An 18-month follow-up investigation of motor coordination and working memory in primary school children

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Abstract

The aim of the current study was to examine the relationship between motor coordination and visual working memory in children aged 5–11 years. Participants were 18 children with movement difficulty and 41 control children, assessed at baseline and following an 18-month time period. The McCarron Assessment of Neuromuscular Development provided a measure of motor skills and the CogState One-Back task was used to assess visual working memory. Multi-level mixed effects linear regressions were used to assess the relationship between fine motor skills, gross motor skills, and visual working memory. The results revealed that for children with movement difficulty, better fine motor skills at baseline significantly predicted greater One-Back accuracy and greater (i.e., faster) speed at 18-month follow-up. Conversely, fine motor skills at baseline did not predict One-Back accuracy and speed for control children. However, for both groups, greater One-Back accuracy at baseline predicted better fine and gross motor skills at follow-up. These findings have important implications for the assessment and treatment of children referred for motor difficulties and/or working memory difficulties.

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1. Introduction

It is now generally agreed that there is an important relationship between motor and cognitive development. Diamond (2000) argued that the two domains may be fundamentally interrelated and summarizes evidence from various developmental disorders and neuroimaging studies suggesting that the important relationship between motor and cognitive development is mediated by the close co-activation of the cerebellum and the prefrontal cortex. Research also supports parallel development for motor and cognitive processes as both show an accelerated developmental progression between ages 5 and 10 years (Anderson, 2002; Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002) as well as continued development into early adulthood (Diamond, 2000). Further evidence for the relationship between motor and cognitive development comes from studies involving individuals with deficits in either domain. For example, there is accumulating evidence that children with motor deficits such as Developmental Coordination Disorder (DCD) demonstrate difficulties in complex cognitive functioning, including executive functions (EF) (Alloway, 2007; Michel, Roethlisberger, Neuenschwan- der, & Roebers, 2011; Piek, Dyck, Francis, & Conwell, 2007).

Recently, a number of studies have shown an important relationship between motor skills and the EF domain of working memory (Alloway, 2007; Piek et al., 2007; Rigoli, Piek, Kane, & Oosterlaan, 2012), that is, the ability to store and manipulate information over a brief period of time (Baddeley & Hitch, 1974). Specifically, children with DCD have shown poorer performance on working memory tasks than both controls and children with Attention Deficit Hyperactivity Disorder (ADHD) (Piek et al., 2007). Alloway et al. demonstrated a deficit across both visuospatial and verbal working memory in children with DCD but have also suggested a more pronounced deficit in visuospatial memory (Alloway & Temple, 2007). These are concerning findings as working memory has been shown to be a reliable predictor of academic achievement including reading and mathematics skills (Alloway, 2007).

Given findings of a link between DCD and EF, such as working memory, it has been suggested that complex cognitive functions may be involved in the mastery of motor skills (Michel et al., 2011). Although there is a suggestion that EF affects motor performance, longitudinal studies are needed to facilitate causal inferences. Few longitudinal studies have provided evidence for the direction of the relationship between the cognitive and motor domains, although there is initial evidence that early motor development predicts later performance on complex cognitive tasks including working memory (Murray et al., 2006; Piek, Dawson, Smith, & Gasson, 2008; Ridler, Veijola, Tanskanen, et al., 2006). For example, Murray et al. found that early gross motor development, namely the age of learning to stand without support, was related to adult executive functioning such as working memory. Similarly, Piek et al. (2008) found a relationship between early gross motor (but not fine motor) development and later school-aged working memory ability. Thus, it has been proposed that the better the development of the neural systems involved with infant motor function, the better the development of more complex neural circuits involved in executive functions (Murray et al; Ridler et al.). However, these longitudinal studies did not control for baseline cognitive functioning.

A more recent study investigated the cross-sectional and longitudinal relationships between motor skills and spatial working memory in preschool children, while also controlling for potential confounding variables such as age, sex, and parental education (Niederer et al., 2011). Both motor and spatial working memory performance were measured at baseline and again 9 months later. It was found that baseline motor skills (specifically, dynamic balance) was associated with improvements in spatial working memory 9 month later, whereas baseline memory was not associated with an improvement in motor skills (Niederer et al.). Niederer et al. suggested that these results provide evidence that motor skills predict spatial working memory, but not vice versa.

