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3 **Performance under varying constraints in Developmental Coordination Disorder (DCD):**  
4 **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 Bernstein'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

1 is worth re-iterating at this point that the constraints-based-model compliments an information-  
2 processing account of motor performance (4) which is commonly used as a framework to  
3 describe DCD (7), therefore, this account should not be seen as opposing information  
4 processing accounts. Further discussion regarding constraints-based-model and the information  
5 processing account of motor control within a DCD context can be found in a recent paper by  
6 Wilson and colleagues (10). Within the current paper I will describe some of the newer research  
7 within the DCD field and demonstrate how that can be described and interpreted in terms of a  
8 constraints-based approach.  
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### 10 **Perception - action coupling**

11 One of the central tenants to the constraints-based-approach is the inseparable nature of  
12 perception and action and the importance of considering perception within an action context  
13 with effective skill acquisition depending on effective coupling of perception and action (2). Very  
14 recently it has been suggested that the movement behaviour seen in DCD can be explained by a  
15 deficit in the perception-action relationship (11) and that earlier studies may not have identified  
16 this as they studied visual perception in isolation rather than within an action context (12). In  
17 regards to a difficulty in perception-action coupling the authors cite work which considers  
18 perceptual abilities of children with DCD within action related tasks. For example, the  
19 judgement of vertical reaching height and sitting height (13), judgement of horizontal reaching  
20 (14) and judgement of maximum sitting height with standing height artificially altered (15). In all  
21 of these studies children with DCD made less accurate judgments of action capability compared  
22 with their peers, with no clear pattern of over- or under-estimation. These findings provide us  
23 with an important insight into perceptual abilities of children with DCD but they do not tell us  
24 much about how perception may influence action. A more recent collection of studies go some  
25 way to address this by considering how movement is influenced by perceptual tasks of varying  
26 complexities (16, 17). These studies have found that children with DCD were less able (as  
27 compared with their peers) to moderate postural control as perceptual task difficulty increased,  
28 demonstrating the undue influence perception can have on action in this group. These studies  
29 demonstrate difficulties with perceptual tasks within a DCD population and to some extent  
30 difficulties integrating perceptual information into action. Wade and Kazeck (2016) suggested  
31 that these findings indicate a deficit in children with DCD in terms of judging the fit between  
32 their own body-scaled frame of reference and the environment, hence a deficit in the perception-  
33 action relationship (11). A commentary published in response to this paper (10) then goes on to  
34 highlight the importance of brain-based/biological explanations for such a deficit. A deficit at  
35 the neurological level could act as an individual constraint on the perception-action cycle, the  
36 integration of perception and action or on tasks requiring one but not the other process.  
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44 A number of other studies have taken a more explicit look at perception-action coupling in  
45 DCD by varying task constraints with more ecologically valid tasks. Chen et al., (2014)  
46 considered the relationship between perceptual judgements (perceived sitting height) and  
47 movement control (postural sway). Their typically developing children, but not their group with  
48 DCD, showed a relationship between sway and perceived sitting height, whereby less sway was  
49 correlated with a more accurate judgement (15). The authors conclude a difference in the  
50 perception-action coupling of children with and without DCD (15). However, the difference  
51 between the perceptual task (judgement of sitting height) and the movement actually measured  
52 (postural sway) makes it difficult to fully understand this relationship. Chen and Wu (2013)  
53 included correlations between perception and action in more related tasks; the perceived size of a  
54 hole that a golf ball is to be putted into and putting performance (18). They found that putting  
55 performance (distance from hole) and perceived size of the hole were positively related, with a  
56 better putting performance relating to larger estimations of hole size. However, as they  
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1 considered the TD and DCD group together in one correlation this tells us very little about the  
2 relationship in children with DCD compared to their peers.

