Research in Developmental Disabilities 48 (2016) 124–131

Contents lists available at ScienceDirect

Research in Developmental Disabilities

Children with developmental coordination disorder demonstrate a spatial mismatch when estimating coincident-timing ability with tools

Priscila Caçola [a,*], Melvin Ibana [a], Mark Ricard [a], Carl Gabbard [b]

[a] Department of Kinesiology, University of Texas at Arlington, United States
[b] Department of Health and Kinesiology, Texas A&M University, United States

ARTICLE INFO

Article history:
Received 23 March 2015
Received in revised form 20 October 2015
Accepted 23 October 2015
Available online 8 November 2015

Keywords:
Developmental Coordination Disorder
Tool
Coincident timing
Interception
Motor imagery

ABSTRACT

Coincident timing or interception ability can be defined as the capacity to precisely time sensory input and motor output. This study compared accuracy of typically developing (TD) children and those with Developmental Coordination Disorder (DCD) on a task involving estimation of coincident timing with their arm and various tool lengths. Forty-eight (48) participants performed two experiments where they imagined intercepting a target moving toward (Experiment 1) and target moving away (Experiment 2) from them in 5 conditions with their arm and tool lengths: arm, 10, 20, 30, and 40 cm. In Experiment 1, the DCD group overestimated interception points approximately twice as much as the TD group, and both groups overestimated consistently regardless of the tool used. Results for Experiment 2 revealed that those with DCD underestimated about three times as much as the TD group, with the exception of when no tool was used. Overall, these results indicate that children with DCD are less accurate with estimation of coincident-timing; which might in part explain their difficulties with common motor activities such as catching a ball or striking a baseball pitch.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Developmental Coordination Disorder (DCD) is a condition that defines children with motor coordination problems despite having average to high intelligence levels. This disorder impacts about 2–7% of school-age children (American Psychiatric Association, 2013). The evidence is clear that children with DCD have less accurate and slower movements than typically developing (TD) children (Elders et al., 2010; Johnston, Burns, Brauer, & Richardson, 2002; Smits-Engelsman, Bloem-van der Wel, & Duysens, 2006). Recent literature has suggested that these difficulties are the result of an underlying deficit in generating and/or monitoring internal models of action, termed the internal modeling deficit (IMD) hypothesis (e.g., Adams, Lust, Wilson, & Steenbergen, 2014; Deconinck, Spitaels, Fias, & Lenoir, 2009; Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Williams, Thomas, Maruff, & Wilson, 2008; Williams, Omizzolo, Galea, & Vance, 2013; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank 2013). Internal models provide accurate visuospatial mental representation of intended actions and make predictions (estimates) about the mapping of the self to parameters of the external world. These processes enable successful planning and subsequent execution of movement.

* Corresponding author at: Department of Kinesiology, University of Texas at Arlington, Arlington, TX 76019, United States.
E-mail address: cacola@uta.edu (P. Caçola).

http://dx.doi.org/10.1016/j.ridd.2015.10.021
0891-4222/© 2015 Elsevier Ltd. All rights reserved.

Estimation of reach ability involves making judgments about distance in relation to oneself, therefore being a useful approach to testing the IMD hypothesis. Recently, it has been suggested that children with DCD have difficulty estimating reach distance (Gabbard, Caçola, & Bobbio, 2012). These findings were argued to be the result of an inability to formulate an appropriate mental representation of the required reaching action. One important aspect of creating this mental representation is the accurate perception of how much one can extend themselves from the center of the body toward an object of interest. Furthermore, evidence indicates that the estimation problem is also seen when using tools (Caçola, Gabbard, Ibana, & Romero, 2014). A tool is an implement (such as a racquet) that modifies the representation of the body, at least temporarily, and is considered a functional element for perceiving one's own body in space (e.g., Baccarini et al., 2014; Caçola & Gabbard, 2012). On a comparison of TD children and those with DCD on an estimation of reach task with and without tools of different lengths, Caçola et al. (2014) found that those with DCD perform similarly to TD children with and without a small tool, but were significantly less accurate with a longer tool. Arguably, the length of the tool may influence the richness of the sensory experience used to make accurate judgments about reach. Thus, this study suggests that tool length influences the nature of internal modeling in children with DCD.

The paradigm used in Caçola et al. (2014)'s study was "static" in nature, that is, estimating reach to a target that is in a fixed position. Arguably, it does not represent all real-world contexts, because in many aspects of our daily lives the objects that we attempt to interact with are not stationary. This supported the need for the creation of a dynamic (moving) task that explored the IMD hypothesis for reach estimation. Tracking or tracing a certain stimulus smoothly requires a high degree of predictive control (Langaas, Mon-Williams, Wann, Pascal, & Thompson, 1998). Since children with DCD respond slower and make fewer and less effective anticipatory responses with a predictive stimulus (Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013), it is likely that the motion of a target influences accuracy of reach estimation. In a dynamic context, reach estimation becomes an issue of "interception" – intercepting or stopping a moving object accurately. To date, no studies have explored accuracy of the interception point from a dynamic estimation perspective in this population.

