Motor coordination, working memory, and academic achievement in a normative adolescent sample: Testing a mediation model

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Abstract

The aim of the present study was to examine whether the relationship between motor coordination and academic achievement is mediated by working memory (WM) in a normative adolescent sample. Participants included 93 adolescents aged 12–16. The Movement Assessment Battery for Children-2 provided three indicators of motor coordination (Manual Dexterity, Aiming and Catching, and Balance), the WM Index of the Wechsler Intelligence Scale for Children-IV and the N-back paradigm provided two indicators of WM, and the Wechsler Individual Achievement Test-II provided three indicators of academic achievement (Word Reading, Spelling, and Numerical Operations). Structural equation modeling, controlling for verbal comprehension, attention deficit hyperactivity disorder symptoms, and socioeconomic status, suggested that the association between motor coordination and academic achievement may be best understood in terms of a mechanism whereby motor coordination (specifically, Aiming and Catching skills) has an indirect impact on academic outcomes via WM. These findings have important implications for the assessment and treatment of motor coordination and learning difficulties as well as in increasing the understanding of the possible neural mechanisms underpinning the relationship between these areas.

Keywords: Motor coordination; Working memory; Academic achievement; Adolescents; Normative sample

Introduction

There is extensive evidence linking motor coordination and learning outcomes. Research has shown that children with motor difficulties display significant problems in language, reading, spelling, and arithmetic (Alloway, 2007; Archibald & Alloway, 2008; Dewey, Kaplan, Crawford, & Wilson, 2002) and children with learning disabilities, such as dyslexia, have shown a high rate of motor difficulties (Fawcett & Nicholson, 1995). Furthermore, studies have found motor coordination in young children to be a unique, significant predictor of later achievement in reading and mathematics (Kurdek & Sinclair, 2001). Consequently, it has been argued that motor coordination may be crucial in identifying children at risk for academic underachievement (Son & Meisels, 2006), although the nature of this relationship remains unclear. Recent research, however, has suggested an important link between motor coordination, working memory (WM), and learning outcomes (Alloway, 2007).

WM refers to the ability to store and manipulate information over a brief period of time (Baddeley & Hitch, 1974). According to the widely used and accepted Baddeley (2000) model, WM comprises four components. The central executive controls resources and monitors information processing, as well as being responsible for various regulatory functions (Baddeley & Hitch, 1974). The central executive system is supported by separable components for the temporary storage of verbal (i.e., the phonological loop) and visuospatial (i.e., the visuospatial sketchpad) information. Finally, the episodic buffer is responsible for integrating information from the different components of WM and long-term memory (Baddeley, 2000). A substantial body of research now suggests that WM capacity is a reliable predictor of various cognitive skills

such as general fluid intelligence (Engle, Tuholski, Laughlin, & Conway, 1999) as well as academic skills such as reading and mathematics (Alloway, 2009) and language comprehension (Nation, Adams, Bowyer-Crane, & Snowling, 1999).

Recently, WM has been linked to motor coordination. For example, Piek and colleagues (2004) found that after controlling for age, gender, and verbal IQ, motor coordination was significantly associated with WM in children aged 6–15. In this study, motor coordination was operationalized by a composite score comprising both fine (e.g., beads in a box and nut and bolt activities) and gross (e.g., balancing on one foot, jumping) motor tasks. Therefore, differential relationships between WM and certain aspects of motor coordination were not examined. In a later study (Piek, Dyck, Francis, & Conwell, 2007), children with developmental coordination disorder (DCD) were slower than attention deficit hyperactivity disorder (ADHD) and control groups on the same WM task used in Piek and colleagues' (2004) study, but also performed less accurately on another measure of WM. DCD group composition was not known in this study, that is, the proportion of children experiencing mainly fine motor or gross motor difficulties, or a combination of both.

Conversely, in a study that identified "motor impaired" children by using a cutoff below the 10th percentile on the Movement Assessment Battery for Children (MABC) Manual Dexterity subscale (consisting of tasks such as threading, drawing, posting coins in a box, and pegboard), it was found that these children did not perform worse on a WM task of Backwards Color Recall when compared with those without motor impairments (Michel, Roethlisberger, Neuenschwander, & Roebers, 2011). Furthermore, correlations revealed that although the WM task was correlated with Manual Dexterity performance in the motor-impaired group (even after controlling for intelligence), interestingly, this association was not apparent in the control group (Michel et al., 2011). These results suggest the possibility of specific relationships between WM and certain aspects of motor coordination. For example, Manual Dexterity may not have an important association with WM.

