Performance under varying constraints in Developmental Coordination Disorder (DCD): Difficulties and compensations

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Abstract

Purpose of review: Developmental Coordination Disorder is by very nature a disorder of movement and coordination. The constraints-based approach to motor control advocates the idea that the environment, the task and the individual can all constrain and promote movement/coordination. The purpose of this review is to describe factors which have been shown to explain the movement patterns in DCD and discuss these in light of the constraints-based approach.

Recent findings: Recent findings considering the perception-action relationship, the control of movement, the role of vision and individual differences in DCD can all be considered under the constraints-based approach which focuses less on deficits and more on compensations to the constraints facing movement control.

Summary: This paper has demonstrated the usefulness of the constraints-based approach in considering DCD and has also raised important questions regarding how we group and describe these individuals.

Introduction

The constraints-based approach to understanding motor control describes factors which constrain or influence an emerging movement (1-3). Newell (1986) classified constraints into three distinct categories which provide a coherent framework for understanding an emerging coordination pattern: individual, environmental and task (3). Despite the terminology these constraints should not be viewed as intrinsically negative but rather influential on movement behaviour. *Individual* constraints include factors such as height, weight, limb length, strength and internal motivations. *Environmental* constraints can be physical in nature such as ambient light, temperature, but can also be social such as the presence of a peer group. Finally, *task* constraints relate to task goals, rules of the task and equipment relevant to complete the task. The way in which these constraints shape and influence movement is unique to each one of us and continually changes so that the emerging movement may be different from one moment to the next (1). The constraints-based-approach is typically viewed as an ecological based theory and so is perceived, by some, as opposing information processing accounts of motor performance. However, Anson et al. (2005) argue that these two leading theories of motor control are in fact more similar than they are different (4). Taking motor skill acquisition as an example Anson et al. (2005) compare the information processing account (Fitts' three stage model of learning, (5)) with the constraints-based-approach to skill acquisition (3) in doing this they find more similarities than differences and they demonstrate that both accounts describe very similar stages and processes (4). Furthermore, a detailed account of 24 of Bernstein's publications on motor control highlights the importance of both motor programmes (central to information processing) and organism-environment interactions (central to the ecological account) to Bernstien's concept of motor control (6) once again drawing parallels between these two 'opposing' theories.

The constraints-based-approach is thought to be helpful in describing and understanding motor control in DCD as it encompasses *all* of the factors involved in movement and allows us to consider these together rather than in isolation (7). Within this framework the motor and/or perceptual difficulties experienced in DCD are a constraint upon perceptual-motor function and therefore, the movements we see in this population are emergent functional adaptations (or compensations if one wishes) to these constraints or difficulties. For example Debrabant et al (2016) recently identified very specific alternations to the white matter of a group of children with DCD, this then acts as an individual constraint which influences the emerging movement (8). An appealing aspect of this approach is that it is not just children with DCD who face constraints to movement behaviour but rather it is *all* children who face these constraints and *all* children who must adapt to their own unique individual constraints during development (9). This allows us to conceptualise DCD less in terms of deficits and more in terms of compensations. It is worth re-iterating at this point that the constraints-based-model compliments an information-processing account of motor performance (4) which is commonly used as a framework to describe DCD (7), therefore, this account should not be seen as opposing information processing accounts. Further discussion regarding constraints-based-model and the information processing account of motor control within a DCD context can be found in a recent paper by Wilson and colleagues (10). Within the current paper I will describe some of the newer research within the DCD field and demonstrate how that can be described and interpreted in terms of a constraints-based approach.