Therefore, the purpose of the present study was to explore the IMD hypothesis in a task that simulated estimating interception points of objects with and without tools of varying lengths. To that end, we adapted a coincident timing task where typically developing children and those with DCD had to estimate (via use of motor imagery) interception points. Coincident timing or interception ability can be defined as the capacity to precisely time sensory input and motor output, regardless of the direction of the object motion. In order to explore whether the accuracy of the estimated interception ability depends on the direction of a moving object, we used two tasks: (1) target moving toward and (2) target moving away. One might expect that estimation of objects moving toward will be more accurate since most real-world situations involve motion toward the individual (e.g., catching a ball). Based on previous reports of static reach estimation, it was also expected that children with DCD would be less accurate than the TD group, however; we also predicted that the accuracy distinction would only be significant when using longer tools. In addition to gaining a better understanding of how children with DCD plan motor actions, the results will be important to clarify the IMD hypothesis further, thus shedding light on the issues underlying DCD.

2. Method

2.1. Participants

A total of 48 children ranging from 7- to 13 years of age completed this study: 25 children categorized with DCD (17 boys, 8 girls; mean age: 8.84 ± 1.57 years) and 23 TD children (10 boys, 13 girls; mean age: 9.6 ± 1.94 years). For the DCD group, licensed occupational therapists were asked to refer children diagnosed with DCD or Dyspraxia. That is, those without diagnosed cognitive impairments and/or co-morbidities. Qualification for DCD was based on the fit to the diagnostic criteria defined by the DSM-5 (APA, 2013): (A) a score below the 9th percentile on the Movement Assessment Battery for Children, 2nd edition, MABC-2 (Henderson, Sugden, & Barnett, 2007); (B) motor coordination difficulties that had an impact on their daily function as assessed by a parental report (Developmental Coordination Disorder Questionnaire, DCD-Q, Wilson et al., 2009); (C) elimination of another general medical condition such as cerebral palsy, hemiplegia or muscular dystrophy (report from pediatrician/parent). All children were identified as right-handed based on verbal preference for writing and drawing.

The TD (control group) children were recruited from flyers in and around the university and nearby schools. They were identified as having age-appropriate motor skills, scoring at or above the 20th percentile on the MABC-2 and scoring as "probably not DCD" on the DCD-Q questionnaire.

The experimental protocol and consent form were approved by the Institutional Review Board (IRB) for the ethical treatment of human subjects. Children and parents were informed of the experimental procedures before participating in this study, parents signed the consent form and all children provided verbal consent.

2.2. Measures and procedures

Participants completed two experiments: (1) target moving toward and (2) target moving away, in reference to target direction. Fig. 1 provides a visual description of the general paradigm for both experiments. Participants were asked to accurately determine the interception point (where their arm or tool meets the moving target), without actually moving. That process (estimation) was performed via use of motor imagery. The correct interception point was based on the