Additional evidence for the predictive relationship from motor to cognitive functioning comes in several forms. First, research shows that sensory and motor regions of the brain are typically the first to mature (Casey et al., 2005). Second, there is also accumulating evidence that physical activity and high levels of aerobic fitness during childhood may enhance neurocognition, including working memory (Sibley & Etnier, 2003). These data provides indirect evidence that motor coordination may predict EF given the link between motor coordination and physical activity (Cairney et al., 2005). It has also been suggested, however, that complex cognitive and motor functions display an equally protracted developmental course continuing into early adulthood, with both the prefrontal cortex and cerebel-
lum reaching maturity quite late; this suggests that motor performance affects cognitive functioning and vice versa (Diamond, 2000). Notwithstanding this evidence, longitudinal research is needed to confirm the directional relationship between the motor and cognitive domains.

The current study employed an 18-month follow-up design to investigate the relationship between motor coordination and visual working memory in primary school-aged children with and without movement difficulty. This extends Niederer et al.’s (2011) 9-month follow-up study examining the relationship between spatial working memory and motor skills (namely, agility and dynamic balance) in a young preschool-aged sample. In addition, the current study examined the relationship between working memory and both fine and gross motor skills given that previous research has suggested specific associations between the different domains. For example, in a normative study involving 7-year-old children, a significant association was found between working memory and postural flexibility whereas none was found between working memory and a fine motor pegboard task (Roebers & Kauer, 2009). Piek et al. (2008) also found that early gross motor development, but not fine motor, was related to later working memory ability. These results suggest the possibility of specific relationships between working memory and certain aspects of motor coordination which may be explained by shared underlying neural processes.

A reciprocal relationship between motor skills and visual working memory was hypothesized, specifically, that motor skills would predict visual working memory performance and vice versa, in children with and without movement difficulty. In addition, it was predicted that gross motor skills would demonstrate a more important relationship with working memory than fine motor skills.

2. Method

2.1. Participants

A total of 195 children recruited from six primary schools across two Australian cities consented to the broader project investigating motor development in children. Inclusion for the current study was based on completeness of data for the main variables of interest. Exclusion criteria included known intellectual or physical disability, ADHD diagnosis, or any other persistent condition affecting development (e.g., pervasive developmental disorder) ascertained by a parent-rated developmental history questionnaire. Remaining participants included 161 children (73 male, 88 female) aged between 5 years, 7 months and 11 years, 4 months (Mean = 8.56, SD = 1.46) at baseline testing.

From the total sample, 18 children (11 boys and 7 girls) were identified as experiencing movement difficulty by scoring a Neuromuscular Developmental Index (NDI) at or below 75 (<5th percentile) on the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). Children who scored at or above 100 (i.e., 50th percentile) at baseline were included in the control group (14 boys and 27 girls). As the children were attending mainstream schools they were assumed to be of at least average intelligence.

2.2. Measures

2.2.1. McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997)

The MAND is an individually administered, norm-referenced assessment tool comprising ten tasks, five fine motor tasks and five gross motor tasks. The fine motor tasks include ‘Beads in a Box’ (right and left hand), ‘Beads on a Rod’ (eyes open and closed), ‘Finger Tapping’ (right and left hand), ‘Nut and Bolt’ (large and small bolt), and ‘Rod Slide’ (right and left hand). The gross motor tasks consist of ‘Hand Strength’ (right and left hand), ‘Finger–Nose–Finger’ (eyes open and closed), ‘Jumping’, ‘Heel–Toe–Walk’ (forward and backward), and ‘Standing on One Foot’ (eyes open and closed on each leg). Scores on each of the ten tasks are converted to scaled scores (Mean = 10, SD = 3). The sum of the ten scaled scores is converted to the Neuromuscular Developmental Index (NDI; Mean = 100, SD = 15), representing a measure of overall motor skills. For the current study, the sum of scaled scores for the fine and gross motor tasks were used to provide a measure of fine motor and gross motor skills respectively. Test–retest reliabilities amongst the ten individual tasks vary between .67 and .98 over a one-month interval (McCarron, 1997). The MAND has demonstrated good concurrent validity (Tan, Parker, & Larkin, 2001).
2.2.2. One-Back task—CogState Brief Battery (CogState Ltd., Melbourne, Australia)