In a normative study investigating the relationship between different aspects of motor coordination and cognitive control in 7-year-old children, a significant association was found between Backwards Color Recall and postural flexibility, whereas no significant association was found between Backwards Color Recall and a fine motor pegboard task (Roebers & Kauer, 2009). Longitudinal research examining the predictive ability of motor skills on later WM has also revealed an important relationship between gross motor skills and WM. Piek and colleagues (2008) found a relationship between early gross motor (but not fine motor) development (assessed by the parent-rated ages and stages questionnaire from 4 months to 4 years of age and includes items such as "does your child usually pick up a small toy with only one hand?" and "does your child climb onto furniture?") and later school-aged WM ability. In another study, Murray and colleagues (2006) found early gross motor development (i.e., age of learning to stand without support) to be related to adult executive functioning, including WM. Similarly, in relation to the link between academic outcomes and certain aspects of motor coordination, Gaysina, Maughan, and Richards (2010) did not find any significant association between fine motor skills and academic difficulties in the reading domain at age 15.

Evidence suggesting important links between certain aspects of motor coordination and outcomes of cognitive functioning (namely, WM and academic achievement) provides support for specific neural mechanisms underlying these relationships. The pyramidal motor system provides a direct pathway for projections from the motor areas of the cortex to go to the muscles via the spinal cord (Piek, 2006). The corticospinal tract forms part of the pyramidal system and consists of axons of cortical neurons which are concentrated in the primary motor cortex of the frontal lobe (Carlson, 2010). Axons of the lateral corticospinal tract form synapses with motor neurons which control muscles of the distal limbs that move arms, hands, and fingers. Thus, the lateral corticospinal tract is said to be important for Manual Dexterity (Carlson, 2010). Conversely, the indirect pathway for projections from the motor areas of the cortex involves the structures of the extrapyramidal system such as the cerebellum (Piek, 2006). The cerebellum is crucial for motor control as it is associated with functions such as timing, motor learning, and regulation of muscle tone which are important for smooth and coordinated movement (Piek, 2006). Furthermore, certain parts of the cerebellum are said to be associated with specific aspects of motor control, for example, the vermis has been linked to postural reflexes (important for balance), whereas the lateral zone of the cerebellum has been linked to the control of independent limb movements particularly rapid, skilled movements (Carlson, 2010) such as Aiming and Catching skills.

Diamond (2000) highlighted the important role of the cerebellum (specifically, the lateral portion of the cerebellum, namely, the neocerebellum) not only in subserving motor function but also in cognitive functioning. Nicolson and colleagues (2001) propose a cerebellar deficit hypothesis when attempting to explain the reading and motor problems often seen in children with dyslexia. In addition to their observed motor deficits (e.g., balance and muscle tone problems), these children have also demonstrated difficulties with time estimation and skill automatization, pointing to a deficit of the cerebellum. Nicolson and colleagues also provide direct evidence for this theory through imaging studies. In fact, Rae and colleagues' (1998) study of metabolic abnormalities in developmental dyslexia provided evidence for lateral cerebellum involvement in dyslexic dysfunction.

In Nicolson and colleagues' model (2001), it is argued that the cerebellum contributes to cognitive processes that rely on internal speech, namely, verbal short-term memory or WM. According to Baddeley (2003), articulatory rehearsal mechanisms are important to retain verbal items in store. Nicolson and colleagues' cerebellar deficit hypothesis proposes that articulation

difficulties, resulting from the mild motor difficulties of cerebellar dysfunction, then lead to verbal short-term or WM difficulties, through its impact on subvocal rehearsal. It is further suggested that the resulting problems of cerebellar dysfunction, namely, difficulties in automation of skills and production of inner speech, then lead to deficits in automating word recognition processes and in phonological awareness (Nicolson et al., 2001), thus providing a framework for the involvement of the cerebellum in reading difficulties, as well as in WM.

Other studies have also implicated the cerebellum in WM (Ravizza, McCormick, Schlerf, Justus, & Ivry, 2006) and other academic areas such as mathematics (Feng, Fan, Yu, Lu, &Tang, 2008). Consequently, it appears that the cerebellum may play an important role when understanding the relationships found between specific aspects of motor coordination and cognitive areas such as WM and academic achievement. Evidence for the close co-activation of the cerebellum and prefrontal cortex (which has a well-established role in complex cognitive functions such as WM) in functional neuroimaging (Diamond, 2000) provides further evidence for a relationship between motor coordination and cognitive outcomes including WM.