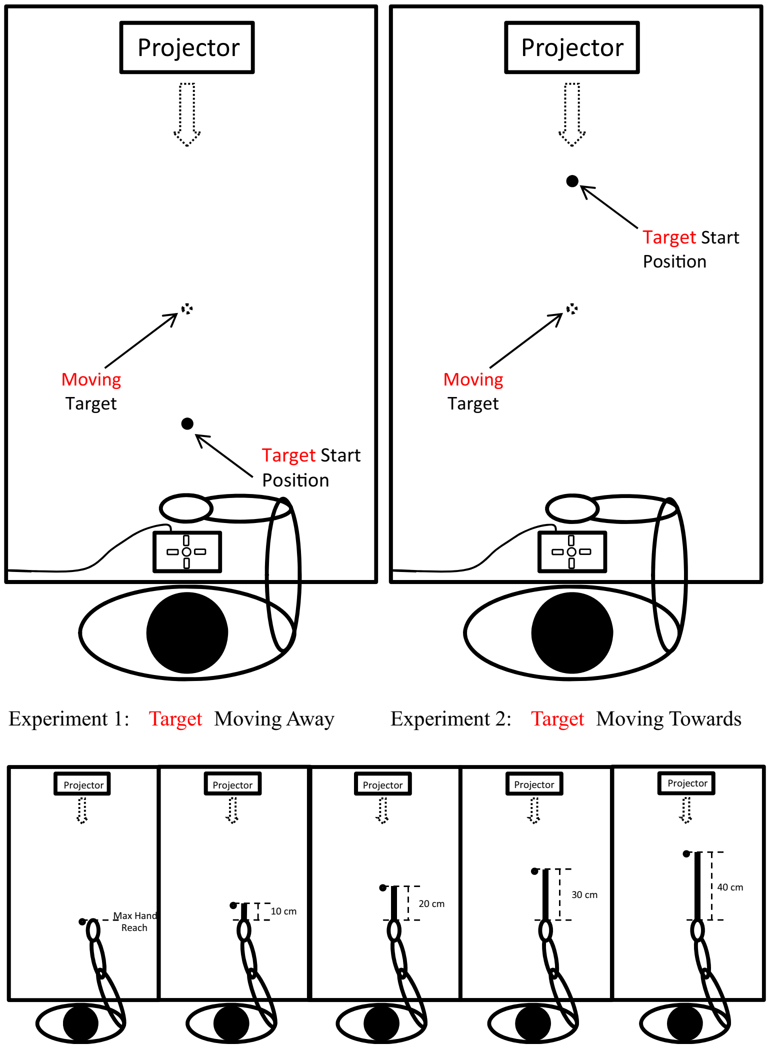

Fig. 1. General experimental set-up and representation of the arm and tool conditions (keypad was located underneath the tabletop).

participants' actual maximum reach; therefore, each participant had their own scaled interception point. Each participant's maximum reach was the same for both experiments. Five conditions were performed with each experiment (arm [no tool] and tools of 10, 20, 30, and 40 cm). The choice of tool lengths was based on previous distinctions found by tool length in the Caçola et al. (2014) study and anatomical (body size characteristics) and functional implications for use by children (Caçola & Gabbard, 2012). Each condition involved 3 trials, for a total of 15 trials per participant.

Prior to the experiments, participants were systematically positioned in the chair and introduced to the task for determining 'actual' maximum reach – full extension of the right limb and middle finger to pull back a penny using a $1-df$ reach (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989). A $1-df$ reach involved a comfortable effort of the forearm, and upper arm acting as a single functional skeletal unit. In essence, actual reach was 'scaled' to individual arm lengths, therefore allowing acceptable comparison. The maximum reach for each one of the tool conditions was also determined (by adding the length to their arm maximum reach), and participants were allowed to explore their reach with the arm and tools in the practice phase.

For all conditions, participants wore a modified commercial racquet glove that was sized to fit their right arm. The glove had a finger-nail size piece of white luminescent tape that was attached to the tip of the middle finger. In addition, a retractable antenna-type pointer was attached to the palm of the glove with the tip of the pointer even with the tip of the middle finger of the glove. The tip of the pointer also had a piece of tape attached since both conditions were conducted in very dim lighting. For the TOOL conditions, the pointer was extended to each of the four lengths (10–40 cm) out from the tip of the middle finger site, whereas for the ARM, the pointer was retracted (or placed) at actual middle finger tip. Each participant's maximum reach was individually scaled with the arm and tool, and the maximum reach determined each participant's interception point. These measurements provided the base-line comparison for the estimates of reach.

Before starting the study, participants were able to perform exploratory actions (no more than two) to determine where they could reach with their arm and with the tool. At that point, they were taught how to use motor imagery to estimate their reach interception with and without tools. They were told to close their eyes and visualize (kinesthetically 'feel') themselves reaching without moving their arm. After that, they were taught to do the same with their eyes open, and look at the tip of their fingers or the tool and 'feel' themselves extending the arm and seeing (in their mind) where they could intercept the target. Even though actual imagery ability was not assessed, all children understood the instructions and were allowed two practice trials with each condition. As noted earlier, the "static" version of this experimental paradigm has been reported using TD children and those with DCD (Caçola et al., 2012, 2014).

During the experimental trials, participants were asked and regularly reinforced to kinesthetically 'feel' themselves executing the movement ("feel your arm extending...") with their right hand; therefore being more sensitive to the biomechanical constraints of the task (Sirigu & Duhamel, 2001; Stevens, 2005). With both experiments, participants imagined the motion of their arm/tool extending forward simultaneously as the target moved (toward or away from the body), and were told to "stop" the target as it arrived at the correct point where it met their arm/tool in a straight position. The right hand was placed within a drawn box on the table close to the torso at midline and the non-dominant limb was placed by the keypad, located underneath the tabletop. Participants never moved their arm during trials, except for pushing the key on the keypad. In the tool conditions, participants were instructed to focus on the illuminated tip of the pointer that was extended to each one of the lengths, in order to make the interception judgments.

Data collection began with a 5 s verbal "Ready!" signal – that was followed by a central fixation point lasting 3 s. For the "target moving towards" experiment, the target appeared immediately thereafter, at about 80 cm from the participant, and moved toward (closer) to the participant in 2 cm increments every 500 ms. For the "target moving away" experiment, the target appeared immediately thereafter at a location 4 cm away from the participant, and moved away from the participant in 2 cm increments, every 500 ms. Participants were instructed to push the center button of the keypad with their left hand when they believed that the target had arrived at their interception point. No feedback was given on the performance of the subjects, however, simple motivational types of feedback were offered constantly.

