three components: (i) high frequency (HF) band (0.15-0.4 Hz), (ii) low frequency (LF) band (0.04-0.15), and (iii) very low frequency (VLF) band ($\leqq$ 0.04 Hz). Only the power spectra in the HF band was used since it reflects parasympathetic nervous activity [29].

In order to clarify the relative changes of the sympathetic and parasympathetic balance across conditions, the low to high frequency ratio of heart rate (LF/HF) was determined. The LF/HF ratio is typically used as a defined index of autonomic control of the heart [29]. An increase in LF/HF ratio would indicate a dominant sympathetic over parasympathetic control, and vice versa.

In addition, we calculated the sample entropy (SampEn), a non-linear measure of the regularity of time series data [28]. SampEn (m, r, N) is the negative logarithm of the conditional probability that a dataset of length N, having repeated itself for m points within tolerance r, will also repeat itself for m+1 points. SampEn was calculated with m = 2 and r = 0.2 multiply by standard deviation of N. SampEn was used because (1) it can be applied to time series data of short duration [30], such as 2 minutes intervals in the present study, and (2) it is a non-linear analysis technique which provides additional information not available from conventional linear HRV analysis [28]. To summarize, we used four cardiac measures as dependent variables: HR, HF, LF/HF, and SampEn.

Procedure

The study was conducted in a sound-proof room. Cardiac responses were collected at baseline, and in two conditions of task difficulty, LD and HD. Participants completed 3 trials each for the LD and HD condition. Trials were blocked by task difficulty conditions, and block order was random and counterbalanced across participants. Half of the children performed the LD condition first, and the other half the HD condition first. Before each block, participants performed a baseline trial., thus each participant completed 8 trials, 2 at baseline, and 3 trials each for the LD and HD condition. The NASA-TLX was administered at the end of the LD and HD conditions.

Statistical analysis

The Workload score from the NASA-TLX was computed across participants for each condition, presenting as the measure of subjective mental workload. To analyze overall Workload score, a Group (2) × Task Difficulty (2) repeated measures ANOVA was used to determine possible differences in Group, Task Difficulty and the interaction for both tasks.

Separate one-way MANOVA was used to test trials effect for each condition. Since there were no trial effects revealed, mean scores were used as the estimates for each condition. Separate Group (2) by Task Difficulty (3) repeated measures ANOVA was used to determine possible differences in Group, Task Difficulty and the interaction for both tasks. For interactions, we used repeated contrasts to determine whether the two groups changed cardiac responses across task difficulty. Alpha was set at $p < .05$, and data analyses were completed using SPSS 14.0.1 (Chicago, IL).

Results

Subjective mental workload

For the signal detection task, the mean (SD) NASA-TLX workload score was 59.58 (16.35) for the LD condition, and 72.87 (13.79) for the HD condition, this difference was significant, $F(1, 58) = 3.17$, $p < .05$. For the digit memory task, the mean (SD) NASA-TLX workload score was 58.14 (13.92) for LD condition, and 71.96 (16.88) for HD condition, this difference was also significant, $F(1, 58)= 4.13$, $p < .05$. These results confirmed that the HD condition was higher mental workload than the LD condition for both tasks.

Cardiac measure

Main effect of Group

Figure 3a illustrated Group effect for LF/HF ratio in signal detection task. Mean (SD) LF/HF ratio was 3.28 (2.41) for DCD, and 2.61 (1.25) for TDC. Children with DCD displayed significantly higher LF/HF ratio than the TDC group, $F(1, 58)= 4.484$, $p < .05$.

Figure 3b illustrated group effect for LF/HF ratio in digit memory task. Mean (SD) LF/HF ratio was 3.46 (2.85) for DCD, and 2.86 (1.31) for TDC. Children with DCD displayed significantly higher LF/HF ratio than the TDC group, $F(1, 58)= 4.167$, $p < .05$.

Figure 3 about here

Main effect of Task Difficulty

Figure 4a illustrated a Task Difficulty effect in signal detection task for HR, $F(2, 58)= 9.221$, $p < .05$, HF, $F(2, 58)= 29.001$, $p < .05$, and LF/HF ratio, $F(2, 58)= 9.300$, $p < .05$. Repeated contrast showed: baseline > LD > HD for HF, and an opposite trend: baseline < LD < HD for HR and LF/HF ratio.

