The Inability To Mentally Represent Action May Be Associated With Performance Deficits in Children With Developmental Coordination Disorder

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ABSTRACT

Several research studies indicate that children with developmental coordination disorder (DCD) show delays with an array of perceptual-motor skills. One of the explanations, based on limited research, is that these children have problems generating and/or monitoring a mental (action) representation of intended actions, termed the "internal modeling deficit" (IMD) hypothesis. According to the hypothesis, children with DCD have significant limitations in their ability to accurately generate and utilize internal models of motor planning and control. The focus of this review is on one of the methods used to examine action representation—motor imagery, which theorists argue provides a window into the process of action representation (e.g., Jeannerod, 2001. Neural simulation of action: A unifying mechanism for motor cognition. Neuroimage, 14, 103–108.). Included in the review are performance studies of typically developing and DCD children, and possible brain structures involved.

KEYWORDS: Action representation, developmental coordination disorder, internal modeling deficit, motor imagery

THE INABILITY TO MENTALLY REPRESENT ACTION MAY BE ASSOCIATED WITH PERFORMANCE DEFICITS IN CHILDREN WITH DEVELOPMENTAL COORDINATION DISORDER

A literature search of published work clearly indicates that the topic of developmental coordination disorder (DCD) has emerged as a vibrant line of inquiry over the last two decades. Wilson and Larkin (2008) point out that, not only has this research impacted thoughts on developmental disabilities in general, it also has stimulated the bonding of several relevant cross-disciplines to work on a single project. By definition, DCD is a term describing motor impairment in the absence of neurological disease, any known physical disorder, developmental delay, mental retardation, and low IQ (American Psychiatric Association, 2000). The movements of children with DCD are often described as clumsy and uncoordinated and lead to difficulties with performing many of the activities of daily living and sports that typically developing children perform easily. The prevalence of DCD has been estimated to be as high as 6% for children in the age range of 5–11 years (NIH, 2006); estimates range from 5% to 20% with at least 2% being affected severely. More recently, evidence has shown that a significant number of children will continue to have persistent difficulties into adulthood (Kirby, Edwards, Sugden, & Rosenbaum, 2010).

In regard to motor control, the literature indicates quite clearly that children with DCD display deficits with an array of perceptual-motor skills (Astill & Utley, 2006; Cherng, Liang, Chen, & Chen, 2009; Deconinck et al., 2006, 2008a; Tsai, Pan, Cherng, Hsu, & Chiu, 2009; Tsai, Wilson, & Wu, 2008). The present review and commentary focuses on the idea that an underlying problem may be a deficit in generating and/or monitoring an action representation termed the “internal modeling deficit” (IMD) hypothesis. According to the hypothesis, children with DCD have significant limitations in their ability to accurately generate and utilize internal models of motor planning and control. From another perspective, these children have deficits in their ability to mentally represent action—known as action representation. These representations, that
are associated with internal models, are hypothesized to be an integral part of action planning. Furthermore, there are indications that motor imagery (MI) provides a window into the process of action representation. This paper reviews the literature that highlights the notion that with DCD, there may be a significant deficit in the ability to mentally represent action. Included in the review are performance studies of typically developing and DCD children, and possible brain structures involved.

**ACTION REPRESENTATION**

Motor programming theory suggests that an integral component in an effective outcome is an adequate action representation of the movements. This view contends that action representation is a component of an internal forward model, which is a neural system that simulates the dynamic behavior of the body in relation to the environment (e.g., Wolpert, 1997; Wolpert & Kawato, 1998). This theory proposes that internal models make predictions (estimates) about the mapping of the self to parameters of the external world; processes that enable successful planning and execution of action. These representations are hypothesized to be an integral part of action planning (Caeyenbergs, Roon, Swinnen, & Smits-Engelsman, 2009; Choudhury, Charman, Bird, & Blakemore, 2007a, 2007b; Molina, Tijus, & Jouen, 2008; Skoura, Papaxanthis, Vinter, & Pozzo, 2005; Wolpert, 1997); Choudhury et al. and Molina et al. reference this idea to children. Skoura, Vinter, and Papaxanthis (2009) suggest that improvement in action representation in childhood may be due to refinement of internal models.

Complementing the forward model idea and central to the present discussion is the suggestion that MI provides a window into the process of action representation; that is, it reflects an internal action representation (Jeannerod, 1997, 2001; Munzert, Lorey, & Zentgraf, 2009).