Perception - action coupling

One of the central tenants to the constraints-based-approach is the inseparable nature of perception and action and the importance of considering perception within an action context with effective skill acquisition depending on effective coupling of perception and action (2). Very recently it has been suggested that the movement behaviour seen in DCD can be explained by a deficit in the perception-action relationship (11) and that earlier studies may not have identified this as they studied visual perception in isolation rather than within an action context (12). In regards to a difficulty in perception-action coupling the authors cite work which considers perceptual abilities of children with DCD within action related tasks. For example, the judgement of vertical reaching height and sitting height (13), judgement of horizontal reaching (14) and judgement of maximum sitting height with standing height artifically altered (15). In all of these studies children with DCD made less accurate judgments of action capability compared with their peers, with no clear pattern of over- or under-estimation. These findings provide us with an important insight into perceptual abilities of children with DCD but they do not tell us much about how perception may influence action. A more recent collection of studies go some way to address this by considering how movement is influenced by perceptual tasks of varying complexities (16, 17). These studies have found that children with DCD were less able (as compared with their peers) to moderate postural control as perceptual task difficulty increased, demonstrating the undue influence perception can have on action in this group. These studies demonstrate difficulties with perceptual tasks within a DCD population and to some extent difficulties integrating perceptual information into action. Wade and Kazeck (2016) suggested that these findings indicate a deficit in children with DCD in terms of judging the fit between their own body-scaled frame of reference and the environment, hence a deficit in the perception-action relationship (11). A commentary published in response to this paper (10) then goes on to highlight the importance of brain-based/biological explanations for such a deficit. A deficit at the neurological level could act as an individual constraint on the perception-action cycle, the integration of perception and action or on tasks requiring one but not the other process.

A number of other studies have taken a more explicit look at perception-action coupling in DCD by varying task constraints with more ecologically valid tasks. Chen et al., (2014) considered the relationship between perceptual judgements (perceived sitting height) and movement control (postural sway). Their typically developing children, but not their group with DCD, showed a relationship between sway and perceived sitting height, whereby less sway was correlated with a more accurate judgement (15). The authors conclude a difference in the perception-action coupling of children with and without DCD (15). However, the difference between the perceptual task (judgement of sitting height) and the movement actually measured (postural sway) makes it difficult to fully understand this relationship. Chen and Wu (2013) included correlations between perception and action in more related tasks; the perceived size of a hole that a golf ball is to be putted into and putting performance (18). They found that putting performance (distance from hole) and perceived size of the hole were positively related, with a better putting performance relating to larger estimations of hole size. However, as they considered the TD and DCD group together in one correlation this tells us very little about the relationship in children with DCD compared to their peers.

In a recent study, Wilmut, Du and Barnett (2016) considered perception and action in a navigation task (19). Essentially children with DCD were faced with an aperture that either did or did not require a shoulder rotation for safe passage. Participants completed two tasks: 1) a perceptual task (within an action context), participants were asked to make passability judgements, i.e. 'would you need to rotate your shoulders to pass through this aperture'; and 2) an action task, participants were asked to walk up to and through the same set of apertures. In terms of judgement of passability, the children with DCD *under-estimated* the space needed with respect to typical performance. In contrast, when moving, the children with DCD *over-estimated* the space needed with respect to typical performance. This study demonstrates that perception in children with DCD can change when action is present compared to when it is not and so one cannot assume that perceptual judgement without an action is the same as that judgement with an action. In this study, passability judgements were made from a distance of 7m while in the 'action' condition the decision making process (to turn or not to turn) could have been made when the individual was much closer to the aperture. This demonstrates a change in constraints across these tasks, the effect of which may have been different across groups, hence why we see such a difference in the emerging judgement and a deficit in perception-action coupling in DCD. This highlights the limitation of trying to consider perceptual judgement without action. Wilmut et al. (2016) went on to consider the relationship between passability judgements and movement adaptations, this was done by comparing the aperture size at which a turn was perceived to be required in the perceptual task and the aperture size at which a turn was executed in the action task (19). Intriguingly a positive relationship was found between passability judgements and movement adaptations in the children with DCD but *not* the TD children. This finding demonstrates that, in children with DCD, what the individual perceives in a static condition is then realised in a dynamic context. Given the importance of perception-action coupling within the constraints-based-approach and the suggestion that the locus of motor difficulties lies within the strength between the perception-action relationship (7) these studies provide an important first step to understanding this relationship in children with DCD and how it constrains subsequent movements.