Ultimately, in light of the increasing evidence of a link between motor coordination and cognitive outcomes such as WM and academic achievement, what role does WM play in the relationship between motor coordination and academic achievement? Alloway (2007) separated a DCD sample based on high and low visuospatial memory ability scores (averaged across short-term and WM tasks) and found that the low visuospatial memory ability group performed significantly worse on literacy and numeracy compared with the high visuospatial memory group. This finding remained after controlling for Vocabulary and Block Design (a nonverbal IQ task involving a motor component) scores, suggesting that the link between visuospatial memory and learning outcomes in children with DCD can be explained by more than just general ability and the motor components of such visuospatial memory tasks (Alloway, 2007). Thus, it is possible that the combined storage and processing component of the memory tasks is important when understanding how memory and learning outcomes are linked in children with DCD.

This is further supported by a recent intervention study involving children with DCD and comorbid learning difficulties (Alloway & Warner, 2008). Following the 13-week program of task-specific motor exercises, motor coordination and visuospatial WM showed improvement, but there was no improvement in verbal WM or reading and math scores. First, the results suggest that motor coordination may be more important in predicting visuospatial WM than verbal WM which is not surprising given that visuospatial processing (with or without a motor component) was found to be the greatest deficit in a meta-analysis examining the information processing deficits characterizing DCD (Wilson & McKenzie, 1998). The improvement in visuospatial WM in Alloway and Warner's intervention study may be understood in terms of the movement planning and control components of such visuospatial WM tasks, which can be improved by movement training. However, given that neither verbal WM nor reading and mathematics scores improved, this may suggest that it is the processing and storage component of the memory tasks (which is dissociable from the motor component) that influences learning outcomes in children with DCD (Alloway & Warner, 2008). Therefore, such findings suggest that motor coordination is not directly related to learning outcomes rather, the relationship may be mediated by the ability to simultaneously process and store information (i.e., WM ability).

Although preliminary evidence provides important insights into the relationship between motor coordination, WM, and learning outcomes, a number of issues need to be addressed. First, the present study controls for the confounding influence of ADHD symptomatology. This is important given that ADHD has been linked to motor problems (Pitcher, Piek, & Hay, 2003), WM (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005), and learning outcomes (Semrud-Clikeman et al., 1992). Also, previous research investigating motor coordination, WM, and academic outcomes has involved atypical population groups. Therefore, further investigation using a normative population is needed. It has been noted that correlational studies using normative samples are important in order to provide a better understanding of relationships found in children with DCD (Roebers & Kauer, 2009). This is important given the methodological problems associated with the use of clinical samples, for example, overestimating associations between domains (Roebers & Kauer, 2009). In addition, research in the area has involved younger samples aged 5–11 (e.g., Alloway & Warner, 2008). Thus, it is important to examine whether these findings extend to an adolescent population, particularly since recent findings have demonstrated how relationships between ability domains differ across age cohorts of 3–14 years of age (Dyck, Piek, Kane, & Patrick, 2009) and that the dimensional structure of executive functions also appears to undergo developmental changes, with the underlying processes being less distinguishable in the earlier years (Miyake et al., 2000).

The present study examined a mediating model of the relationship between motor coordination, WM, and academic achievement in adolescents from a normative sample whilst controlling for potentially confounding factors such ADHD symptoms, verbal ability, socioeconomic status (SES), age, and gender. It was hypothesized that motor coordination (as measured by Manual Dexterity, Aiming and Catching, and Balance) would have a positive direct effect on academic achievement (as measured by Numerical Operations, Word Reading, and Spelling); motor coordination would have a positive effect on WM (as measured by verbal and visuospatial WM) through a direct path; WM would have a positive direct effect on academic
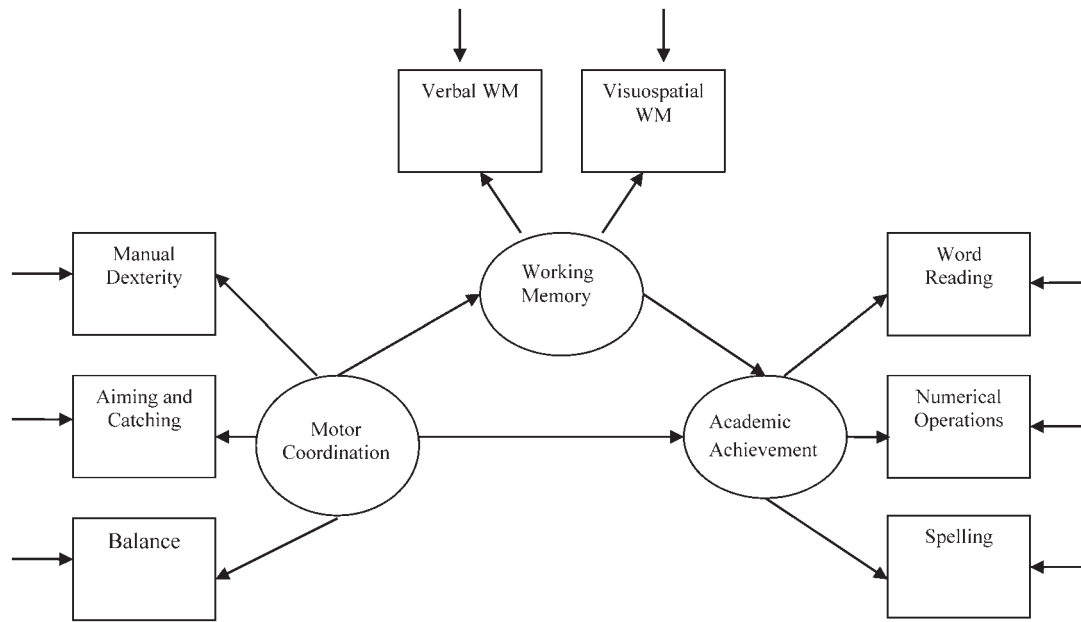
Fig. 1. Diagrammatic representation of the proposed mediating model.