Figure 4b illustrated a Task Difficulty effect in digit memory task for HR, $F(2, 58)= 5.118$, $p < .05$, HF, $F(2, 58)= 7.578$, $p < .05$, LF/HF ratio, $F(2, 58)= 6.250$, $p < .05$. Repeated contrast showed: baseline > LD for HF, and an opposite trend: baseline < LD for HR and LF/HF ratio.

Figure 4 about here

Interaction effect of Group x Task Difficulty

Figure 5 illustrate Group x Task Difficulty interactions in signal detection task for HF, $F(2, 58)= 5.830$, $p < .05$, LF/HF ratio, $F(2, 58)= 3.183$, $p < .05$, and SampEn, $F(2, 58)= 4.236$, $p < .05$. Repeated contrasts indicated that the differences between the two groups were significantly different between the LD and HD condition for all HRV measures except the HR. The TDC group tended to increase LF/HF ratio in the HD relative to the LD condition compared to DCD. In addition, TDC tended to decrease HF and SampEn in the HD relative to LD condition compared to the DCD group. There were no significant effects for digit memory task.

Figure 5 about here

Discussion

Our study is the first to report cardiac autonomic responses to tasks requiring perceptual and cognitive effort in children with DCD. The central aims were to investigate the potential differences in HRV measures between DCD and TDC, and to examine HRV changes in response to various levels of task difficulty. We found: (1) a Group effect in both signal detection task and digits memory task; (2) a Task Difficulty effect among baseline, LD, and HD condition in signal detection task, and between baseline and LD condition in digit memory task; and (3) a Group x Task Difficulty interaction in signal detection task only. These results are discussed subsequently in that order. The consequences of the reported findings for the relation between task difficulty and DCD are also discussed.

Group Effect

Our first hypothesis that changes in HRV measures would be significantly different between DCD and TDC groups was supported. Averaging over task conditions, children with DCD had significantly higher LF/HF ratio than TDC group. In studies of physical training, aerobically trained children decreased LF/HF ratio, expressed as a predominance of sympathetic activity over parasympathetic control [13]. Studies have also shown that low aerobic fitness is associated with lower HF power [8] resulting in higher LF/HF ratio. The increased LF/HF ratio suggests a negative connection with aerobic fitness. Children with DCD participate less in physical activity [5] and to have a lower peak oxygen consumption in the maximal cardiopulmonary test, demonstrating a lower level of cardiopulmonary fitness [39]. As a result, the increased LF/HF ratio may be due to a lower level of aerobically fitness for children with DCD.

Task Difficulty Effect

Averaging over two groups, our results *partially* support the second hypothesis that manipulation of task difficulty influences HRV responses. In signal detection task, changes in HRV were found between each level of task difficulty. Previous research reported an increased HR [4] and LF/HF [19], and reduced HF power [25, 34] with increasing task difficulty. Porges [24] suggested that the suppression of parasympathetic activity (HF power) is the primary source of HRV, which is mediated by phasic changes in neural efferent output via vagus from brainstem to the sinoatrial node of the heart. The suppressed HF power represents diminished vagus influence on HR, causing sympathetic to outweigh parasympathetic control. Our results reflect previous findings which showed a parasympathetic withdrawal with the autonomic balance tilting toward sympathetic activity as a result of exposure to attention-demanding tasks. However, in digit memory task, we did not find any differences between LD and HD condition. This failure to detect a Task Difficulty effect requires an explanation.

One possible explanation of our results depends on magnitude of task difficulty. The idea is that effort expended to meet a behavioral challenge will correspond to the magnitude of task demand. A HD task would trigger a greater cardiac response than a LD task. Studies have demonstrated that attention-related cardiac response is more prominent under moderately difficult than easy condition [1]. In this respect, the HD condition in digit memory task does not appear sufficient to change HRV. However, the NASA-TLX workload score for digit memory task was significantly higher for HD compared to LD condition, implying that HD was more difficult than LD for all participants. Consequently, low magnitude of difficulty does not seem to explain our results.

Whether the responses of HRV reflect various levels of task difficulty is debatable. While some studies found that HRV is sensitive to small increments in task difficulty, others found HRV is only sensitive to major changes in task difficulty (i.e. rest vs. task execution). Aasman et al. [1] manipulated task difficulty by adding a dot pattern that degraded the visual stimulus, making it harder to detect. Their findings supported the former claim with respect to small changes in task difficulty. However, studies manipulating task difficulty by varying number of alphabet letters in memory support the latter. A memory task composed of three items did not change HRV, compared with a memory task of a single item [20]. Neither did increasing the item to five change these results [26]. A feature extraction task, such as that used above [1], is very different from a memory task. Divergent research results may due to differences in the inherent tasks.