Movement control

The way in which we start a movement can influence how that movement is finished. A number of studies have considered this type of movement control in children with DCD using an 'end-state-comfort' task. This effect describes the phenomenon whereby the hand is rotated into an uncomfortable start position if it means the hand will end in a comfortable end position (20-22). For example, if aiming to turn a wine glass from an inverted to an upright position most adults would rotate their arm into a thumb down position (uncomfortable grasp), grasp the glass, and then rotate back to a thumb up position (comfortable grasp). End-State-Comfort has been studied in children with DCD in five studies with differing results. Noten, Wilson, Ruddock and Steenbergen (2014) and Smyth and Mason (1997) used a bar transport task and found no differences between children with DCD and typically developing children in terms of the way in which they control movement (23, 24). Adams, Ferguson, Lust, Steenbergen and Smits-Engelsman (2016) used both a bar transport task and a sword task (which requires a higher precision of control at the end of the movement compared to the bar transport task) (25). Once again children with DCD showed a similar level of control in the bar transport task. However, in the sword task children with DCD ended fewer movements in end-state-comfort compared to their peers. The different pattern of results between these tasks was attributed to the different levels of precision of control required (25). Two further studies used tasks requiring large hand rotations (26) and tasks requiring sequential movements (27) and both found that the children with DCD ended fewer movement in end-state-comfort compared with their peers.

Much has been written regarding these planning tasks and whether these deficits are due to an internal modelling deficit (28) or due to a difficulty judging the affordances of the environment (11). This paper will not re-iterate the merits, or otherwise, of these arguments, rather I will consider the emerging movements in terms of the unique pattern of constraints placed on the individual. The studies described above demonstrate very different patterns of behaviour depending on task constraints, with children with DCD performing differently to their peers when task complexity is high but similarly when task complexity is low. Essentially this is demonstrating a change in emerging behaviour with a change in *task* constraint; the way in which children with DCD compensate for an increased complexity of the task sets them apart from their peers. Van Swieten et al. (2010) and Wilmut and Byrne (2014) describe this in terms of 'costs' citing both a large initial rotation of the hand as a cost and ending in an uncomfortable position as a cost (26, 27). Essentially, the cost of an uncomfortable end position outweighs the cost of a large initial rotation of the hand in typical development. While, in DCD an opposite pattern is seen whereby the cost of a high initial rotation outweighs the cost of an uncomfortable end position. Therefore, under one set of constraints (when the movement is very simple) a movement behaviour emerges which happens to have the same outcome in both TD and DCD. In contrast, under a different set of constraints (when the movement is more complex) the way in which the two populations compensate or adapt to the constraint is different and so the emerging behaviour has a different outcome. Shadmehr et al (2010) build on this idea of the 'cost' of a movement and demonstrate that the time taken to make a saccadic movement is related to the perceived reward (or benefit) of a stimulus (29). The way in which Shadmehr et al. (2010) model this relationship explains some of the variation seen across conditions (e.g. schizophrenia, alcoholism, Parkinson's disease) in terms of saccadic duration and the way in which reward is weighted. This idea of 'cost' and 'benefit/reward' sits very closely to the constraints-based-approach with the way in which one assigns costs or benefit/reward being an individual constraint which influences the emerging movement.

The role of visual information

Over the last two decades there have been many studies considering how children with DCD use and respond to visual information with research suggesting that children with DCD rely more heavily on visual information compared to proprioceptive information (for example see (30, 31)), that they are less adaptive to the removal of vision (32) and that they can, at times, struggle to correctly interpret visual information (for example see (28). Underlying the quality of visual information is the ability to control and appropriately direct one's gaze. Sumner, Hutton, Kuhn and Hill (2016) conducted a comprehensive study into the control of eye movements in children with DCD (33). This study found a number of atypicalities, for example, children with DCD showed reduced fixation stability (i.e., when asked to fixate these children execute more saccades away from the target than peers) and a difficulty maintaining smooth pursuit (spending less time in pursuit of a moving target compared with their peers). Deficits in vertical (34) and horizontal (35) smooth pursuit in children with DCD had also been identified in earlier studies. The findings of Sumner et al. (2016) reflect a real difference in how gaze is controlled in lab based tasks in children with DCD.