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

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

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4 Much has been written regarding these planning tasks and whether these deficits are due to an  
5 internal modelling deficit (28) or due to a difficulty judging the affordances of the environment  
6 (11). This paper will not re-iterate the merits, or otherwise, of these arguments, rather I will  
7 consider the emerging movements in terms of the unique pattern of constraints placed on the  
8 individual. The studies described above demonstrate very different patterns of behaviour  
9 depending on task constraints, with children with DCD performing differently to their peers  
10 when task complexity is high but similarly when task complexity is low. Essentially this is  
11 demonstrating a change in emerging behaviour with a change in *task* constraint; the way in which  
12 children with DCD compensate for an increased complexity of the task sets them apart from  
13 their peers. Van Swieten et al. (2010) and Wilmot and Byrne (2014) describe this in terms of  
14 'costs' citing both a large initial rotation of the hand as a cost and ending in an uncomfortable  
15 position as a cost (26, 27). Essentially, the cost of an uncomfortable end position outweighs the  
16 cost of a large initial rotation of the hand in typical development. While, in DCD an opposite  
17 pattern is seen whereby the cost of a high initial rotation outweighs the cost of an uncomfortable  
18 end position. Therefore, under one set of constraints (when the movement is very simple) a  
19 movement behaviour emerges which happens to have the same outcome in both TD and DCD.  
20 In contrast, under a different set of constraints (when the movement is more complex) the way  
21 in which the two populations compensate or adapt to the constraint is different and so the  
22 emerging behaviour has a different outcome. Shadmehr et al (2010) build on this idea of the  
23 'cost' of a movement and demonstrate that the time taken to make a saccadic movement is  
24 related to the perceived reward (or benefit) of a stimulus (29). The way in which Shadmehr et al.  
25 (2010) model this relationship explains some of the variation seen across conditions (e.g.  
26 schizophrenia, alcoholism, Parkinson's disease) in terms of saccadic duration and the way in  
27 which reward is weighted. This idea of 'cost' and 'benefit/reward' sits very closely to the  
28 constraints-based-approach with the way in which one assigns costs or benefit/reward being an  
29 individual constraint which influences the emerging movement.  
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### 35 **The role of visual information**

36 Over the last two decades there have been many studies considering how children with DCD use  
37 and respond to visual information with research suggesting that children with DCD rely more  
38 heavily on visual information compared to proprioceptive information (for example see (30, 31)),  
39 that they are less adaptive to the removal of vision (32) and that they can, at times, struggle to  
40 correctly interpret visual information (for example see (28). Underlying the quality of visual  
41 information is the ability to control and appropriately direct one's gaze. Sumner, Hutton, Kuhn  
42 and Hill (2016) conducted a comprehensive study into the control of eye movements in children  
43 with DCD (33). This study found a number of atypicalities, for example, children with DCD  
44 showed reduced fixation stability (i.e., when asked to fixate these children execute more saccades  
45 away from the target than peers) and a difficulty maintaining smooth pursuit (spending less time  
46 in pursuit of a moving target compared with their peers). Deficits in vertical (34) and horizontal  
47 (35) smooth pursuit in children with DCD had also been identified in earlier studies. The  
48 findings of Sumner et al. (2016) reflect a real difference in how gaze is controlled in lab based  
49 tasks in children with DCD.  
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54 Similar findings have been demonstrated in a more ecologically valid task where gaze behaviour  
55 of children was recorded during a ball catching task. Children scoring below the 16<sup>th</sup> percentile  
56 on the MABC-2 (Movement Assessment Battery for Children – 2<sup>nd</sup> ed.) (36) and so deemed 'at  
57 risk of DCD' demonstrated less 'quiet eye' tracking of the ball prior to a catching attempt as  
58 compared to those scoring above the 16<sup>th</sup> percentile (37). In this case 'quiet eye' refers to a  
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1 fixation or tracking gaze that focuses on a specific object for a minimum of 100ms prior to a  
2 movement, research has demonstrated the importance of this during skilled action such as  
3 catching (38). Interestingly, a further study considered whether quiet eye training and directive  
4 instructions regarding *where* one should look while throwing and catching a ball can change gaze  
5 direction in children with DCD (39). This study demonstrated that quiet eye training improved  
6 the ability of these children to focus on a target prior to throwing (a ball against a wall), which  
7 was then followed by a better anticipation and pursuit tracking of the ball as it approached  
8 (following rebound from the wall). This finding is also supported by successful intervention  
9 protocols which can improve smooth pursuit in lab based tasks in children with DCD (34).  
10 Although eye movement changes in the quiet eye study did not result in a greater number of  
11 balls caught, they did improve catch attempts made by the children in the quiet eye training  
12 group in terms of an increase elbow flexion at the point of catch which is an indication of a well-  
13 developed catching style. In this collection of studies we see a difference in emerging behaviour  
14 across two groups which is seemingly a result of an *individual* constraint. This emerging behaviour  
15 is then influenced by a period of training (or learning), thus demonstrating how compensations  
16 or adaptations to constraints can change over time.  
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### 20 **Individual differences**