The One-Back task assesses visual working memory and forms part of the CogState battery. CogState comprises a set of computer tasks adapted from standard neuropsychological tests which are designed to tap a range of information processing and attentional skills (e.g., psychomotor function, visual attention, executive function and memory). In the One-Back task, a single playing card is presented in the center of the screen. For each new card, participants must decide if the card is the same as the previous card and are instructed to respond as accurately and as quickly as possible. Responses are given by keystroke, ‘D’ for no and ‘K’ for yes, and an error beep is sounded for incorrect responses. Participants are given practice trials and once demonstrating an understanding of the task (i.e., successfully completing a sufficient number of practice trials), the formal trials are presented. For the current study, the accuracy (percentage of correct responses) and speed (reaction time) variables were used.

The CogState was specifically designed for repeated assessment of cognitive function, and Mollica, Maruff, Collie, and Vance (2005) found CogState to be an appropriate assessment battery for measuring cognitive change in children, with minimal practice effects. The CogState Battery has also demonstrated acceptable construct and criterion validity (Maruff et al., 2009).

2.3. Procedure

Ethical approval was granted by the Curtin University Human Research Ethics Committee and the RMIT University College Human Ethics Advisory Network. School principals were contacted by mail seeking permission to recruit participants via their school. Consenting schools distributed information packs to all students and written consent was provided by participants and their parents. Subsequently, participants were individually tested by a trained examiner at the school. The MAND and One-Back data from baseline testing and the 18-month follow-up were used for the current study. At each data collection point, measures were carried out over two or three sessions in order to avoid fatigue, with a total testing time of approximately 1–1.5 h. Order of presentation was randomized and it was ensured that distractions were kept to a minimum. Parents completed a developmental history questionnaire which provided information on exclusion criteria.

2.4. Data analysis

A series of multi-level mixed effects linear regressions (Bryk & Raudenbush, 1987; Dimitrov & Rumrill, 2003) were conducted to determine whether movement difficulty (movement difficulty versus control children) significantly moderated the cross-lagged correlations between measures of motor ability and measures of visual working memory. The regression model was ‘mixed’ in the sense that it included fixed effects (age, time [baseline, 18-month follow-up], group [movement difficulty, no movement difficulty], and Time × Group) as well as random effects (site, school, and student). The regression model was ‘multi-level’ in the sense that student was nested within school (6 levels), and school was nested within site (2 levels). The multi-level mixed effects (MLM) regression models were implemented through SPSS’s Generalized Linear Mixed Models (GLMM: SPSS Version 19). The model is ‘generalized’ in the sense that it can accommodate outcomes that are non-normally distributed. Four pairs of regression models were tested. The models are described in Table 2.

3. Results

3.1. Descriptives

Means, standard deviations and ranges for age and the MAND and One-Back variables at baseline (T1) and 18-month follow-up (T2) are presented in Table 1.
The cross lagged-correlations between T1 and T2 variables for children with movement difficulty ($n = 18$) and control children ($n = 41$) are reported in Tables 3 and 4 respectively. The pattern of significant correlations across the two groups strongly suggests that movement difficulty moderates the relationship between fine motor skills at T1 and One-Back accuracy at T2, and between fine motor skills at T1 and One-Back speed at T2. There is also a suggestion that movement difficulty moderates the relationship between One-Back speed at T1 and fine and gross motor skills at T2, and between One-Back accuracy at T1 and fine and gross motor skills at T2. Mixed effects linear regression analyses were subsequently conducted to determine whether the cross-lagged correlations were significantly moderated by movement difficulty.