Similar findings have been demonstrated in a more ecologically valid task where gaze behaviour of children was recorded during a ball catching task. Children scoring below the 16th percentile on the MABC-2 (Movement Assessment Battery for Children – 2nd ed.) (36) and so deemed 'at risk of DCD' demonstrated less 'quiet eye' tracking of the ball prior to a catching attempt as compared to those scoring above the 16th percentile (37). In this case 'quiet eye' refers to a fixation or tracking gaze that focuses on a specific object for a minimum of 100ms prior to a movement, research has demonstrated the importance of this during skilled action such as catching (38). Interestingly, a further study considered whether quiet eye training and directive instructions regarding *where* one should look while throwing and catching a ball can change gaze direction in children with DCD (39). This study demonstrated that quiet eye training improved the ability of these children to focus on a target prior to throwing (a ball against a wall), which was then followed by a better anticipation and pursuit tracking of the ball as it approached (following rebound from the wall). This finding is also supported by successful intervention protocols which can improve smooth pursuit in lab based tasks in children with DCD (34). Although eye movement changes in the quiet eye study did not result in a greater number of balls caught, they did improve catch attempts made by the children in the quiet eye training group in terms of an increase elbow flexion at the point of catch which is an indication of a well-developed catching style. In this collection of studies we see a difference in emerging behaviour across two groups which is seemingly a result of an *individual* constraint. This emerging behaviour is then influenced by a period of training (or learning), thus demonstrating how compensations or adaptations to constraints can change over time.

Individual differences

A key element of the constraints-based-framework is the idea of the individual being a constraint on emerging movement. In fact, one could argue that the only real difference between a child with and a child without DCD is the nature of the unique pattern of individual constraints that influence that child's motor behaviour. However, caution is needed when we simplify differences in this way. The constraints-based-account of motor control would suggest that the constraints we face on a day to day basis are unique to *every single individual* and therefore individual constraints influencing one child with DCD will be distinctly different to those influencing another. There has been much written on the issue of individual differences within this population which deals with issues regarding co-occurring difficulties (40) and severity of motor impairment and method of recruitment and selection (41). In fact, a number of studies have focused on these demographic characteristics as an explanation for different emerging behaviours. For example, Adams et al. (2016) suggest differences in patterns of motor control across studies could be explained by one study using a DCD population below the 5th percentile, while another uses a population below the 15th percentile (25). This assertion is supported by two studies by Purcell, Wann, Wilmut and Poulter who separate children with DCD below the 5th percentile and those between the 10th and 15th into two groups and observe very different patterns of behaviour across these groups in terms of a road crossing task (42, 43). These findings clearly demonstrate that different constraints influence emerging behaviour *within* the group we have labelled as 'DCD'. Although these studies provide an important insight into the *individual* as a constraint they still group participants and so are still assuming that emerging movement patterns are the same across a number of individuals. Some recent studies do include an analysis of 'individual differences' which attempt to describe patterns of behaviour at the individual level (for example see (44-47)). Typically these papers consider whether individuals with DCD fall inside or outside the typical group mean (plus or minus one or two standard deviations) and broadly speaking children with DCD show a mixed pattern with some skills falling within a typical range while other skills do not. It is worth noting at this point that there is normally no clear standard 'DCD' pattern of behaviour, but rather the profile is unique to each individual. Although it is difficult to draw conclusion about group behaviour with this work it is vital if we are to understand the unique constraints on individuals with DCD and how these differ *within* this population. This approach would require a move towards formulating hypotheses and predictions which are based on individual differences as well as those which are based on group differences.