achievement; and motor coordination would have a positive effect on academic achievement through an indirect path with WM mediating this relationship. Fig. 1 provides a diagrammatic representation of the proposed mediating model.

Finally, the directional nature of the relationship between motor and cognitive domains remains unclear given the very few longitudinal studies in the area (Murray et al., 2006; Piek, Dawson, Smith, & Gasson, 2008). Studies have provided initial evidence that motor coordination predicts performance on complex cognitive tasks including WM (Murray et al., 2006; Piek et al., 2008). However, given that complex cognitive and motor development display equally protracted developmental courses continuing into early adulthood and both the prefrontal cortex and cerebellum reach maturity late (Diamond, 2000), this may suggest that motor performance affects cognitive functioning and vice versa. Therefore, the current study also investigated an alternative model whereby the meditational role of motor coordination in the relationship between WM and academic achievement was examined. It is also important to note that the present correlational data cannot, of course, be used to establish cause-and-effect relationships. Therefore, the aim of the study was to determine the degree to which the proposed causal model had the capacity to generate our correlational data.

Method

Participants

Sixty government, private, and independent secondary schools were randomly selected from available lists. These schools were from varying areas of SES, in order to ensure a representative sample of the population. From these schools, five schools (representing these various school groups) consented to promote the project. Participants were also recruited through public advertisements in community newspapers, radio, and snowballing (i.e., existing participants recruit future participants through their associations). Inclusion criteria for the study were adolescents aged 12–16. Exclusion criteria included a minimum Verbal Comprehension Index (VCI) of 80 as measured by the Wechsler Intelligence Scale for Children-IV (WISC-IV) in order to exclude any adolescent whose difficulties might be attributed to general delayed development (Henderson & Barnett, 1998; Piek et al., 2004), as well as no presence of a physical disability, chronic illness, or a medical condition that affects development (such as neurological disorder and Down syndrome, ascertained by a parent report). The final sample included 93 adolescents, 38 girls and 55 boys, with a mean age of 14.2 ($SD = 1.1$). The SES scores were derived from the Australian Prestige Scale (Daniel, 1983) which rates the prestige of occupations in Australia, with scores ranging from 1 (reflecting high prestige) to 6.9 (reflecting low prestige). The occupation rated as most prestigious out of mother's and father's occupation was used as the SES score ($M = 3.77$, $SD = 1.00$, range = 1.80–6.60).

Measures

Movement Assessment Battery for Children-2. The three subscales from the MABC-2 (Henderson, Sugden, & Barnett, 2007) were utilized to provide the observed variables for the construct motor coordination. The MABC-2 is a standardized test used for the identification and description of children with movement difficulties. It consists of tasks suitable for three age bands (i.e., age band 3–6, 7–10, and 11–16 years) and tasks are grouped into the subscales: Manual Dexterity, Aiming and Catching, and Balance. For the 11–16 years age band, Manual Dexterity comprises three tasks including turning pegs with preferred and non-preferred hand, a bimanual task to make a triangle with nuts and bolts, and a drawing trail. The Ball Skill tasks include aiming and throwing at a wall target, and catching a ball with one hand. The Balance subscale involves a two-board balance task, walking toe-to-heel backwards, and a zigzag hopping task. Age-based standard scores are derived for the three subscales ($M = 10$, $SD = 3$) and for the Total Test Score (TTS; $M = 10$, $SD = 3$). A TTS of 67 (equivalent to a standard score of 7 on the MABC-2) and above (i.e., >15th percentile) suggests no evidence of movement difficulty, a score between 57 and 67 (6–15th percentile) suggests that the child is "at risk" of having a movement difficulty, and a TTS up to and including 56 (i.e., equivalent to a TTS standard score from 1 to 5) indicates significant movement difficulty (≤5th percentile). The age-standardized Manual Dexterity, Aiming and Catching, and Balance subscale scores were used for the purposes of this study.