The correlations between the T2 outcomes and age and gender are reported in Table 5. The only significant correlation was between age and One-Back speed, $r(N = 59) = -.596$, $p < .001$. Age should therefore be included as a covariate in regression models 2b and 4b. In order to facilitate comparisons across the full set of regression models, however, age was also included as a covariate in the other four regression models.
3.3. Multi-level mixed effects linear regression

All regression analyses controlled for the clustering of students within schools, and schools within sites. The results of the analyses are reported in Table 6. For both groups (movement difficulty and controls), greater One-Back accuracy at T1 predicted better fine motor skills at T2, $F(1, 54) = 6.35,$
p = .015, and better gross motor skills at T2, \( F(1, 54) = 7.32, p = .009 \). All other main effects for the continuous T1 predictors were either non-significant or varied as a function of group.

Consistent with earlier suggestions, movement difficulty moderated the relationship between fine motor skills at T1 and One-Back accuracy at T2, \( F(1, 54) = 9.50, p = .002 \), and between fine motor skills at T1 and One-Back speed at T2, \( F(1, 54) = 9.50, p = .002 \). The two-intercept model (Kenny, Kashy, & Cook, 2006) was used to ‘unpack’ these moderator effects. For the children with movement difficulty, better fine motor skills at T1 significantly predicted greater One-Back accuracy at T2, \( F(1, 55) = 18.13, p = .001 \); for the control children, however, fine motor skills at T1 did not predict One-Back accuracy at T2, \( F(1, 54) = 0.112, p = .739 \). For the children with movement difficulty, better fine motor skills at T1 significantly predicted greater (i.e., faster) One-Back speed at T2, \( F(1, 54) = 12.48, p = .001 \); for the control children, however, fine motor skills at T1 did not predict One-Back speed at T2, \( F(1, 54) = 0.259, p = .613 \).

### 4. Discussion

Studies employing normative samples (Piek et al., 2004; Roebers & Kauer, 2009) as well as those involving children with DCD (Alloway, 2007; Michel et al., 2011) have demonstrated an important association between motor development and cognitive functions such as working memory. However, research examining the direction of the relationship is limited (Niederer et al., 2011). The current study, involving primary school-aged children, investigated the relationship between motor skills and visual working memory over an 18-month period. Findings demonstrated that for children with movement difficulty, better fine motor (but not gross motor) skills at baseline significantly predicted greater One-Back accuracy and greater (i.e., faster) speed (i.e., reaction time) at 18-month follow-up.

<table>
<thead>
<tr>
<th>T2 outcome</th>
<th>T1 predictors</th>
<th>( F(1, 54) )</th>
<th>( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1a: fine motor</td>
<td>MD group</td>
<td>11.73</td>
<td>.001**</td>
</tr>
<tr>
<td></td>
<td>1 Back accuracy</td>
<td>6.35</td>
<td>.015*</td>
</tr>
<tr>
<td></td>
<td>Interaction</td>
<td>2.72</td>
<td>.105</td>
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<tr>
<td>Model 1b: 1 back accuracy</td>
<td>MD group</td>
<td>11.03</td>
<td>.002**</td>
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<tr>
<td></td>
<td>Fine motor</td>
<td>15.88</td>
<td>&lt;.001***</td>
</tr>
<tr>
<td></td>
<td>Interaction</td>
<td>17.97</td>
<td>&lt;.001***</td>
</tr>
<tr>
<td>Model 2a: fine motor</td>
<td>MD group</td>
<td>21.30</td>
<td>&lt;.001***</td>
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<td></td>
<td>1 back speed</td>
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<td>.359</td>
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<tr>
<td></td>
<td>Interaction</td>
<td>1.70</td>
<td>.197</td>
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<tr>
<td>Model 2b: 1 back speed</td>
<td>MD group</td>
<td>8.24</td>
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<td></td>
<td>Fine motor</td>
<td>18.09</td>
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<td></td>
<td>Interaction</td>
<td>14.17</td>
<td>&lt;.001***</td>
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<td>MD group</td>
<td>38.51</td>
<td>&lt;.001***</td>
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<td></td>
<td>1 back accuracy</td>
<td>7.32</td>
<td>.009***</td>
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<tr>
<td></td>
<td>Interaction</td>
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<tr>
<td>Model 3b: 1 back accuracy</td>
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<td></td>
<td>Gross motor</td>
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<tr>
<td></td>
<td>Interaction</td>
<td>2.04</td>
<td>.159</td>
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<tr>
<td>Model 4a: gross motor</td>
<td>MD group</td>
<td>46.64</td>
<td>&lt;.001***</td>
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<tr>
<td></td>
<td>1 back speed</td>
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<td>.379</td>
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<td>Interaction</td>
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<td>.130</td>
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<td>Model 4b: 1 back speed</td>
<td>MD group</td>
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<td></td>
<td>Gross motor</td>
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<tr>
<td></td>
<td>Interaction</td>
<td>1.25</td>
<td>.268</td>
</tr>
</tbody>
</table>