The stimuli and responses were collected through using an overhead projection system linked to a PC programmed with Visual Studio and linked to a Cedrus RB-530 response pad, which collected participants' responses. Visual images are systematically projected onto a table surface at midline (90°). The table was constructed on a sliding bracket frame, allowing it to be moved back and forward for adjustment to the participant. All participants sat in an adjustable chair fixed to the floor and aligned with the center of the table and projected image. During all procedures, the room was darkened with the exception of light from the computer monitor. The target image was a penny-size circle of a 2 cm radius. Individual testing required approximately 30 min and was completed within a single session; all testing was conducted in an isolated room. The authors would like to acknowledge that this dataset and procedures are a subset of a larger protocol involving two more orientations (left and right).

2.3. Data analysis

A "match" variable was calculated to represent the distance (cm) between the true (accurate) interception point and the estimated distance determined by the child in each trial; the value was calculated as the average out of the 3 trials for each condition. A match value of "0" was the correct estimation, while a negative value reflected an underestimation and a positive value an overestimation.

These data were analyzed with the same procedure for each experiment – using a 2 (Group – TD/DCD) × 5 (Condition – Arm/10 cm/20 cm/30 cm/40 cm) repeated measures analysis of variance (ANOVA) procedure. As appropriate, post hoc analyses using Tukey's tests and simple main effect analyses were performed. The significance level (alpha) was set at 0.05.

3. Results

3.1. Experiment 1 (target moving toward)

Fig. 2 depicts the match comparisons between the groups. Across the five conditions, the DCD group overestimated approximately twice as much as the TD group (DCD: 10.83 ± 12.90; TD: 5.04 ± 7.79). ANOVA results indicated no effect for Condition, $F(4, 184) = 1.12$, $p = .34$, $\eta^2 = .02$ or Condition × Group interaction, $F(4, 184) = .74$, $p = .56$, $\eta^2 = .01$. However, there was a significant main effect for Group, $F(1, 46) = 4.64$, $p = .03$, $\eta^2 = .09$. Values for Conditions by Group were: Arm – TD: 7.47 ± 8.87, DCD: 11.62 ± 14.84; Tool 10 cm – TD: 5.44 ± 8.55, DCD: 10.69 ± 12.76; Tool 20 – TD: 3.18 ± 7.34, DCD: 11.36 ± 12.41; Tool 30 – TD: 3.88 ± 7.21, DCD: 10.40 ± 12.36; Tool 40 – TD: 5.24 ± 6.76, DCD: 10.10 ± 12.99.

3.2. Experiment 2 (target moving away)

Fig. 3 depicts the match comparisons between the groups. Across conditions, the DCD group underestimated about three times as much as the TD group (DCD: −5.72 ± 8.38; TD: −1.51 ± 5.90). With this experiment, there was a significant effect for Condition, $F(4, 184) = 19.82$, $p < .01$, $\eta^2 = .30$ and a Condition × Group interaction, $F(4, 184) = 2.81$, $p = .02$, $\eta^2 = .05$. Post hoc analyses for conditions showed that each was significantly different from another, with the exception of the pairs Tool 20–Tool

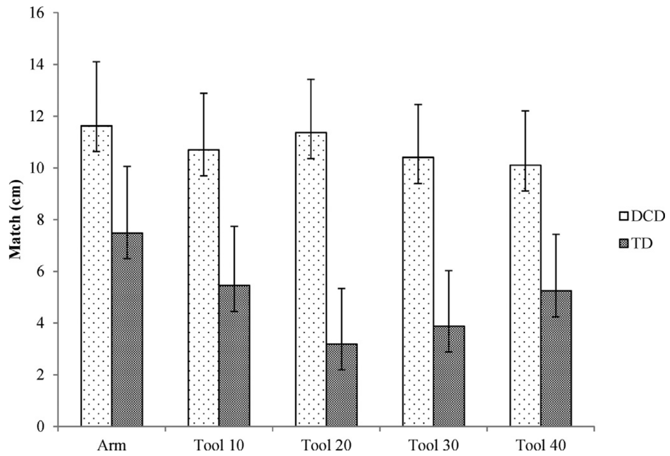

Fig. 2. Match across conditions for Experiment 1 (target moving toward). There is a significant difference between the groups, with the DCD group overestimating twice as much as the TD group.