The present study compared a signal detection task and a digit memory task. Our signal detection task involved signal discrimination of line length rather than feature extraction reported by Asman et al. [1] Our memory task involved a digit string rather than remembering alphabet letters as reported by Mulder and Mulder [20], and Pruyn et al. [26]. We only found HRV changes between LD and HD condition in signal detection task rather than digit memory task. Although our digit memory task was different than previous studies [20, 26], we similarly found no task difficulty effect. The signal detection and digit memory tasks are different in nature, these divergent findings thus are possibly due to the different tasks used.

Group by Task Interaction

Group by Task interaction showed that the TDC group, had larger changes in HRV from LD to HD condition than the DCD group when performed signal detection task. Specifically, the TDC group, reduced HF power and increased LF/HF ratio, by a greater margin than the DCD group. Since HF power represents parasympathetic activity and LF/HF ratio corresponds to sympathetic-parasympathetic balance, these interactions can be interpreted as TDC group suppressing parasympathetic activity and their sympathetic dominates parasympathetic control by a greater level than children with DCD.

This interaction was also true for SampEn. A noticeable drop in SampEn was observed from LD to HD condition for TDC group while DCD group did not change. SampEn score is inversely related to regularity, that is, high SampEn score has less regularity and vice versa. In human studies, high-dose atropine infusion blocks parasympathetic activity, producing an increased HR regularity (decreased SampEn) [22]. Sympathetic stimulants (i.e., isoproterenol) decreased SampEn scores [40] while sympathetic blockade (i.e., propranolol) increased SampEn scores [14]. SampEn is sensitive to both sympathetic and parasympathetic activity. Therefore, we concluded that the TDC group had a greater net effect of sympathetic activity than DCD group when performing the signal detection task.

Importantly, these interactions were found only for the signal detection task, but not for the digit memory task. There are several possible explanations. First, increased anxiety and stress can be facilitated by attention-demanding tasks [18]. A number of studies regarding anxiety have found HRV measures, especially HF power, are reduced while experiencing anxiety. Both anxiety and worry demonstrated to be associated with decreased parasympathetic activity [31, 36]. Accordingly, children with DCD might be less anxious while executing signal detection task with HD condition.

Another possible explanation is that children with DCD may have problems perceiving visual stimuli, such that they experienced greater difficulty with signal detection task compared to digit memory task. Research from our laboratory [7] reported that the responses of the action system differ between DCD and TDC groups when engaged in signal detection task with a higher load. We extend these previous results to the responses of the cardiac autonomic system. We found that responses of the autonomic system were different between the two groups when performing a signal detection task. Our signal detection task required both perceptual contact with visual stimuli and continuous attraction. It is possible that children with DCD have greater difficulty performing task demands perceptual rather than cognitive effort.

In the present study, a limited range of measures were analyzed cardiac responses, while children engaged in attention-demanding tasks. Previous research [4] has reported that respiratory rate increased as attention investments increased, producing a concomitant decline in HF power. To account for the complexity of the cardiac responses, more measures such as respiration, blood pressure should be recorded. Although DCD is frequently associated with ADHD, the present study recruited DCD children free of a diagnosis of ADHD [21]. It is of concern to scrutinize the difference for autonomic responses between children with DCD and those comorbid with DCD and ADHD. Lastly, given that different trends in HRV were observed between signal detection task and digit memory task, it is perhaps necessary to utilize different kinds of attention-demanding tasks (i.e. reaction time, mental arithmetic, and Stroop task) to consolidate present findings in future studies.

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Table 1. Demographic data in the DCD and TDC group.

	DCD (n=30)	TDC (n=30)
Age	9.40(.49)	9.20(.41)
BH	139.07(6.43)	139.60(6.17)
BW	37.88(10.92)	37.73(9.21)
BMI	19.33(4.29)	19.22(3.95)
IQ	99.8(15.69)	101.46(15.33)
ADHD-DTRS	2.21 (1.15)	2.23 (1.19)
MABC	19.97(3.67)	5.33(1.37)

BH: body height; BW: body weight; BMI: Body mass index, IQ: intelligent quotient, ADHD-DTRS: Attention deficit and hyperactivity disorder: Diagnostic Teacher Rating Scale, MABC: total impairment score of MABC.