MD = movement difficulty.

* \( p < .05 \).

** \( p < .01 \).

*** \( p < .001 \).
Conversely, neither fine nor gross motor skills at baseline predicted One-back performance for control children. However, for both groups, greater One-Back accuracy at baseline predicted better fine and gross motor skills at follow-up. Consequently, a reciprocal relationship between fine motor skills and One-Back accuracy was suggested for the children with movement difficulty.

These results provide some support for the argument that motor and cognitive development (particularly executive functions) are fundamentally interrelated (Diamond, 2000; Koziol, Budding, & Chidekel, 2011). Perceptual and motor capacities develop first, but movement and cognitive functions then unfold through a process of continual sensorimotor learning under dynamic environmental conditions (Koziol et al.). As such, action and cognition coexist—goal-directed action comes to define the development of children over the school years and beyond. Taken a step further, Koziol et al. argue that cognition becomes almost subordinate to movement when behavior is automated; but executive functions are needed for novel and complex situations.

The current results also provide some support for previous findings that higher levels of motor skill predict better cognitive functioning (Murray et al., 2006; Piek et al., 2008; Ridler et al., 2006). Previous research has found infant motor development to predict school aged children’s cognitive functioning (specifically, processing speed and working memory) (Piek et al.) as well as adult executive functioning (Murray et al., 2006). It has been suggested that this predictive relationship may be understood in terms of common neural mechanisms (Murray et al., 2007). For example, there is evidence that adult brain volume in the frontal cortex, cerebellum, and basal ganglia regions is linearly related to the speed of infant motor development (Ridler et al., 2006) and aspects of cognition. Early maturation of basic neural circuits that underpin motor skill development may also facilitate frontal and subcortical networks and consequently cognitive function later in life (Murray et al., 2007).

Interestingly, however, in the current study motor skills (i.e., fine motor skills) predicted working memory in the children with movement difficulty but not in the control group. It is also important to acknowledge the role of individual experiences on the relationship between motor and cognitive development. For example, there is increasing evidence that children with motor difficulties withdraw from physical activity (Cairney et al., 2005) and the social environment (Smyth & Anderson, 2000). It is likely that reduced opportunity to practice in the physical and social domains will constrain the acquisition of motor and cognitive self-regulatory skills (Michel et al., 2011). In fact, there is now much evidence to show that increased physical activity enhances cognitive functioning (Tompsonowski, Davis, Miller, & Naglieri, 2008), benefits that are now better understood in terms of physiological and learning/developmental mechanisms (Sibley & Etnier, 2003). Taken together, there is strong evidence that movement is vital to cognitive development.

The results of this study also demonstrate a predictive relationship between fine motor skills and One-Back speed for children with movement difficulty (but not control children), supporting previous findings. Piek et al. (2007) found that children with DCD performed more slowly and had greater variability on a task measuring both working and behavioral inhibition, but did not produce more errors than the ADHD or control groups (Piek et al., 2007). The authors suggested that the poorer performance speed and variability found in these studies may be related to cerebellar processes (Piek et al., 2007). Michel et al. (2011) investigated the executive functions of inhibition and set-shifting, and also found that children with coordination difficulties were slower in performing inhibition and attention shifting tasks but did not produce more errors than the control group (Michel et al., 2011). It was argued that these results were unlikely to be entirely due to information-processing speed or due to the motor demand of the task as the children did not perform slower on a simple reaction task that required the same motor response. Furthermore, the motor demands were minimal. Michel et al. suggested that children with motor deficits have slower performance due to the complex demands of such tasks such as the speed-accuracy trade-off component requiring the need to react as fast and accurate as possible (Michel et al., 2011).