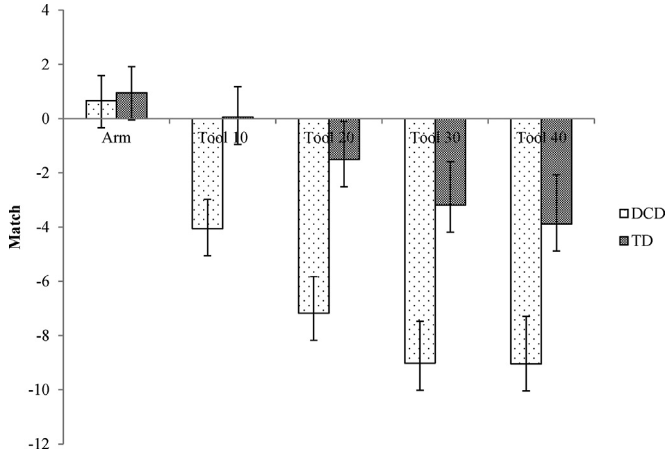

Fig. 3. Match across conditions for Experiment 2 (target moving away). There is a significant difference for all variables and interaction, with the simple main effect analysis indicating that the groups were significantly different in all conditions except for the Arm. Across conditions, the DCD group underestimated about three times as much as the TD group.

40 and Tool 30–Tool 40, with $ps > 05$. Simple main effect analysis on the interaction indicated that the groups were significantly different in all conditions except for the Arm. In the Arm condition, the TD group was slightly less accurate than the DCD group; however, the difference was not significant. In addition, there was a significant main effect for Group, $F(1, 46) = 7.51$, $p < .01$, $\eta^2 = .14$. Values for Conditions by Group were: Arm – TD: $.95 \pm 3.57$, DCD: $.66 \pm 5.36$; Tool 10 cm – TD: $.05 \pm 5.25$, DCD: -4.05 ± 5.48; Tool 20 – TD: -1.50 ± 5.03, DCD: -7.17 ± 8.00; Tool 30 – TD: -3.18 ± 7.08, DCD: -9.01 ± 8.22; Tool 40 – TD: -3.88 ± 6.85, DCD: -9.04 ± 10.11.

4. Discussion

The present study compared accuracy of estimated interception ability in TD children and those with DCD with their arm and tools of varying lengths (10–40 cm), using a coincident-timing paradigm. Estimations were determined in two experiments: target moving toward the participant (Experiment 1) and target moving away (Experiment 2). The overall results indicate that children with DCD have problems representing a motor action that requires the use of coincident-timing; an ability that may apply to common motor activities such as catching or striking a ball. This study provides evidence that for children with DCD, the difficulties in action representation (i.e. internal modeling deficit) also translate to tasks involving coincident timing estimations and tool use.

These results highlight a distinct error trend within each experiment. While the (correct) interception point for both experiments was the same, participants imagined their arm moving in Experiment 1 (target moving toward) while the target was in far space and moved toward them. This direction reflected a type of estimation that must be done in a realistic situation, such as when individuals are planning on the skill of catching or striking a ball. Findings demonstrated that the only difference found was between the groups – while error was independent of condition (arm or tools), the DCD group consistently made more mistakes in regards to the interception point when compared to the TD group. However, in Experiment 2 (target moving away), the process of deciding where the interception point would be occurred while the target was in near space and moving away from the individual, such as when an individual tosses a tennis ball away from himself and intercepts the ball with the racquet. In this case, the results indicate that error was dependent upon condition (significantly increasing as tool length increased), and that groups were distinct in all but the arm condition.

With that said, more interesting from our perspective was group comparisons – we found that children with DCD overestimated about twice as much as the TD group, supporting the notion that children with DCD are less adept at determining terminal accuracy than their peers (e.g., Elders et al., 2010; Smits-Engelsman, Niemeijer, & van Galen, 2001; Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003). This difficulty may have resulted in the children estimating their interception ability earlier than the TD group, and pushing the keypad faster. It is possible that children with DCD adopt a conscious strategy in order to compensate for some fundamental spatial and/or temporal inadequacies (Estil, Ingvaldsen, & Whiting, 2002). In other words, while both groups of children overestimated their interception point, children with DCD overestimated more because they need this "extra" time to plan and respond to visual information. Along with this explanation, previous research has indicated that children with DCD find it hard to modify a planned movement compared to TD children (Mandich, Buckolz, & Polatajko, 2003). Mon-Williams et al. (2005) suggest that children with DCD find the cost of executing an incomplete movement and updating online too high in comparison to the benefits of planning and executing a movement early.

However, it is important to note that errors with Experiment 1 for both groups remained consistent as tool length increased. These results reinforce the notion that a tool modifies, at least temporally, the body schema, which is considered a functional element for perceiving one's own body in environmental space. Our data indicates that across tool length conditions, children were able to incorporate the tool into their peripersonal (near) space and adjusted their interception point accordingly, even in a dynamic setting. This finding may reflect the experience that both groups had with tool use. Furthermore, Experiment 1 reflected a very common direction of interception adopted in real life activities, such as catching and striking a ball. The lack of differences in conditions (arm and tool lengths) supports the notion that, although it is known that children with DCD are less physically active and participate less in sports (Magalhães, Cardoso, & Missiuna, 2011), we can speculate that they had less experience using tools in a coincident-timing context.