**ACTION REPRESENTATION AND MI**

MI is defined as an internal rehearsal of movements from a first-person perspective without any overt physical movement. From another perspective, MI, also known as kinesthetic imagery, is an active cognitive process during which the representation of a specific action is internally reproduced in working memory without any overt motor output (Decety & Grezes, 1999). In addition to the reasonable case that MI is a reflection of action representation and motor planning, studies have found that there is a high correlation between real and simulated movements (e.g., Glover, Dixon, Castiello, & Rushworth, 2005; Heremans, Helsen, & Feys, 2007; Nikulin, Hohlfleld, Jacobs, & Curio, 2007; Michelon, Vettel, & Sachs, 2005; Sharma, Jones, Carpenter, & Baron, 2008; Young, Pratt, & Chau, 2009). Complementing those findings is the idea that motor control and motor simulation states are functionally equivalent (Jeannerod, 2001; Kunz, Creem-Regehr, & Thompson, 2009; Lorey et al., 2010; Munzert & Zentgraf, 2009). Also known as “simulation theory,” this idea postulates that mental (covert) and executed (overt) actions rely on similar motor representations. Such research has drawn the interest of (for example) clinicians working to stimulate neuromuscular pathways. For example, with stroke patients, injured athletes, and those with cerebral palsy, imagery is considered an attractive means to access the motor network and restore motor function without actual overt action. Also, a relatively large body of literature indicates that sport psychologists use mental rehearsal as a means to facilitate practice and improve performance in athletes (see reviews by Munzert, Lorey, & Zentgraf, 2009; Sharma et al., 2009; Steenbergen, Craje, Nilsen, & Gordon, 2009). Furthermore, evidence has been reported showing that MI follows the basic tenets of Fitts’ Law (Solodkin, Hustik, Chen, & Small, 2004; Stevens, 2005). That is, simulated movement duration like actual movement, decreases with increasing task complexity.

As opposed to visual imagery (VI), defined as the internal enactment or reenactment of perceptual experiences (Barsalou, 2008), neuroimaging and neuropsychological studies indicate that MI is more affected by biomechanical (kinesthetic) constraints, which are commonly associated with action processing (see review by Pelgrims, Andres, & Olivier, 2005; Stevens, 2005). The notion that MI elicits corticomotor excitability associated with action is supported by the work of Neuper, Scherer, and Pfurtscheller (2005), Stinear, Byblow, Steyvers, Levin, and Swinnen (2006), and Takahashi et al. (2005).

It has also been hypothesized that MI plays an important role in the prediction of one’s actions (e.g., Bourgeois & Coello, 2009; Kunz, Creem-Regehr, & Thompson, 2009; Lorey et al., 2010). Arguably, one of the important aspects of an action plan is the ability to predict the outcome and consequences of intended actions. Imagining an action can serve several useful goals to that endeavor. For example, during imagery important timing information is provided by the forward model which aids in predicting the sensory consequences of the movement. According to Bourgeois and Coello (2009), motor representation can be viewed as a component of a predictive system, which includes a neural process that simulates through MI the dynamic behavior of the body in relation to the environment.

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STUDIES OF TYPICALLY DEVELOPING CHILDREN

Studies of typically developing children indicate that the emergence of MI begins around age 5 (Funk, Brugger, & Wilkening, 2005; Gabbard, Cordova, & Ammar, 2007; Kosslyn, Margolis, Barrett, Goldknopt, & Daly, 1990) with considerable refinement in ability shown between early adolescence (12 years>) and early adulthood (Choudhury et al., 2007a, 2007b; Gabbard, 2009). As a general observation of studies involving a range of age, older populations perform better than younger groups (e.g., Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Molina, Tijus, & Jouen, 2008; Skoura, Vinter, & Papaxanthis, 2009). Furthermore, those findings suggest that the ability to mentally represent actions (i.e., action representations) follows a similar age-related trend.

Association With Brain Development

Work with typically developing children and adults suggests that there is a close link between development of the parietal cortex, action representation, and the ability to formulate internal models associated with MI; suggesting that both are refined throughout the adolescent years (e.g., Blakemore & Sirigu, 2003; Choudhury et al., 2007a, 2007b; Gerardin et al., 2000; Koscik, O’Leary, Moser, Andreasen, & Nopoulos, 2009; Lacourse, Orr, Cramer, & Cohen, 2005; Skoura, Vinter, & Papaxanthis, 2009). According to Skoura and colleagues (2009), one could also speculate that deficits in action representation in children could be related to the maturational processes in the parietal cortex. With increasing age, the maturational processes in parietal cortex increase neural efficiency and may aid older children (10 years>) to progressively improve their ability to generate accurate motor predictions. The researchers also brought attention to the idea, as others have noted, that we cannot rule out other factors, such as attention and the capacity to understand and follow task instructions, as influences on children’s MI performance.