The results also provide support for the notion that working memory predicts motor skill performance. Children with DCD have shown working memory deficits (Alloway & Temple, 2007) as well as difficulties in other executive functions such as inhibition and set-shifting (Michel et al., 2011). However, the direction of causation has been difficult to establish. In the current study, accuracy on the One-back task predicted fine and gross motor performance for children with movement difficulty and control children. Conversely, Niederer et al. (2011) found that baseline dynamic balance was associated with
improvement in spatial working memory whereas baseline memory was not associated with any improvement in motor skills in preschool children after the 9-month period. However, there were several limitations to the study: it involved a short period of 9 months to examine the longitudinal changes, and included only two motor skill areas (namely, agility and dynamic balance). It is also plausible, however, that the nature of the relationship at this young age is different to that of older children; action acts as a control parameter for the development of cognitive functions in young children (like Piaget’s theory), but the relationship is more reciprocal in later childhood. Dyck, Piek, Kane, Hay, and Patrick (2009) found that the strength of association between motor and cognitive areas does vary with age which may reflect changes in the connectivity of neural systems. However, the cross-sectional nature of Dyck et al.’s study cannot exclude the possibility of cohort effects in their findings.

Finally, previous findings have suggested possible specific relationships between working memory and certain motor skill areas (Michel et al., 2011; Piek et al., 2008; Roebers & Kauer, 2009). For example, studies have suggested that gross motor areas may be more closely linked with cognitive functions (such as working memory) than fine motor areas (Piek et al., 2008; Roebers & Kauer, 2009). In the current study, however, fine motor (but not gross motor) performance was important in predicting working memory performance for the children with movement difficulty (but not for the control group). Conversely, working memory performance predicted fine and gross motor skills for both groups. Consequently, it appears that specific associations exist depending on the direction of the relationship and whether an individual experiences movement difficulties or not. Findings in the literature may also vary according to developmental level for example, gross motor development may have more predictive ability at very young ages. This highlights the need for future studies to examine these specific relationships further.

Although to our knowledge the current study is one of the few to investigate the predictive relationship between motor skills and executive function, the study has some limitations. The findings revealed an important association between the motor and visual working memory variables assessed. However, the study did not include a measure of verbal working memory nor did it investigate other executive function domains, such as inhibition and set-shifting. Consequently, future research can extend on these results by further examining cognitive areas which have previously shown to be linked with motor skills in cross-sectional studies (Alloway, 2007; Michel et al., 2011; Piek et al., 2004). It is also important to note that the One-back task may be considered a measure of storage rather than of the processing component of working memory. However, Unsworth and Engle (2007) have suggested that simple (i.e., short term memory) and complex (i.e., working memory) span tasks largely measure the same basic processes and therefore argue against the notion that short-term memory and working memory are different constructs. Furthermore, although participants of this study were attending mainstream schools and were excluded if they had previously been identified with an intellectual disability, the current study did not include a measure of IQ to control for general delayed development. Consequently, future studies may extend on the current results by employing different measures, controlling for other potentially confounding variables not assessed in the current study, and by investigating the longer-term longitudinal relationship between motor and cognitive domains.

5. Conclusion

The current results support previous findings of a close association between motor and cognitive development. Importantly, it was found that for children with movement difficulty, fine motor skills significantly predicted later One-Back accuracy and speed. Furthermore, for both movement difficulty and control groups, greater One-Back accuracy at baseline predicted better fine and gross motor skills following the 18-month period. These findings have important implications. For example, when a child has been referred for potential cognitive difficulties, it is important that their level of motor functioning is also considered. Similarly, if a child presents with movement difficulties, it may be important to assess their performance in cognitive areas such as working memory. The results also suggest that intervention in the motor domain may also support cognitive development and vice-versa. The important association found between motor skills and working memory also has practical implications given the strong predictive ability of working memory for academic functioning.
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References