The original MABC (Henderson & Sugden, 1992) is well established as a research tool and has favorable psychometric properties (Henderson et al., 2007). Reliability coefficients range from 0.73 to 0.84 for the subscale scores and 0.80 for the MABC-2 TTS. There is also evidence demonstrating criterion-related and discriminative validity (Henderson et al., 2007). Schulz and colleagues (2011) provided recent evidence for the structural validity (i.e., factor structure) of the MABC-2 across the three age-bands. Based on their findings in a large normative sample, the authors also noted that confidence in the structural validity of the three MABC-2 components becomes stronger for older children (i.e., age band 11–16 years).

Wechsler Individual Achievement Test-II. The Wechsler Individual Achievement Test-II (WIAT-II) Australian (Wechsler, 2007) is an individually administered test of achievement in individuals aged 4–85, assessing academic skills in the domains of reading, writing, mathematics, and oral language. In the present study, the age-standardized Word Reading, Spelling, and Numerical Operations subtest scores ($M = 100$, $SD = 15$) were used to provide observed variables for the construct academic achievement. These academic areas were chosen because they comprise essential aspects of academic achievement and have been examined previously in studies investigating the relationship between motor, WM, and academic outcomes (e.g., Alloway, 2007). The Word Reading subtest involves reading aloud from a graded word list. Numerical Operations assesses the ability to solve written calculation problems and simple equations involving the basic operations of addition, subtraction, multiplication, and division. The Spelling subtest assesses the ability to spell dictated words.

The WIAT-Australian has demonstrated an overall total composite reliability of 0.98, and test–retest reliabilities varying from 0.80 to 0.96 for subtests (Wechsler, 2007). The WIAT-II Australian also has good content, construct, and criterion-related validity (Wechsler, 2007).

WISC-IV: Australian. The WISC-IV (Wechsler, 2003) measures cognitive ability in children aged 6 to 16 years 11 months. The 10 core subtests yield a Full-Scale IQ and are organized to yield four composite scores ($M = 100$, $SD = 15$), namely: VCI, Perceptual Reasoning Index, WM Index (WMI), and Processing Speed Index. For the purposes of this study, the VCI was used as a control variable and to exclude any adolescent whose difficulties might be attributed to general delayed development. The age-standardized WMI score (comprising digit span and letter-number-sequencing (LNS) subtests to assess verbal WM) was used to provide an observed measurement for the construct, WM. The WISC-IV is a widely used measure of intelligence in children and has excellent internal consistency, test–retest reliability, criterion validity, and construct validity (Wechsler, 2003).

N-back task. The N-back task assesses visuospatial WM and was used to provide the second observed variable for the construct WM. This task involves a visuospatial variant of the N-back task, designed after Gevins and Cutillo (1993) and Jansma and colleagues (2000), and has been adapted to make it more attractive and appropriate for children (van Leeuwen, van den Berg, Hoesktra, & Boomsma, 2007). An apple is presented on the computer screen which has four holes from which a caterpillar appears. Respondents are instructed to stop the caterpillar from eating the apple by pressing one of the four buttons that corresponds spatially with the hole the caterpillar appeared from. There are four conditions of graded difficulty in which respondents are required to indicate where the caterpillar was one move back, two moves back, three moves back, or four moves back, respectively. The caterpillar appears on the screen for 1 s and is then followed by a warning tone which prompts children to respond. Each condition consists of a practice block (10 trials) and a block in which performance

is measured (32 trials). The task was discontinued if participants performed below chance levels, that is, 8 or less correct trials on a condition. Task performance was measured by the total number of correct responses on all trials administered (maximum score of 128 correct responses over the four conditions), with higher scores indicating better visuospatial WM thereby capturing the full dimension of visuospatial WM performance. For the purposes of the present study, the raw score of total number of correct responses was converted to a *z*-score. The N-back task is a widely used measure of WM and in a study examining a sample of adolescents with the current version of the N-back task, test–retest (carried out 2–3 weeks after initial assessment) reliabilities of 0.70 and 0.66 were reported for the 3- and 4- back conditions, respectively (van Leeuwen et al., 2007). For such tasks measuring specific abilities, it has been noted that reliabilities of 0.7 or higher are considered satisfactory, whereas reliabilities of 0.5 and 0.6 may be considered as modest (Kuntsi, Stevenson, Oosterlaan, & Sonuga-Barke, 2001; van Leeuwen et al., 2007).