Another aspect associated with the cognitive aspects of action representation is development of the prefrontal cortex (e.g., Skoura et al., 2009). That is, evolution of a general capacity to establish relations between data separated in space and time (Diamond, 2002). Molina, Tijus, and Jouen (2008) suggest that MI in children can be interpreted in terms of a general development of cognitive processes involved in motor representation principally determined by internal changes in the prefrontal and parietal structures of the brain.

Interestingly, the cerebellum, although not given the attention of the structures previously mentioned, has been associated with the ability to internalize representations, as noted in the internal (forward) model literature (e.g., Bastian, 2006; Blakemore, Frith, & Wolpert, 2001; Blakemore & Sirigu, 2003; Shadmehr & Krakauer, 2008). The general notion is that the cerebellum is presumed to be involved in motor prediction, a function of the internal model, and thus would be critical for action representation and processing. For example, activation of the cerebellum early in learning might correspond to the error signals between the predicted and actual outcomes of movements, which are used to refine the forward model’s predictions and guide acquisition of new internal models (Blakemore, Frith, & Wolpert, 2001). Some investigators suggest that the cerebellum acquires and stores internal models of the motor system (Miall, Weir, Wolpert, & Stein, 1993; Wolpert, Miall, & Kawato, 1998; Kawato, 1999; Imamizu et al., 2000). Support for these ideas is largely based on deficits in patients with cerebellar dysfunction or on functional imaging studies (Maschke, Gomez, Ebner, & Konczak, 2004; Smith & Shadmehr, 2005). Interestingly, Blakemore and Sirigu (2003) reported that both the parietal cortex and the cerebellum provide internal models of different nature. The researchers speculated that whereas a cerebellar internal model makes rapid predictions about the sensory consequences of self-generated movement at a very low level of movement execution, a model in the parietal cortex might address more cognitive aspects of movements. More specific to MI in children, Caeyenberghs and colleagues (2009) have suggested that the cerebellum plays an important role in the reduction of MI accuracy, since it is thought to encode internal models that reproduce the essential properties of action representations.

Children With DCD

As noted earlier, the literature presents a rather convincing case that children with DCD are likely to show an IMD (e.g., Deconinck, Spitaels, Fias, & Lenior, 2008b; Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Maruff, Wilson, Trebilco, & Currie, 1999; Pettit et al., 2008; Van Waelvelde et al., 2006; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Williams, Thomas, Maruff, & Wilson, 2008; Wilson et al., 2004). Those experiments used an array of (so-called) MI tasks and paradigms. For example, mental rotation involving the hand and whole-body, distance estimation with the effector (hand), and tasks involving the comparison (chronometry) of actual and simulated actions such as pointing, aiming, and walking; tasks that for the most part, have been reported as valid with adult populations. Typically, with the chronometry tactic, MI ability is judged by the closeness of the relationship (time) between simulated and actual movement. Similar to this
For example, Van Waelvelde and colleagues (2006) used a rhythmic finger-tapping task in combination with a jumping and a drawing activity to evaluate children with DCD and a matched control group. In children with DCD, an increased temporal variability was found with finger tapping when compared with a control group. Errors in time correlated significantly with the jumping and drawing task, while errors in space did not. It was concluded that children with DCD have more problems in building up an internal representation of the movement. The researchers went on to suggest that deficits in temporal movement parameterization might be one of the underlying causes of poor motor performance in some children with DCD.

Williams and colleagues (2006) also investigated the so-called IMD hypothesis using the mental rotation paradigm with typically developing children and a sample of children with DCD (ages 7–11). Results indicated partial support for the hypothesis that children with DCD would display an atypical pattern of performance on the hand rotation task, requiring implicit use of MI. Overall, there were no significant differences between the DCD and control groups when the hand task was completed without explicit instructions, on either response time or accuracy. However, when imagery instructions were introduced, the controls were significantly more accurate than the DCD group, indicating that children with DCD were unable to benefit from explicit cuing. In essence, the researchers found support for the IMD hypothesis with DCD children.