On the other hand, Experiment 2 was characterized by a difference in direction of error between the arm and tool conditions (not significant). While participants slighted overestimated their interception point with their arm, they underestimated their ability in all tool conditions, with significant differences between condition error except between the pairs of Tool 20 and 30 with Tool 40. The fact that participants (mostly) underestimated their ability is quite likely associated with the direction of the target – it seems reasonable to believe that the targets moving away from the participant would trigger underestimation in all participants, with a larger error in children with DCD. The direction of the target, however, deeply influenced the amount of error across conditions, with error increasing for both groups as tool length increased (up to 30 cm). This finding, speculatively, refers to the visual ability of participants – while the error increased progressively in both groups, it was difficult for participants to make decisions when the direction shifted from peripersonal (near) to extrapersonal (far) space from the arm to the 20 cm tool, perhaps due to a shifting of visual attention and feedback as the target moved away from the participant (Rodríguez-Herreros, De Grave, Lópes-Moliner, Brenner, & Smeets, 2013).

The constant error in Experiment 1 was opposite to the consistent increase in error amount as tool length increased in Experiment 2, a possible reflection of lack of experience in intercepting objects that move away from oneself, in both groups. It is important to emphasize that Experiment 1 provides a more functional, realistic view of coincident timing abilities (e.g., intercepting a ball moving toward the body). As noted in the introduction, a few studies have investigated this specific issue in the context of catching (Deconinck et al., 2006; Van Waelvelde, De Weerdt, De Cock, & Smits-Engelsman, 2004). It has been suggested that poor catching performance in children with DCD is due to deficits in timing expressed by slower reaction times (Henderson, Rose, & Henderson, 1992), a distinct lack of knowledge of ball flight cues (Lefebvre & Reid, 1998) poor grasping skills, and less efficient use of different movement strategies than younger TD children (Van Waelvelde et al., 2004). While problems in temporal aspects of movement control have been examined in a vast number of studies of DCD as a manifestation of the planning process (Debrabant et al., 2013; Wilmut & Wann, 2008), it is important to note that differences between TD and children with DCD are not in the temporal control and structure, but rather in distinct changes in peak closing velocity for catching (Deconinck et al., 2006). Therefore, as mentioned by Estil et al. (2002), temporal deficits cannot be ruled out as an alternative explanation to spatial deficits. In the present study, we believe that the deficits found in children with DCD are due, most likely, to a combination of several deficits that involve spatial, temporal, and kinematic issues.

The use of motor imagery with an estimation of reach task involving the arm and a tool extension provides a unique problem to be solved by the actor – first, one needs not only to imagine oneself performing the movement, but must also account for metrics of space (distance) and the ability to calculate action possibilities within an imagined length. The difficulty that children with DCD have with their motor skills may be in part related to their inability to estimate space surrounding them. That is, they may have problems intercepting moving objects accurately due to lower ability to accurately estimate their reach with and without tools. The paradigm used in the present study combined aspects of motor imagery, use of predictive information and anticipatory actions, dynamic action representation, and coincident-timing; all of which allows for a unique view of the internal modeling deficit hypothesis. The results found here support the increasing body of evidence indicating that children with DCD have difficulty representing a predictive model of a prospective action (Adams et al., 2014) with unique spatial constraints provided by tool use. The spatial mismatch or skewed perception associated with estimation of coincident-timing ability is present in children with DCD and impairs accuracy of movements, regardless of tool extension length (Experiment 1) and direction of interception.

4.1. Limitations and implications

Whereas the present study addressed significant questions, we need to recognize the limitations of the study. While we attempted the match the groups as best as possible, the TD group was almost a full year older than the children with DCD. However, the difference was not statistically significant, and we believe that the differences reflected the groups and not the ages. The test paradigm was related to movement estimations – dynamic representations that attempt to provide a realistic approximation of the combination of internal representations and the imagery of arm and tool use. However, they were still representations of movements and not real actions, which deprived participants from feedback that could have improved performance. Another limitation and need for future study is the issue of hand preference – all participants in this study were right-handers. The literature shows that children with DCD typically display a higher frequency of left-handedness (>30%) compared with the general population (Goez & Zelnik, 2008). Still, our study is the first to connect action representations with tool use in a dynamic setting, providing evidence for a reduced ability in children with DCD to generate and/or engage in action representations involving coincident-timing ability and tool use. This finding is an important step toward understanding the mechanisms that subserve poor motor skill in children with DCD, particularly in the case of deficits of action representation in a dynamic context. Using a tool that requires the coupling of spatial and motor representations creates a functional outcome to explore motor skill deficits. With the difficulties found here being a defining characteristic of DCD, the presence of such markers could possibly be used to offer novel diagnostic avenues to be explored in the future. Exploring spatial mismatch in both static and dynamic environments seems to be a promising avenue for such an endeavor. A larger-scale study based on children spanning multiple critical developmental periods would need to be conducted to further explore this possibility.