Strengths and weaknesses of ADHD symptoms and normal behavior. The parent-rated strengths and weaknesses of ADHD symptoms and normal behavior (SWAN) scale (Swanson et al., 2001) is based on the ADHD symptoms listed in the Diagnostic and Statistical Manual of Mental Disorders-IV and involves observations based on the last month with reference to other children of the same age. The first nine items of the scale describe symptoms relating to inattention, while the second nine items relate to hyperactive/impulsive behaviors. Items are phrased in order to sample the full dimension of a particular behavior. An example of an item is: "How does this child pay attention to detail?" Scoring for each item ranges from "far below average" (scored as +3) to "average" (scored as 0), and "far above average" (scored as −3) in order to reflect both strengths and weaknesses. An overall SWAN score was calculated by averaging the scores on the 18 items. For the present study, the raw overall SWAN score was converted to a *z*-score. Hay and colleagues (2007) found the SWAN to be an accurate reflection of the ADHD phenotype, and Polderman and colleagues (2007) found that the SWAN rating scale yields a normal distribution of scores, making it a useful instrument for examining variation of (hyper) activity and attention in the general population. The Cronbach α for current study was 0.97, demonstrating excellent internal reliability.

Australian Prestige Scale. Daniel's Prestige Scale (Daniel, 1983) rates occupational status on a scale of 1 (representing higher prestige) to 6.9 (representing lower prestige). High prestige occupations reflect power and privilege and require educational qualifications as well as high earning capacity. The occupation of "housewife," "student," or "unemployed" has no code on the scale. Occupational prestige based on parental occupation was coded as a continuous score and was used as an indicator of SES in the current study. When both parents were working, the most prestigious occupation was used. Daniel's scale has been widely used in health and social research (Smith, Owen, & Baghurst, 1997).

Procedure

This study followed the ethical guidelines of the National Health and Medical Research Council of Australia and was granted approval from the Curtin University Human Research Ethics Committee and from the representative bodies for the participating schools. Principals were contacted by mail seeking permission to recruit via their school and the project was then promoted in school newsletters. Interested adolescents and their parents provided written consent for participation. Participants were individually tested by a single trained examiner using standardized instructions. Testing time was 4.5 h which was broken into two sessions, with the MABC-2 and WISC-IV (respectively) administered in the first session and the WIAT-II and N-back (respectively) administered in the second session. Parents completed the SWAN questionnaire. Testing sessions were carried out at the family home or Curtin University, depending upon family preference. Most sessions occurred at the family home; however, it was ensured that distractions in both settings were kept to a minimum.

Data Analysis

Structural equation modeling (SEM), with maximum likelihood estimation, was used to determine the degree to which WM mediates the relationship between motor coordination and academic achievement. The analysis was implemented through LISREL (Version 8.54; Jöreskog, & Sörbom, 2004). For relatively simple models such as our one-mediator model, sample sizes between 100 and 150 have been recommended (Hair, Black, Babin, Anderson, & Tatham, 2006). Our current sample size of 93 falls just short of this recommendation, but should still be sufficient to provide stable estimates of the path coefficients. Furthermore, a sample size of 93 provides approximately seven participants for each parameter in the saturated model, which exceeds the minimum requirement of five participants per parameter recommended by Kline (2005). The assumption of multivariate normality was met.

Results

Descriptives

Table 1 provides the means, standard deviations, and ranges for the variables measuring motor coordination, WM, and academic achievement.

Five adolescents scored at or below the 5th percentile on the MABC-2 total score (indicating significant movement difficulty) and two scored between the 6th and 15th percentile (regarded as "at risk"). The prevalence of significant movement difficulty (≤5th percentile) was 5.4%, which is comparable with previous estimates of 6% (APA, 2000). The numbers of adolescents scoring below the 25th percentile (Shafrir & Siegal, 1994) on the Word Reading, Numerical Operations, and Spelling subtests of the WIAT-II were 7, 12, and 5, respectively. Two participants with significant movement difficulty (≤5th percentile) also demonstrated learning difficulties (≤25th percentile on the WIAT-II). One participant demonstrated Spelling and Numerical Operations difficulties, and the other, Word Reading and Numerical Operations difficulties.

Correlations

Potential control variables included, age, gender, SES, ADHD symptoms, and VCI. All indicators, except for the N-back task (z-score), are represented by age-standardized scores. Given that no significant correlation was found between the N-back task and age ($r = .15$, $p = .151$), age was not retained as a control variable. The VCI, SWAN, and SES variables significantly correlated with indicators of WM and/or academic achievement and were thus retained as control variables. A covariance structure analysis was conducted to determine whether the partial correlations among the eight indicators (after controlling for SES, ADHD symptoms, and VCI) varied as a function of gender. As they did not, gender was ignored in all further analyses of these partial correlations, $\chi^2 (36) = 35.03$, $p = .51$.