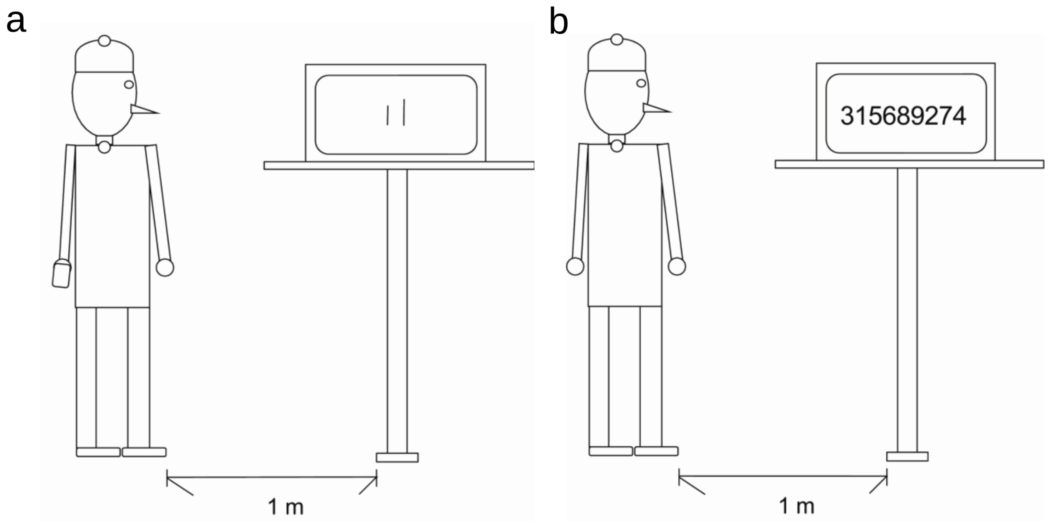

Figure 1. Experimental setup for (a) signal detection task, and (b) signal detection task.

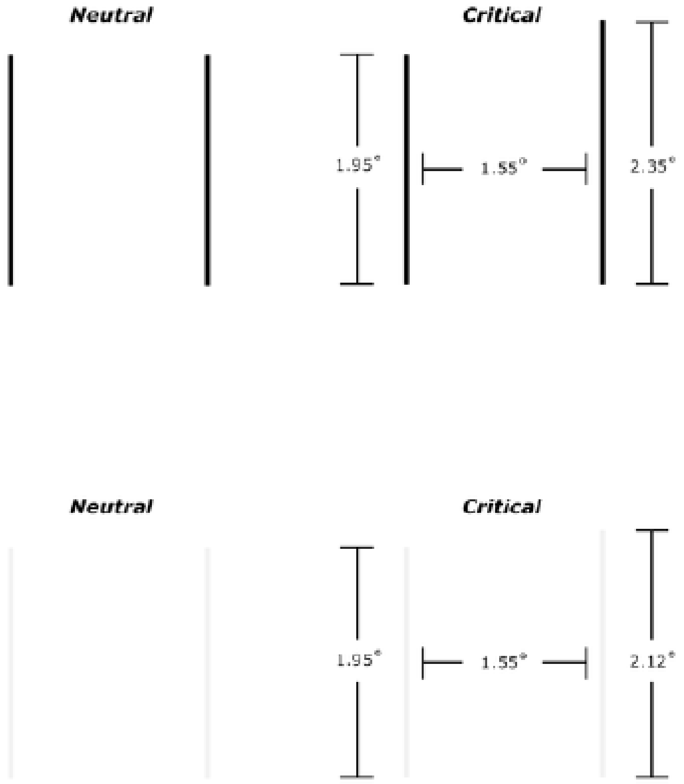

Figure 2. Signal detection task: : low difficulty (upper part) and high difficulty (lower part) conditions.