Another way to consider unique constraints and how these influence movement outcome is to measure how emerging movement *changes* in *each* individual given changes to task, environment and individual constraints rather than trying to group individuals together. To date, learning studies in children with DCD have provided a really important understanding of skill acquisition within this population, many of which have explored how different tasks/environments promote or suppress learning which allows us to consider the findings within a constraints-based approach. Snapp-Childs et al. (2013) report improvements in children with DCD in both spatial and temporal elements of a 3D tracking task while using a robotic arm to provide graded assistance to movement (48). During practice children progressed through levels of difficulty; only moving onto the next stage when they had successfully completed the previous stage. Both the children with and without DCD improved as a result of the training, but interestingly, children with DCD demonstrated a higher rate of learning which allowed them to attain the same level of performance as typically developing children by the end of the training (48). Essentially this task manipulates task constraints, initially the task is easy as assistance to movement is high as learning takes place, assistance to movement is reduced and so task constraints change. This sits within the 'challenge point framework'(49) which states that in order for an individual to acquire a skill there needs to be a balance between the difficulty of the task and the initial skill level of an individual. If the task is too difficult and the skill level too low then skill acquisition is unlikely, similarly if task difficulty is low and skill level high no skill improvement will be seen. Therefore, as skill improves, task difficulty needs to increase in order to see an increase in skill level. Other studies which have used varying task constraints have also shown positive effects of learning in children with DCD or studies have been able to use this as an explanation for a lack of learning in this population (for recent examples see (48, 50-56). However, all of these studies have all averaged across participants thus losing the within participant variation and treating all *individuals* with DCD as though they are the same.

Concluding remarks

In this paper I have discussed recent findings in the DCD field within the constraints-based-approach to movement control. This provides us with a useful framework within which the abilities and movement of children and adults with DCD can be considered. Using this framework allows us to consider the adaptations and compensations these individuals make in light of their unique pattern of constraints. Central to the constraints-based approach is the notion that any given movement is a functional adaptation to a set of given constraints and these constraints are unique to each individual. Under these parameters one very quickly realises that movement patterns will vary both *within* and *between* individuals whether those individuals are 'typically' developing or developing with DCD. Davids et al. (2010) advocate that rather than a comparison to a 'typical' movement pattern, the movement patterns of children with movement disorders should be viewed as functional and emergent given the individual constraints (9). Clearly the term 'functional' here poses a challenge, the movements that are made by children with DCD may be functional in terms of the pattern of individual constraints that they are under, but they are clearly not functional in terms of their daily occupations or scholastic efforts. Putting this aside the question as to whether we should compare movement from one individual to another (whether they are both atypically developing, both typical developing or either side of this divide) given the unique pattern of constraints on every single individual is an interesting one. To date, nearly all research involving a DCD population compares performance against a 'typical' or 'optimal' performance, indeed this could be said to be true of the majority of research into all movement disorders. It is all too easy to make predictions about group differences, to average across a group and to discuss 'typical' and 'atypical'. However, I for one cannot help but feel that this might be causing us to miss something important. Spending time considering how movement behaviour changes as a result of changes to task, environment or individual constraints all *within* the same individual may help to shed some light on how differently ‘typically’ developing children and children with DCD compensate for their unique pattern of constraints. Some of the research reviewed within this article has already started to do this.

Compliance with Ethics Guidelines

Conflict of Interest

Kate Wilmut has nothing to disclose.

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

References

1. Davids K. The constraints-based approach to motor learning: implications for a non-linear pedagogy in sport and physical education. In: Renshaw I, Davids K, Savelsbergh GJP, editors. Motor learning in practice: A constraints-led approach. NY, USA: Routledge; 2010.

*2. Davids K, Button C, Bennett S, editors. Dynamics of skill acquisition. A constraints-led approach. Champaign, IL: Human Kinetics; 2008.

A very good overview of the constraints-based-approach

3. Newell KM. Constraints on the development of coordination. In: Wade MG, Whiting HTA, editors. Motor development in children: Aspects of coordination and control. Amsterdam: Martinus Nijhoff Publishers; 1986. p. 341-61.

*4. Anson G, Elliott D, Davids K. Information processing and constraints-based views of skill acquisition: Divergent or complementary? Motor Control. 2005;9:217-41.