Indicators that are "driven" by the same latent construct will necessarily correlate. In the present study, however, two of the MABC-2 subscales—Manual Dexterity and Aiming and Catching—were not significantly correlated and therefore could not appear in the same model as indicators of the same latent construct. It was therefore decided to test three separate mediator models; one for each of the three MABC-2 subscales (namely, Manual Dexterity, Aiming and Catching, and Balance). An important correlational assumption underlying mediation states that the independent variable (motor coordination as measured by each of the three MABC-2 subscales) must be significantly correlated with both the mediator (WM) and the outcome variable (academic achievement). The model using Aiming and Catching satisfied all correlational assumptions described above and, thus, met this underlying premise to mediation testing (Baron & Kenny, 1986). However, the models with Manual

Table 1. Means, standard deviations (*SD*), and range of scores

	Mean	SD	Range
MABC-2 Manual Dexterity[a]	9.57	2.47	3.0–15.0
MABC-2 Aiming and Catching[a]	11.03	2.73	4.0–16.0
MABC-2 Balance[a]	11.42	2.98	4.0–14.0
WISC-IV Working Memory Index[a]	103.75	12.47	59.0–141.0
N-back[b,c]	88.17	19.69	6.0–124.0
Z N-back[d]	0.00	1.00	−4.17 to 1.82
WIAT-II Word Reading[a]	107.44	10.62	77.0–128.0
WIAT-II Numerical Operations[a]	106.85	14.73	63.0–139.0
WIAT-II Spelling[a]	107.19	11.68	67.0–129.0
SWAN[b,e]	−0.9989	1.02	−3.0 to 1.22
ZSWAN[d]	0.00	1.00	−1.95 to 2.16
WISC-IV Verbal Comprehension Index[a]	106.63	11.25	81.0–132.0
SES[f]	3.77	1.00	1.80–6.60

Notes: MABC-2 = Movement Assessment Battery for Children-2; WISC-IV = Wechsler Intelligence Scale for Children-IV; WIAT-II = Wechsler Individual Achievement Test-II; SWAN = Strengths and weaknesses of ADHD symptoms and normal behavior.
[a]Age-standardized score.
[b]Raw score.
[c]Total number of correct responses.
[d]z-score.
[e]Scores are calculated by averaging the total of the 18 ADHD items.
[f]The occupation rated as most prestigious out of mothers' and father's occupation.

Dexterity and Balance did not satisfy these assumptions, leading to the immediate rejection of these models. The measurement error associated with the Aiming and Catching subscale was fixed at one minus its reliability coefficient, and its factor loading was fixed at the square root of its reliability coefficient (*see* Goodwin & Plaze, 2000, p. 286).

Finally, Spelling was removed because, unlike Word Reading and Numerical Operations, it did not correlate with motor coordination, and its inclusion rendered the pathway between motor coordination and academic achievement non-significant (Table 2).

LISREL Analysis

Pearson's correlations (controlling for ADHD symptoms, VCI, and SES) were input to LISREL for structural equation modeling. The parameter estimates and standard errors for the saturated model are given in Fig. 2. The path from motor coordination to academic achievement was not significant. The hypothesis that motor coordination would have a direct impact on academic achievement in this model was therefore not supported. All other hypotheses were supported. Specifically, the path from motor coordination to WM was significant, as was the path from WM to academic achievement. This indirect pathway was significant ($p = .003$), indicating that motor coordination has an indirect effect on academic achievement through WM.

Fit indices providing an indication of the overall fit of the model can be found in Table 3. The fit statistics for this model suggest a good fit to the data—$\chi^2(3) = 5.12$, $p = .16$; a non-significant χ^2 value ($p \geq .05$; Kline, 2005); the χ^2/df ratio is below 2 (Kline); the Comparative Fit Index is >0.90 (Kline, 2005); and the Standardized Root Mean Square Residual is <0.10 (Kline, 2005). Although the Root Square Mean Square Error of Approximation for the saturated model is above the desired 0.05 level and above the more liberal cutoff of 0.08 (i.e., 0.092), Tabachnick and Fidell (2001) note that this index may be less preferable with smaller samples due to the tendency to over-reject the true model. Overall, the results indicate good data-model fit.