5. Conclusion

The present study found evidence that children with DCD, compared to TD children, have less efficient mental representations of their interception abilities, with unique constraints provided by tool use. We further surmise that underscoring that deficit is the difficulty on mentally estimating dynamic action in a coincident-timing context. In summation, while TD children and those with DCD do not show optimal accuracy when mentally representing the interception of moving targets, children with DCD are significantly less accurate, which provides evidence of the IMD hypothesis in this context. That finding may explain important issues that children with DCD have with motor skills that involve accurate timing between one's self and (moving) environmental stimuli. The spatial mismatch or skewed perception associated with estimating coincident-timing ability with tools is present in children with DCD, potentially impairing (and explaining) their difficulties with motor skills.

References

Adams, I. L. J., Lust, J. M., Wilson, P. H., & Steenbergen, B. (2014). Compromised motor control in children with DCD: A deficit in the internal model? A systematic review. *Neuroscience and Biobehavioral Reviews, 47*, 225–244. http://dx.doi.org/10.1016/j.neubiorev.2014.08.011

American Psychiatric Association (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington: American Psychiatric Association.

Baccarini, M., Martel, M., Cardinali, L., Sillan, O., Farnè, A., & Roy, A. C. (2014). Tool use imagery triggers tool incorporation in the body schema. *Frontiers in Psychology, 5*, 492. http://dx.doi.org/10.3389/fpsyg.2014.00492

Caçola, P., & Gabbard, C. (2012). Modulating peripersonal and extrapersonal reach space: A developmental perspective. *Experimental Brain Research, 218*(2), 321–330. http://dx.doi.org/10.1007/s00221-012-3017-8

Caçola, P., Gabbard, C., Ibana, M., & Romero, M. (2014). Tool length influences reach distance estimation via motor imagery in children with Developmental Coordination Disorder. *Journal of Clinical and Experimental Neuropsychology, 36*(6), 596–606. http://dx.doi.org/10.1080/13803395.2014.918092

Carello, C., Grosofsky, A., Reichel, F., Solomon, H. Y., & Turvey, M. T. (1989). Visually perceiving what is reachable. *Ecological Psychology, 1*(1), 27–54.

Debrabant, J., Gheysen, F., Caeyenberghs, K., Van Waelvelde, H., & Vingerhoets, G. (2013). Neural underpinnings of impaired predictive motor timing in children with Developmental Coordination Disorder. *Research in Developmental Disabilities, 34*(5), 1478–1487. http://dx.doi.org/10.1016/j.ridd.2013.02.008

Deconinck, F. J. A., De Clerq, D., Savelsbergh, G. J. P., Van Coster, R., Oostra, A., Dewitte, G., et al. (2006). Adaptation to task constraints in catching by boys with DCD. *Adapted Physical Activity Quarterly, 23*, 14–30.

Deconinck, F. J. A., Spitaels, L., Fias, W., & Lenoir, M. (2009). Is Developmental Coordination Disorder a motor imagery deficit? *Journal of Clinical and Experimental Neuropsychology, 31*, 720–730. http://dx.doi.org/10.1080/13803390802484805

Elders, V., Sheehan, S., Wilson, A. D., Levesley, M., Bhakta, B., & Mon-Williams, M. (2010). Head-torso-hand coordination in children with and without Developmental Coordination Disorder. *Developmental Medicine & Child Neurology, 52*, 238–243.

Estil, L. B., Ingvaldsen, R. P., & Whiting, H. T. A. (2002). Spatial and temporal constraints on performance in children with movement co-ordination problems. *Experimental Brain Research, 147*, 153–161. http://dx.doi.org/10.1007/s00221-002-1193-7

Gabbard, C., Caçola, P., & Bobbio, T. (2012). The ability to mentally represent action is associated with low motor ability in children: A preliminary study. *Child: Care, Health and Development, 38*(3), 390–393. http://dx.doi.org/10.1111/j.1365-2214.2011.01257.x

Goez, H., & Zelnik, N. (2008). Handedness in patients with Developmental Coordination Disorder. *Journal of Child Neurology, 23*(2), 151–154.

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

Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2007). *Movement assessment battery for children* (2nd ed.). San Francisco, CA: Pearson.