Provides a very good discussion of the information processing and ecological theories of motor control

5. Fitts PM. Perceptual-motor skill learning. In: Melton AW, editor. Categories of human learning. NY: Academic Press; 1964. p. 243-85.

6. Bongaardt R, Meijer OG. Bernstein's Theory of Movement Behavior: Historical Development and Contemporary Relevance. Journal of Motor Behavior. 2000;32(1):57-71.

7. Sugden D, Wade MG. Typical and atypical motor development: Wiley; 2013.

8. Debrabant J, Vingerhoets G, Van Waelvelde H, Leemans A, Taymans T, Caeyenberghs K. Brain connectomics of visual-motor deficits in chidlren with Developmental Coordination Disorder. Journal of Pediatrics. 2016;169:21-7.

9. Davids K, Savelsbergh GJP, Miyahara M. Identifying constraints on children with movement difficulties: implications for pedagogues and clinicians. In: Renshaw I, Davids K, Savelsbergh GJP, editors. Motor learning in practice: A constraints-led approach. NY, USA: Routledge; 2010.

**10. Wilson PH, Dewey D, Smits-Engelsman B, Steenbergen B. Hybrid is not a dirty word: Commentary on Wade and Kazeck (2017). Human Movement Science. 2017.

A very comprehensive overview of current issues in DCD

*11. Wade MG, Kazeck M. Developmental Coordination Disorder and its cause: The road less travelled. Human Movement Science. 2016;http://dx.doi.org/10.1016/j.humov.2016.08.004.

This paper explores ideas surrounding typical and atypical movement and is based partly on the constraints-based-approach to movement

12. Wade MG, Johnson D, Mally K. A dynamical systems perspective in persons diagnosed with Developmental Coordination Disorder: Theory and Practice. In: Sugden DA, Chambers M, editors. Children with developmental coordination disorder. London, England: Whurr Publishing; 2005.

13. Johnson DC, Wade MG. Judgement of action capabilities in children at risk for Developmental Coordination Disorder. Disability and Rehabilitation. 2007;29(1):33-45.

14. Johnson DC, Wade MG. Children at risk for Developmental Coordination Disorder: Judgement of changes in action capabilities. Developmental Medicine and Child Neurology. 2009;51:397-403.

*15. Chen FC, Tsai CL, Wu SK. Postural sway and perception of affordances in children at risk for developmental coordination disorder. Experimental Brain Research. 2014;232(7):2155-65.

This study considers perception-action coupling in DCD

16. Chen FC, Tsai C-L, Stroffregen TA, Chang C-H, Wade MG. Postural adaptations to a suprapostural memory task among children with and without developmental coordination disorder. Developmental Medicine and Child Neurology. 2012;54:155-9.

17. Chen FC, Tsai CL, Stroffregen TA, Wade MG. Postural responses to a suprapostural visual task among children with and without developmental coordination disorder. Research in Developmental Disabilities. 2011;32(5):1948-56.

*18. Chen FC, Wu SK. Perceived Hole Size, Performance, and Body Movement During Putting in Children With and Without Probable Developmental Coordination Disorder. Motor Control. 2013;17:382-98.

This study considers perception-action coupling in DCD

**19. Wilmut K, Du W, Barnett A. Navigating through apertures: perceptual judgements and actions of children with Developmental Coordination Disorder. Developmental Science. 2016.

This study considers perception-action coupling in DCD

20. Rosenbaum DA. Human movement initiation: specification of arm, direction and extent. Journal of Experimental Psychology: General. 1980;109:444-74.

21. Rosenbaum DA, Cohen RG, Meulenbroak RG, Vaughan J. Plans for grasping objects. In: Latash M, Lestienne F, editors. Motor Control and Learning over the Lifespan. New York: Springer; 2006. p. 9-25.

22. Wunsch K, Henning A, Aschersleben G, Weiss PL. A Systematic Review of the End-State Comfort Effect in Normally Developing Children and in Children With Developmental Disorders. Journal of Motor Learning and Development. 2013;1:59-76.