21 A key element of the constraints-based-framework is the idea of the individual being a constraint  
22 on emerging movement. In fact, one could argue that the only real difference between a child  
23 with and a child without DCD is the nature of the unique pattern of individual constraints that  
24 influence that child's motor behaviour. However, caution is needed when we simplify differences  
25 in this way. The constraints-based-account of motor control would suggest that the constraints  
26 we face on a day to day basis are unique to *every single individual* and therefore individual  
27 constraints influencing one child with DCD will be distinctly different to those influencing  
28 another. There has been much written on the issue of individual differences within this  
29 population which deals with issues regarding co-occurring difficulties (40) and severity of motor  
30 impairment and method of recruitment and selection (41). In fact, a number of studies have  
31 focused on these demographic characteristics as an explanation for different emerging  
32 behaviours. For example, Adams et al. (2016) suggest differences in patterns of motor control  
33 across studies could be explained by one study using a DCD population below the 5<sup>th</sup> percentile,  
34 while another uses a population below the 15<sup>th</sup> percentile (25). This assertion is supported by two  
35 studies by Purcell, Wann, Wilmut and Poulter who separate children with DCD below the 5<sup>th</sup>  
36 percentile and those between the 10<sup>th</sup> and 15<sup>th</sup> into two groups and observe very different  
37 patterns of behaviour across these groups in terms of a road crossing task (42, 43). These  
38 findings clearly demonstrate that different constraints influence emerging behaviour *within* the  
39 group we have labelled as 'DCD'. Although these studies provide an important insight into the  
40 *individual* as a constraint they still group participants and so are still assuming that emerging  
41 movement patterns are the same across a number of individuals. Some recent studies do include  
42 an analysis of 'individual differences' which attempt to describe patterns of behaviour at the  
43 individual level (for example see (44-47)). Typically these papers consider whether individuals  
44 with DCD fall inside or outside the typical group mean (plus or minus one or two standard  
45 deviations) and broadly speaking children with DCD show a mixed pattern with some skills  
46 falling within a typical range while other skills do not. It is worth noting at this point that there is  
47 normally no clear standard 'DCD' pattern of behaviour, but rather the profile is unique to each  
48 individual. Although it is difficult to draw conclusion about group behaviour with this work it is  
49 vital if we are to understand the unique constraints on individuals with DCD and how these  
50 differ *within* this population. This approach would require a move towards formulating  
51 hypotheses and predictions which are based on individual differences as well as those which are  
52 based on group differences.  
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1 Another way to consider unique constraints and how these influence movement outcome is to  
2 measure how emerging movement *changes* in *each* individual given changes to task, environment  
3 and individual constraints rather than trying to group individuals together. To date, learning  
4 studies in children with DCD have provided a really important understanding of skill acquisition  
5 within this population, many of which have explored how different tasks/environments promote  
6 or suppress learning which allows us to consider the findings within a constraints-based  
7 approach. Snapp-Childs et al. (2013) report improvements in children with DCD in both spatial  
8 and temporal elements of a 3D tracking task while using a robotic arm to provide graded  
9 assistance to movement (48). During practice children progressed through levels of difficulty;  
10 only moving onto the next stage when they had successfully completed the previous stage. Both  
11 the children with and without DCD improved as a result of the training, but interestingly,  
12 children with DCD demonstrated a higher rate of learning which allowed them to attain the  
13 same level of performance as typically developing children by the end of the training (48).  
14 Essentially this task manipulates task constraints, initially the task is easy as assistance to  
15 movement is high as learning takes place, assistance to movement is reduced and so task  
16 constraints change. This sits within the ‘challenge point framework’(49) which states that in  
17 order for an individual to acquire a skill there needs to be a balance between the difficulty of the  
18 task and the initial skill level of an individual. If the task is too difficult and the skill level too low  
19 then skill acquisition is unlikely, similarly if task difficulty is low and skill level high no skill  
20 improvement will be seen. Therefore, as skill improves, task difficulty needs to increase in order  
21 to see an increase in skill level. Other studies which have used varying task constraints have also  
22 shown positive effects of learning in children with DCD or studies have been able to use this as  
23 an explanation for a lack of learning in this population (for recent examples see (48, 50-56).  
24 However, all of these studies have all averaged across participants thus losing the within  
25 participant variation and treating all *individuals* with DCD as though they are the same.  
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### 31 **Concluding remarks**

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

### 3 **Compliance with Ethics Guidelines**

#### 4 **Conflict of Interest**

5 Kate Wilmut has nothing to disclose.

#### 6 **Human and Animal Rights and Informed Consent**

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

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