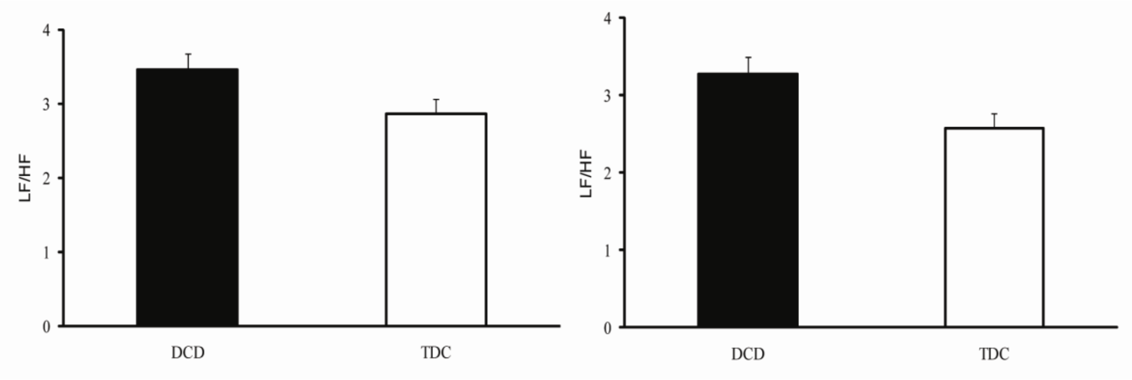

Figure 3. Mean LF/HF ratio for the DCD and TDC group during (a) the signal detection task execution, and (b) signal detection task, showing significant main effect of Group. The error bars are standard errors.

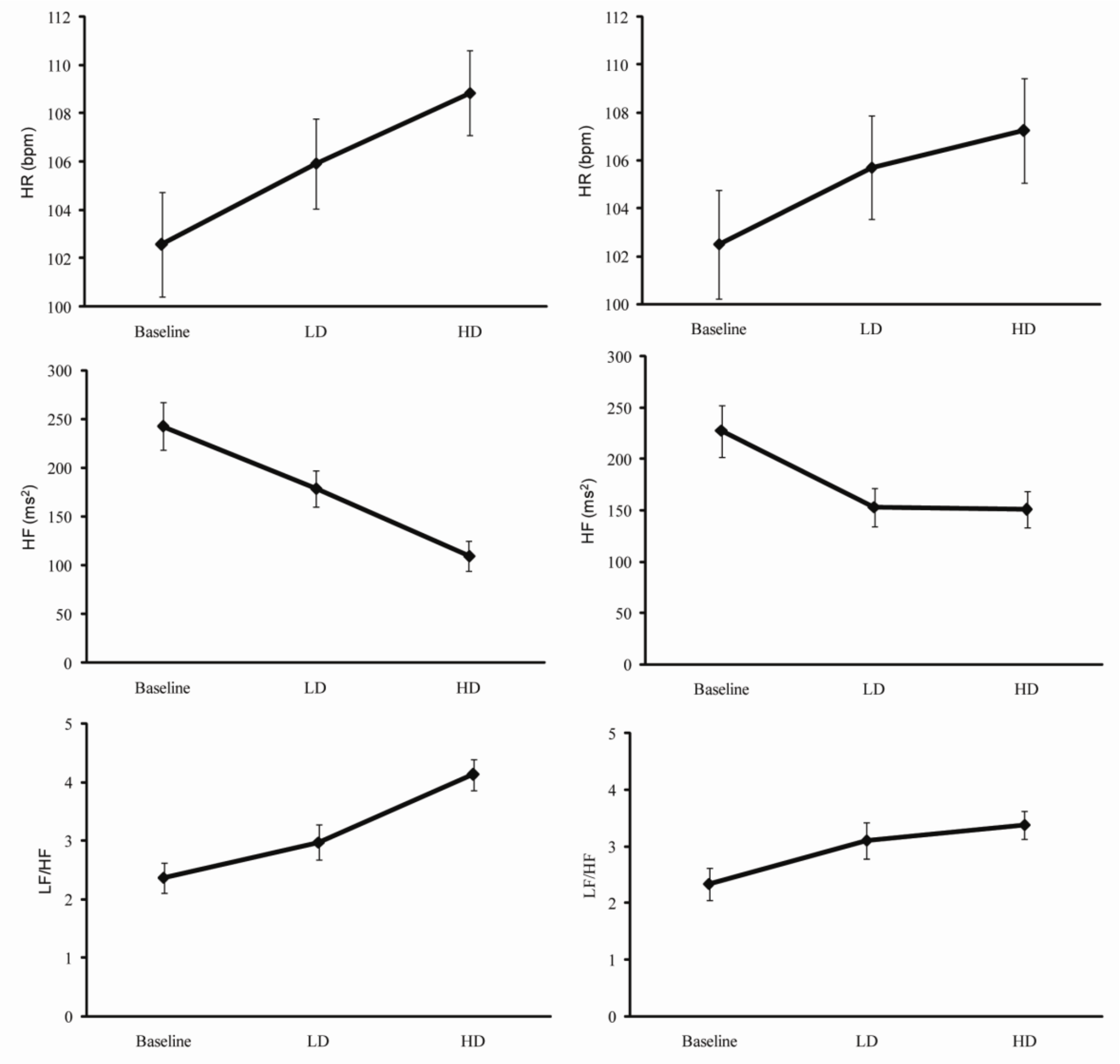

Figure 4. Mean for the HR, HF and LF/HF ratio across task difficulty conditions during (a) signal detection task, and (b) digit memory task, showing significant main effect of Task Difficulty. The error bars are standard errors.