*23. Noten M, Wilson P, Ruddock S, Steenbergen B. Mild impariment of motor imagery skills in children with DCD. Research in Developmental Disabilities. 2014;35:1152-9.

This study considers movement control in DCD using and end-state-comfort task

24. Smyth MM, Mason UC. Planning and execution of action in children with and without developmental coordination disorder. Journal of Child Psychology and Psychiatry. 1997;38:1023-37.

**25. Adams ILJ, Ferguson GD, Lust JM, Steenbergen B, Smits-Engelsman B. Action planning and position sense in children with Developmental Coordination Disorder. Human Movement Science. 2016;46:196-208.

This study considers movement control in DCD using and end-state-comfort task and includes some discussion regarding performance under different task difficulties.

26. van Swieten LM, van Bergen E, Williams JHG, Wilson AD, Plumb MS, Kent SW, et al. A test of motor (not executive) planning in Developmental Coordination Disorder and Autism. Journal of Experimental Psychology: Human Perception and Performance. 2010;36(2):493-9.

**27. Wilmut K, Byrne M. Grip selection for sequential movements in children and adults with and without Developmental Coordination Disorder. Human Movement Science. 2014;36:272-84.

This study considers movement control in DCD using and end-state-comfort task and includes some discussion regarding performance under different task difficulties.

28. Wilson PH, Ruddock S, Smits-Engelsman B, Polatajko H, Blank R. Understanding performance deficits in developmental coordination disorder: a meta-analysis of recent research. Developmental Medicine and Child Neurology. 2013;55(3):217-28.

29. Shadmehr R, de Xivry JJO, Xu-Wilson M, Shih T-Y. Temproal discounting of reward and the cost of time in motor control. The Journal of Neuroscience. 2010;30(31):10507-16.

30. Deconinck FJA, De Clercq D, Savelsberg GJP, Van Coster R, Oostra A, Dewitte G, et al. Visual contribution to walking in children with Developmental Coordination Disorder. Child: Care, Health and Development. 2006;32(6):711-22.

31. Wann JP, Mon-Williams M, Rushton SK. Postural control and coordination disorders: the swinging room revisited. Human Movement Science. 1998;17:491-513.

32. Smyth MM, Anderson HI, Churchill A. Visual information and the control of reaching in children: a comparison between children with and without Developmental Coordination Disorder. Journal of Motor Behavior. 2001;33(3):306-20.

*33. Sumner E, Hutton SB, Kuhn G, Hill EL. Oculomotor atypicalities in Developmental Coordination Disorder. Developmental Science. 2016;DOI: 10.1111/desc.12501

This study looks at gaze control in DCD

*34. Robert MP, Ingster-Moati I, Albuisson E, Cabrol D, Golse B, Vaivre-Douret L. Vertical and horizontal smooth pursuit eye movements in children with developmental coordination disorder. Developmental Medicine and Child Neurology. 2014;56:595-600.

This study looks at gaze control in DCD

35. Langaas T, Mon-Williams M, Wann JP, Pascal E, Tompson C. Eye movements, prematurity and developmental co-ordination disorder. Vision Research. 1998;38:1817-26.

36. Henderson S, Sugden D, Barnett A. Movement Assessment Battery for Children: Second edition. Oxford: Pearson; 2007.

*37. Wilson MR, Miles CAL, Vine SJ, Vickers JN. Quiet Eye Distinguishes Children of High and Low Motor Coordination Abilities. Medicine and Science in Sports and Exercise. 2012;45(6).

This study looks at gaze control in DCD in a naturalistic catching task

38. Vickers JN. Cognition and Decision Making: The Quiet Eye in Action. Champaign: Human Kinertics; 2007.

**39. Miles CAL, Wood G, Vine SJ, Vickers JN, Wilson MR. Quiet eye training facilitates visuomotor coordination in children with developmental coordination disorder. Research in Developmental Disabilities. 2015;40:31-41.