In a subsequent study, Williams, Thomas, Maruff, and Wilson (2008) examined MI ability in children with DCD aged 7–11 years with the intent to determine whether children with varying degrees of motor impairment differed in their ability to perform MI tasks. DCD children were split into two groups (DCD severe [DCD-S], DCD mild [DCD-M]) and compared to age-matched controls. Participants performed two MI tasks—hand (performed without and with specific imagery instructions) and whole-body rotation. Results indicated that children in the DCD-S group had a generalized MI deficit in that they were less accurate across tasks than controls (and the DCD-M group on the hand task) and showed little benefit when given specific imagery instructions. The DCD-M group appeared capable of performing simpler MI transformations, but was less successful as task complexity increased. Unlike the DCD-S group, the DCD-M group did show some benefit from specific imagery instructions with increases in accuracy on the hand task. The findings suggested that a MI deficit does exist in many children with DCD but that its degree can vary. That is, factors such as individual ability level and task complexity appear to be linked to the deficit.

In 2008, Lewis et al. examined movement durations for real and imagined movements in a visually guided pointing task in children aged 8–12 years old and (similar to previous studies noted) found that the DCD group demonstrated an inability to generate imagined movements that was not present in the typically developing participants. Deconinck and colleagues (2008b) investigated the IMD hypothesis with 9-year-old children with DCD using a mental (hand/letters) rotation paradigm. Results indicated that children with DCD were generally slower and made more errors than the typically developing control sample. The researchers concluded that both groups did use an imagery strategy; however, judgments of the DCD group seem to be compromised by a less well-defined internal model.

**IMD and Other Disabilities**

In addition to children with DCD, there are reports of children with other disabilities having exceptional difficulty in mentally representing action. For example, in their review of MI and children with hemiplegic cerebral palsy (CP), Steenbergen and colleagues (2009) noted that converging evidence indicates that motor deficits in those children are not only associated with execution, but also with impaired motor planning. For example, Mutssarts, Steenbergen, and Bekkering (2007) reported that a group of adolescents with CP displayed impaired MI, which they associated with that of anticipatory motor planning. The researchers did differentiate the side of CP impairment by observing that participants with left hemiparetic CP (right congenital brain damage) were less affected than those with right hemiparetic CP.

In 2009, Caeyenberghs, Swinnen, and Smits-Engelsman examined MI ability of children with acquired brain injury (ABI). The researchers used a chronometry, executed compared to imagined paradigm, to investigate the speed-accuracy trade-offs (or Fitts’ law) with an aiming task. Whereas performance of the control group conformed to Fitts’ law, in the ABI group, only executed movements aligned with Fitts’ law. Their conclusion was that children with ABI show an inferior ability to imagine the time needed to complete goal-directed movements.

Another piece of research that appears to hint at the notion of an IMD was reported by Van Roon, Caeyenberghs, Swinnen, and Smits-Engelsman (2010). Children with a learning disorder (LD) and matched controls were asked to smoothly track an accelerating dot by moving an electronic pen on a digitizer. The researchers were examining the children’s prospective motor control. That is, the ability to “predict future responses,” and from one perspective, create a forward (internal)
model. Results indicated that children with LD performed worse than controls. It was suggested that part of the problem was the inability to create an effective internal model. Interestingly, no differences in tracking performance were found between children with LD who scored in the normal range on the MABC (above the 15th percentile) and those who scored in the clinical range (below the 15th percentile).

Brain Deficits Associated With IMD

Obviously, some of the same structures noted with typical development children are relevant with DCD populations. Mentioned with DCD studies are: cortical areas involved in motor processing, such as the premotor area (plays a role in motor planning and sequencing and movement readiness), parietal cortex, and the dorsolateral prefrontal cortex, which are also associated with pre-motor planning (Deconinck et al., 2008b; Wilson et al., 2004).

In regard to the role of the cerebellum mentioned earlier, there are hints that this structure may have specific relevance to children with DCD. Whereas strong evidential support has not been established, some researchers have suggested that these children might have a cerebellar impairment that underscores the general disorder; the idea is described as the cerebellar hypothesis (e.g., Cantin, Polatajkso, Thach, & Jaglal, 2007; Geuze, 2005; Stoodley & Stein, 2009). One of the key arguments is that children with DCD typically display difficulty with the coordination of voluntary movements, including balance and equilibrium; problems that are associated with cerebellar function (Shumway-Cook & Woollacott, 2006; Slobounov, Hallett, Stanhope, & Shibasaki et, 2005). And, as noted earlier, the cerebellum has been associated with internal modeling and the ability to mentally represent action via MI. One key aspect related to internal modeling is that the cerebellum is thought to correct discrepancies between the intended movement and the actual movement through its connections with lower motor neurons and the motor cortex (Barlow, 2002). A problem with this process would theoretically account for inaccurate predictions of the motor plan. Speculatively, if children with DCD have a cerebellar impairment or, many would argue lack of maturity, it seems reasonable to predict difficulties with the ability to mentally represent action with tasks requiring coordination and postural control.