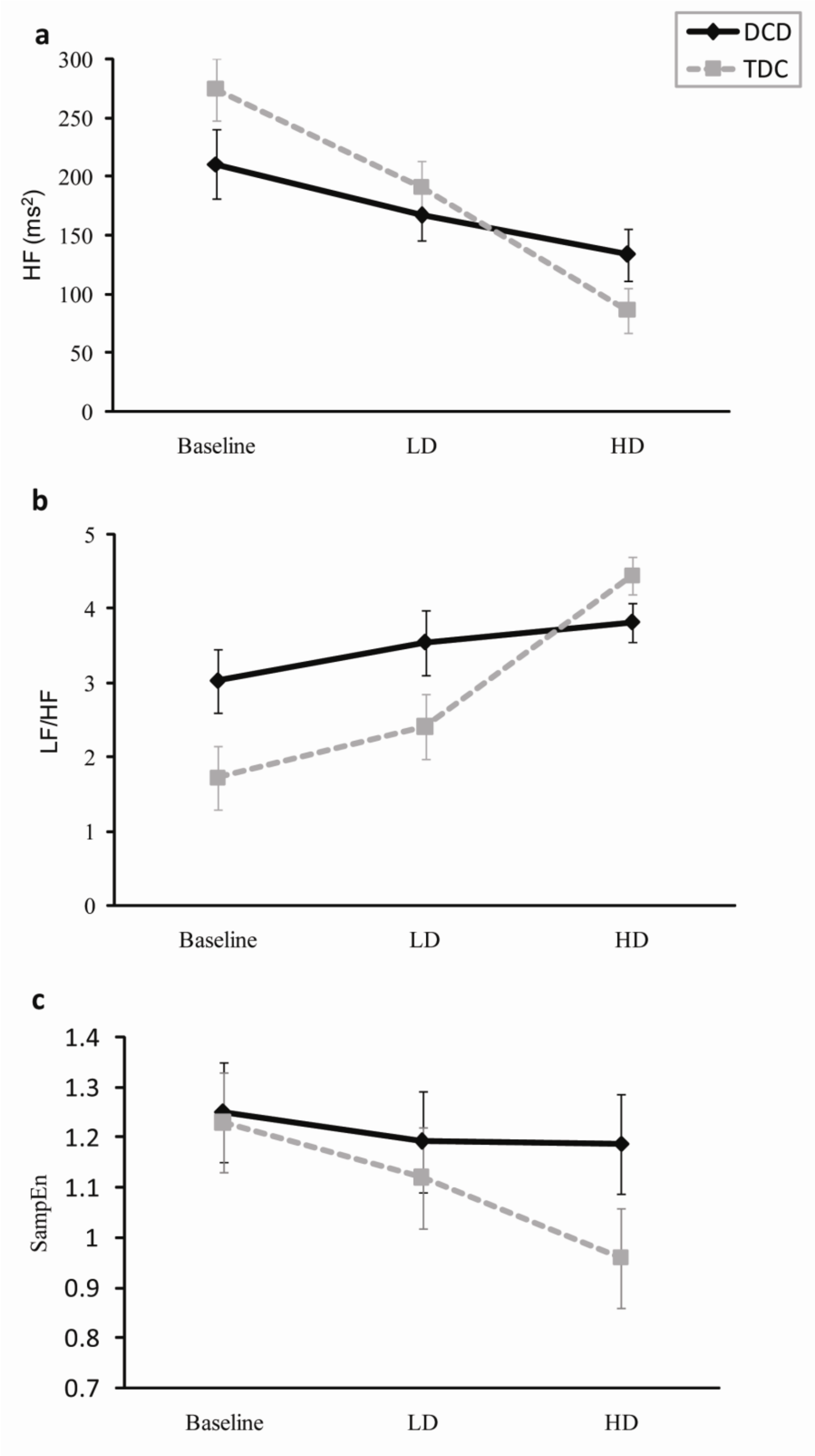

Figure 5. Mean (a) HF, (b)LF/HF ratio, and (c)SampEn for the DCD and TDC groups across task difficulty during the signal detection execution, showing significant Group x Task Difficulty interactions. The error bars are standard errors.