This study looks at how gaze control can be trained / learn in a DCD population and therefore, it sits well with the idea of a constraints-based-approach

40. Blank R, Smits-Engelsman B, Polatajko H, Wilson PH. European Academy for Childhood Disability (EACD): Recommendations on the definition, diagnosis and intervention of developmental coordination disorder (long version). Developmental Medicine & Child Neurology. 2012;54(1):54-93.

41. Wilmut K. Selection and assessment of children with Developmental Coordination Disorder. Developmental Medicine and Child Neurology. 2010;52(3):229.

42. Purcell C, Wann JP, Wilmut K, Poulter D. Roadside judgements in children with Developmental Coordination Disorder. Research in Developmental Disabilities. 2011;32(4):1283-92.

43. Purcell C, Wann JP, Wilmut K, Poulter D. Reduced looming sensitivity in primary school children with Developmental Coordination Disorder. Developmental Science. 2011;15:299-316.

*44. Cantin N, Ryan J, Polatajko HJ. Impact of task difficulty and motor ability on visual-motor task performance of children with and without developmental coordination disorder. Human Movement Science. 2014;34:217-32.

This study includes some degree of consideration for individual constraints of movement in DCD

*45. Gomez A, Piazza M, Jobert A, Dehaene-Lambertz G, C. H. Numerical abilities of school-age children with Developmental Coordination Disorder (DCD): A behavioral and eye-tracking study Human Movement Science. 2016;http://dx.doi.org/10.1016/j.humov.2016.08.008

This study includes some degree of consideration for individual constraints of movement in DCD

*46. Jelsma D, Smits-Engelsman B, Krijnen WP, Geuze R. Changes in dynamic balance control over time in children with and without Developmental Coordination Disorder Human Movement Science. 2016;49:148-59.

This study includes some degree of consideration for individual constraints of movement in DCD

*47. Sumner E, Pratt ML, Hill EL. Examining the cognitive profile of children with Developmental Coordination Disorder. Research in Developmental Disabilities. 2016;56:10-7.

This study includes some degree of consideration for individual constraints of movement in DCD

**48. Snapp-Childs W, Mon-Williams M, Bingham GP. A sensorimotor approach to the training of manual actions in children with developmental coordination disorder. Journal of Child Neurology. 2013;28(2):204-12.

A very interesting study on motor skill acquisition in DCD

49. Guadagnoli MA, Lee TD. Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. Journal of Motor Behavior. 2004;36(2):212-24.

50. Hammond J, Jones V, Hill EL, Green D, Male I. An investigation of the impact of regular use of the Wii Fit to improve motor and psychosocial outcomes in children with movement difficulties: a pilot study. Child Care Health Dev. 2014;40(2):165-75.

51. Howie EK, Campbell AC, Abbott RA, Straker LM. Understanding why an active video game intervention didnot improve motor skill and physical activity in children withdevelopmental coordination disorder: A quantity or qualityissue? Research in Developmental Disabilities. 2017;60:1-12.

52. Jelsma D, Geuze RH, Mombarg R, Smits-Engelsman B. The impact of Wii Fit intervention of dynamic balance control in children with probable Developmental Coordination Disorder and balance problems. Human Movement Science. 2014;33:404-18.

53. Lejeune C, Catale C, Willems S, Meulemans T. Intact procedural motor sequence learning in developmental coordination disorder. Research in Developmental Disabilities. 2013;doi:10.1016/j.ridd.2013.03.017.

54. Magallón S, Crespo-Eguílaz N, Narbona J. Procedural learning in children with developmental coordination, reading, and attention disorders. Journal of Child Neurology. 2015;doi:10.1177/0883073815572227.

55. Snapp-Childs W, Shire K, Hill L, Mon-Williams M, Bingham GP. Training compliance control yields improved drawing in 5-11year old children with motor difficulties. Human Movement Science. 2016;48:171-83.

56. Straker L, Howie E, Smith A, Jensen L, Piek J, Campbell A. A crossover randomised and controlled trial of the impact of active video games on motor coordination and perceptions of physical ability in children at risk of Developmental Coordination Disorder. Human Movement Science. 2015;42:146-60.