In general, most researchers agree that the deficits displayed by these children are the result of a general processing deficit of the motor system as a whole. For example, when information “flows” from the prefrontal to the motor cortex, DCD children, especially younger ones, may be forced to maintain a high level of preprogramming to compensate for difficulties in the perceptual-motor and executive aspects of the movement related to their coordination disorder (Castelnau, Albaret, Chaix, & Zanone, 2008).

CONSIDERATIONS (CAUTION) IN EXPERIMENTAL PARADIGMS

Underscoring the use of tasks for eliciting MI is the notion that it engages MI and that the child has the cognitive ability and attentiveness to understand and complete the task. Of these considerations (constraints), arguably the most debatable is the MI issue. For example, is the child engaging in VI, rather than MI? MI involves the first-person mental simulation of action that “focuses” on the effector (body part involved). An important point is the hypothesized distinction between MI and VI and its connection to the visual systems (dorsal/ventral substrates). Stevens (2005) contends that MI represents the kinesthetic and biomechanical constraints connected with action, associated with the dorsal stream, whereas VI is linked with the spatial component of the perceived environment via the ventral stream. Furthermore, MI elicits corticomotor excitability associated with action and several reports suggest that there is a high correlation between real movements and MI; neither of those observations is associated with VI (Solodkin et al., 2004; Stinear et al., 2006). VI relies heavily on connectivity patterns originating in the occipital areas, which supports the idea that this behavior may be classified as a visual task. Solodkin et al. add to the distinction by concluding that MI complements Fitts’ Law, whereas VI does not. Farahat, Ille, and Thon (2004) reported that the difference in duration of actual and imagined movement for learning to draw graph forms was much smaller when using kinesthetic (motor) imagery compared to VI.

A close review of the studies described here noted that very few indicated in the methodology specific instructions or training regarding the elicitation of MI. One exception stated, “participants were trained and asked to kinesthetically ‘feel’ themselves executing the movement (‘feel your arm extending…’)” (Gabbard, Cordova, & Ammar, 2007; Gabbard, Cordova, & Lee, 2009); a statement that suggests being more sensitive to the biomechanical constraints of the task (Johnson, Corballis, & Gazzaniga, 2001; Sirigu & Duhamel, 2001; Stevens, 2005). Obviously, without brain activity verification there is no way to really know the extent that MI or VI is processing. However, more specific instructions and training, especially with younger children would be better science and necessitate a summary in any scientific report.
CONCLUSIONS AND FINAL COMMENTS

There appears to be substantial evidence that in typically developing children and especially those with DCD (and other motor-related disorders), the inability to mentally represent action may be associated with deficits in motor planning. Primary brain structures and possible impairments or delayed development have focused on the parietal cortex, prefrontal cortex, and cerebellum. Furthermore, there appears to be a general processing deficit of the motor system associated with the flow of information from the prefrontal to the motor cortex. In regard to methodology used to examine action representation, caution should be taken in regard to use of motor (kinesthetic) imagery, rather than VI.

Obviously, further inquiry is needed and relevant research questions remain unclear. Two of the more frequent observations (and some would say criticism) addresses—is the delay displayed in children with DCD different from the developmental immaturity of typically developing children? And, could it be that children with DCD might be poor at using MI because they are clumsy not clumsy because they have poor MI ability? This line of inquiry also needs to include more aspects of both visual and MI (tasks). For example, a study that finds no difference between children with DCD and typically developing peers, may not provide evidence against the internal model deficit theory; only that the children with DCD were not impaired on this particular task. In addition, more specifically, what is/(are) the common neuropsychological deficit(s) among children with different impairments (CP, LD, and ABI) that identify them as having IMD? Perhaps additional studies of brain activity involvement will provide more insight.

In regard to the applied implications of this information, according to Williams et al. (2008), the applied significance relates foremost to teaching methods. Given that children with DCD may have difficulty in mentally representing movements, it is suggested that more kinesthetic approaches are used. That is, approaches to teaching motor skills that focus on “actual” bodily movement and touching to learn, as opposed to the predominant use of visual or verbal stimuli. These modalities reduce the reliance on internal models that are likely to be less than effective. In addition, it has been suggested that early training and movement experience with these children involve a strong emphasis on the development of body and spatial awareness. Underscoring this idea is the importance of a solid fundamental movement foundation with knowledge of what the body can do and how to do it.

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