Summary

In each of the three experiments, we manipulated two levels of task difficulty, low (LD) and high (HD), for a perceptual (signal detection) task and a cognitive (digit memory) task. Postural and cardiac responses were recorded for both children with DCD and a TDC control group. The present research is a first to report both biomechanical and physiological while engaged in a suprapostural task with varying levels of difficulty. This chapter summarizes the results of the three experiments, discussed both the theoretical conclusion and practical implications, and directions for future studies.

Results of the Three Experiments

Experiment 1: Postural responses to a suprapostural visual task

Overall children with DCD exhibited a significantly higher postural motion than the TDC group. More importantly, the TDC group reduced postural motion from the LD to HD condition while children with DCD increased postural motion, reflecting difficulties modulating postural motion in children with DCD, when engaged in a task requiring a higher level of perceptual effort. It is notable that the DCD group significantly reduced the d' score from the LD to HD condition by a greater level than the TDC group, demonstrating that children with DCD had worse performance than the TDC group in a more perceptually demanding task.

Experiment 2: Postural response to a suprapostural cognitive task

Both groups of participants reduced postural motion as a function of task difficulty, and children with DCD exhibited a significantly higher postural motion than the TDC group. More importantly, the TDC group significantly reduced postural motion from the LD to HD condition while children with DCD did not change their level of postural motion, reflecting a difficulty with postural control when engaged in a task requiring a higher level of cognitive effort. For the performance of the digit memory task, participants had a significant lower percent correct in the HD compared to LD condition, indicating a less accurate memory performance in a more demanding task condition.

Experiment 3: Physiological responses to suprapostural tasks

For the signal detection task, main effect of group showed that children with DCD exhibited a significant lower LF/HF ratio than the TDC group, indicating a significant greater predominance of sympathetic activity over parasympathetic control for the TDC group. Main effect of task difficulty showed that summed across groups, HF was greater at baseline than the LD condition as well as greater at the LD than HD condition, while the opposite trend was found for HR and LF/HF ratio, demonstrating a parasympathetic withdrawal with the autonomic balance tilting toward sympathetic activity as a function of perceptual demand. Last but not least, a significant Group by Task Difficulty interaction showed that the TDC group tended to increase LF/HF ratio, and decrease both HF and SampEn from the LD to HD condition by a greater level than the DCD group, indicating that the TDC group changed their autonomic control between the LD and HD condition while children with DCD did not. For the digit memory task, a main effect of group was replicated; the differences between the two groups were found in the LF/HF ratio. A main effect of task difficulty showed that summed across groups, HF was greater at baseline (quiet stance) than the LD condition while the opposite trend of responses was found for HR and LF/HF ratio, indicating changes in autonomic system as a function of task difficulty.

Overall Summary

Biomechanical responses were different between the TDC and DCD groups, when engaged in both the signal detection and digit memory task. The trend of postural responses were different between these two tasks. For the signal detection task, the TDC group *reduced* their postural motion in the more difficult condition, whereas the DCD group *increased* their postural motion. For the digit memory task, the TDC group *reduced* their postural motion in more difficult task condition, whereas the DCD group was *unchanged*. Moreover, the trends of task performance were also different between the two tasks. For the signal detection task, children with DCD were less adept than the TDC group at a task with a higher perceptual demand. However, for the digit memory task, there was no group difference.

Physiological responses were different between the TDC and DCD group when engaged in both the signal detection task and digit memory task. Moreover, the trend of physiological responses were different between these two tasks. For the signal detection task, the TDC group’s cardiac autonomic responses change by a greater level than the DCD group when the task was more difficult. However, for the digit memory task, there was no such effect.

Theoretical Conclusion

Riccio and Stoffregen (1988) and Stoffregen et al. (2000, 2006, 2007) proposed a functional integration between postural activity and a suprapostural task: control of postural motion is not an aim in itself, but is valuable to the extent that it promotes success of other behavioral goals. Postural control is tuned to positively mediate performance of suprapostural tasks. Our experiments suggest that children with DCD seem less able to modulate their postural motion than their typically developing peers, when engaged in perceptual and cognitive tasks. It demonstrates that both the perception-action link, and what we propose as a cognition-action link are both degraded in children at risk for DCD. Studies that report the linkage between biomechanical responses (posture) and behavioral activity (perceptual or cognitive task) provide support for an embodied interpretation of human performance, rather than the more traditional ‘executive function’ interpretation (Wilson & McKenzie, 1998). Children diagnosed, or at risk for DCD are typically seen as ‘clumsy’. This motor difficulty is not associated with a concomitant intellectual deficit, thus an ‘online executive control’ interpretation seems less feasible. The reliance on neurological descriptors, such as ‘executive’ or ‘online control’ add little to our insights about the motor behavior observed in children with DCD. Rather, the possible degrading of the perception-action or cognition-action link supports a more ecological interpretation of DCD. Sensitivity to the demands of both the environment and task would seem to be a functional explanation of the motor difficulties exhibited by these children. In conclusion, our experiments bolster the proposition that DCD is a perceptual motor deficit characterized by a diminished perception-action or cognition-action coupling when a motor response is linked to tasks that demand increased perceptual or cognitive effort.