Johnston, L. M., Burns, Y. R., Brauer, S. G., & Richardson, C. A. (2002). Differences in postural control and movement performance during goal directed reaching in children with Developmental Coordination Disorder. *Human Movement Science, 21*(5–6), 583–601. http://dx.doi.org/10.1016/S0167-9457(02)00153-7

Langaas, T., Mon-Williams, M., Wann, J. P., Pascal, E., & Thompson, C. (1998). Eye movements, prematurity and Developmental Co-Ordination Disorder. *Vision Research, 38*(12), 1817–1826. S0042698997003994.

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

Lewis, M., Vance, A., Maruff, P., Wilson, P., & Cairney, S. (2008). Differences in motor imagery between children with developmental coordination disorder with and without the combined type of ADHD. *Developmental Medicine & Child Neurology, 50*(8), 608–612. http://dx.doi.org/10.1111/j.1469-8749.2008.03030.x

Magalhães, L. C., Cardoso, A. A., & Missiuna, C. (2011). Activities and participation in children with Developmental Coordination Disorder: A systematic literature review. *Research in Developmental Disabilities, 32*, 1309–1316. http://dx.doi.org/10.1016/j.ridd.2011.01.029

Mandich, A., Buckolz, E., & Polatajko, H. (2003). Children with Developmental Coordination Disorder (DCD) and their ability to disengage ongoing attentional focus: More on inhibitory function. *Brain & Cognition, 51*(3), 346–356.

Mon-Williams, M. A., Tresilian, J. R., Bell, V. E., Coppard, V. L., Nixdorf, M., & Carson, R. G. (2005). The preparation of reach-to-grasp movements in adults, children, and children with movement problems. *Quarterly Journal of Experimental Psychology, 58*(7), 1249–1263.

Rodríguez-Herreros, B., De Grave, D. D. J., Lópes-Moliner, J., Brenner, E., & Smeets, J. B. J. (2013). Shifted visual feedback of the hand affects reachability judgments in interception. *Vision Research, 88*, 30–37. http://dx.doi.org/10.1016/j.visres.2013.06.005

Smits-Engelsman, B., Bloem-van der Wel, H. E., & Duysens, J. (2006). Children with Developmental Coordination Disorder respond similarly to age-matched controls in both speed and accuracy if goal-directed movements are made across the midline. *Child: Care, Health & Development, 32*, 703–710.

Smits-Engelsman, B. C. M., Niemeijer, A. S., & van Galen, G. P. (2001). Fine motor deficiencies in children diagnosed as DCD based on poor grapho-motor ability. *Human Movement Science, 20*, 161–182. http://dx.doi.org/10.1016/S0167-9457(01)00033-1

Smits-Engelsman, B. C. M., Wilson, P. H., Westenberg, Y., & Duysens, J. (2003). Fine motor deficiencies in children with developmental coordination disorder and learning disabilities: An underlying open-loop control deficit. *Human Movement Science, 22*, 495–513. http://dx.doi.org/10.1016/j.humov.2003.09.006

Sirigu, A., & Duhamel, J. R. (2001). Motor and visual imagery as two complementary but neurally dissociable mental processes. *Journal of Cognitive Neuroscience, 13*(7), 910–919.

Stevens, J. A. (2005). Interference effects demonstrate distinct roles for visual and motor imagery during the mental representation of human action. *Cognition, 95*(3), 329–350. http://dx.doi.org/10.1016/j.cognition.2004.02.008

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

Williams, J., Omizzolo, C., Galea, M., & Vance, A. (2013). Motor imagery skills of children with Attention Deficit Hyperactivity Disorder and Developmental Coordination Disorder. *Human Movement Science, 32*, 121–135. http://dx.doi.org/10.1016/j.humov.2012.08.003

Williams, J., Thomas, P. R., Maruff, P., & Wilson, P. H. (2008). The link between motor impairment level and motor imagery ability in children with Developmental Coordination Disorder. *Human Movement Science, 27*, 270–285. http://dx.doi.org/10.1016/j.humov.2008.02.008

Wilmut, K., & Wann, J. (2008). The use of predictive information is impaired in the actions of children and young adults with Developmental Coordination Disorder. *Experimental Brain Research, 191*, 403–418. http://dx.doi.org/10.1007/s00221-008-1532-4

Wilson, B. N., Crawford, S. G., Green, D., Roberts, G., Aylott, A., & Kaplan, B. J. (2009). Psychometric properties of the revised Developmental Coordination Disorder questionnaire. *Journal of Physical and Occupational Therapy in Pediatrics, 29*(2), 182–202. http://dx.doi.org/10.1080/01942630902784761

Wilson, P. H., Ruddock, S., Smits-Engelsman, B., Polatajko, H., & Blank, R. (2013). Understanding performance deficits in Developmental Coordination Disorder: A meta-analysis of recent research. *Developmental Medicine & Child Neurology, 55*, 217–228. http://dx.doi.org/10.1111/j.1469-8749.2012.04436.x