Implications for Practice

The results of the present experiments support the notion that children with DCD have difficulties modulating their postural motion, demonstrating a weaker perception-action or cognition-action link. A implications of present experiments is to design or choose appropriate activities which can strengthen perception-action or cognitive-action link. For example, mathematic practice may not be a good choice for children with DCD, but sport items such as softball and table tennis may be better strengthen their weakened perception-action link.

Future Studies

Future studies varying levels of task difficulty can explore whether there is a critical level of perceptual/cognitive demand which will differentiate between children with DCD and their TDC peers. Besides, to date there is no movement evaluation tool to specifically assess the characteristics of perception-action or cognition-action link for children. Another implication is to develop a novel motor evaluation tool to assess these links. In essence, a signal detection task requires vision compared to other perceptual modalities such as auditory or tactile activities, perceived heaviness and length while wielding an object) for children with DCD. We believe these lines of the inquiry that seek to evaluate the dynamic relationship between both perception and action and cognition and action will improve both our understanding of the performance of children at risk for DCD, and will also offer new insights for rehabilitation therapies.

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APPENDIX A

SUMMARY OF SCREENING FOR MOVEMENT DIFFICULTIES

Table 1 summarizes the results of the referral procedure used to screen children for movement difficulties. This screening was used to identify children who would be assessed using the MABC test.

Table 1. Summary of the screening for movement difficulties

	Students who returned consent form	Student referred by classroom teacher	Non-referred students given MABC	Non-referred students below 5th percentile on MABC	Referred students given MABC	Referred students below 5th percentile on MABC
Grade						
4	142	3	142	18	3	3
5	102	3	102	14	3	3
Total	244	6	244	32	6	6

APPENDIX B
INSTRUCTIONS FOR SUPRAPOSTURAL TASKS

Note: The following instructions were not used as script, but rather they served as guidelines for explaining the task procedures. These instructions were tailored to each child to ensure that they fully understand the tasks requirements.

Instructions for signal detection task

Before starting the task, please stand relax behind this line with your feet apart about shoulder width and hold a computer mouse in your dominant hand.

[An experimenter demonstrates the way to stand and hold a computer mouse.]

You are going to look at a laptop screen that has pairs of two lines show up and disappear consecutively. When you see the pairs of two lines are different in length, please use your index finger to hit left button of the computer mouse. You do not have to do any responses when you see the pairs of two lines are the same in length.

[An Experimenter demonstrates acts to response visual stimulation]

Do you have any question about this task? If not, then now, you can practice for 30 seconds.

[A participant practice for 30 seconds. Meanwhile, an experimenter stand behind the child observing if he/she can fully understand and perform this task.]

Do you understand how to perform this task now? Do you need more practice? If not, then we will do this for tree times. And the task will last 2 minutes for each time.

Instructions for digit memroy task

Before starting the task, please stand relax behind this line with your feet apart about shoulder width.

[An experimenter demonstrates standing posture.]

You are going to look at a laptop screen that will show a digit string for 10 seconds and then disappear. Please remember and rehearsal this digit string in mind before it comes off. And then please look at a white screen and rehearsal the digit string in mind, rather than speak it out. When the white screen turn black, I will ask what is the digit number you just saw and see if you can remember this digit string correctly. Do you have any question about this task? If not, then now, you can practice for once.

[A participant practice for 40 seconds (10 seconds to remember and rehearsal a digit string; 30 seconds to rehearsal it). Meanwhile, an experimenter stood behind the participant observing whether the child can perform this task. After practice, an experimenter will ask what the digit string is to ensure participant can fully understand this task. (In practice, the string is comprised by only three digits)]

Do you understand how to perform this task now? Do you need more practice? If not, then we will do this for tree times. And the task will last 2 minutes for each time.