The test of the saturated model indicated that, when WM is controlled, the magnitude of the path coefficient for the direct pathway from motor coordination to academic achievement is trivial. The direct pathway can therefore be dropped from the model without significantly reducing model fit—$\chi^2_{\text{diff}}(1) = 0.00$, $p = .99$) or changing parameter estimates (Fig. 3). The more parsimonious mediator model was therefore selected. The fit indices for the mediator model are reported in Table 3; the parameter estimates for the mediator model are given in Fig. 3.

There is a plausible alternative model in which motor coordination mediates the impact of WM on academic achievement. The previous analysis, however, indicated that the pathway from motor coordination to academic achievement is non-significant. According to our data, therefore, the alternative model is not viable.

Finally, in the proposed measurement model for the current study, all four N-back conditions (i.e., 1-back to 4-back) are presumed to load on a visuospatial WM factor, while the digit-span forward (DSF), digit-span backward (DSB), and LNS tasks from WISC-IV WMI are presumed to load on a verbal WM factor. Previous research has argued for separation of short-term memory and WM (e.g., Baddeley, 2000; Kail & Hall, 2001), which suggests a plausible alternative measurement model for the data in which three of the N-back conditions (2-back, 3-back, and 4-back), the DSB, and LNS tasks load on a WM factor, while the 1-back and DSF measures load on a short-term memory factor. Confirmatory factor analyses was conducted to compare the alternative measurement model (in which 2-back to 4-back, DSB, and LNS load on WM; while 1-back and DSF load on short-term memory) with the proposed measurement model (in which 1–4-backs load on visuospatial WM, while DSF, DSB, and LNS load on verbal WM). A comparison of the fit statistics (Table 4) indicated that the proposed model provides the better fit. These results are in line with previous research, suggesting that simple (i.e., Short-Term Memory [STM]) and complex (i.e., WM) span tasks largely measure the same basic processes and also have correlations with higher order cognitive abilities that are similar in magnitude (Unsworth & Engle, 2007). Unsworth and Engle argue against the notion that STM and WM are different constructs.

Discussion

Research supporting the relationship between motor coordination and academic achievement has accumulated without any clear understanding of the nature of this relationship. The aim of the current study was to advance this understanding. The results indicate that, after controlling for VCI, ADHD symptoms, and SES, WM (verbal and visuospatial WM) mediated the relationship between motor coordination (specifically, MABC-2 Aiming and Catching) and academic achievement (specifically, Word Reading and Numerical Operations). In SEM terms, motor coordination did not have a direct impact on academic achievement; instead, it impacted on academic achievement via WM.

There is extensive evidence demonstrating WM as a reliable predictor of a range of cognitive skills and academic areas, including reading and mathematics (Alloway, 2009). The current study adds to these findings by revealing a very strong

Table 2. Zero-order correlation matrix for the key and control variables

	MABC-2 Manual Dexterity	MABC-2 Aiming and Catching	MABC-2 Balance	WISC-IV WMI	ZN-back	WIAT-II Word Reading	WIAT-II Numerical Operations	WIAT-II Spelling	Gender	VCI	SES	ZSWAN
MABC-2 Manual Dexterity[a]	1.00											
MABC-2 Aiming and Catching[a]	.071	1.00										
MABC-2 Balance[a]	.264*	.423**	1.00									
WISC-IV WMI[a]	.113	.251*	.122	1.00								
ZN-back[b]	.129	.281**	.146	.431**	1.00							
WIAT-II Word Reading[a]	.037	.280**	.128	.453**	.410**	1.00						
WIAT-II Numerical Operations[a]	.173	.229*	.146	.632**	.400**	.545**	1.00					
WIAT-II Spelling[a]	.113	.121	.164	.566**	.269**	.714**	.688**	1.00				
Gender	.235*	−.397**	−.007	−.020	−.051	−.128	−.041	.116	1.00			
WISC-IV VCI[a]	.075	.048	.155	.442**	.253*	.512**	.513**	.535**	−.018	1.00		
SES[c]	−.122	.032	−.099	−.174	−.039	−.246*	−.196	−.252*	−.083	−.384**	1.00	
ZSWAN[b]	−.179	.017	−.057	−.238*	−.196	−.208*	−.406**	−.360**	−.236*	−.324**	.110	1.00

Notes: MABC-2 = Movement Assessment Battery for Children-2; WISC-IV = Wechsler Intelligence Scale for Children-IV; WMI = Working Memory Index; WIAT-II = Wechsler Individual Achievement Test-II; SWAN = Strengths and weaknesses of ADHD symptoms and normal behavior; VCI = Verbal Comprehension Index.

[a]Age-standardized score.

[b]z-score.

[c]The occupation rated as most prestigious out of mothers' and father's occupation.

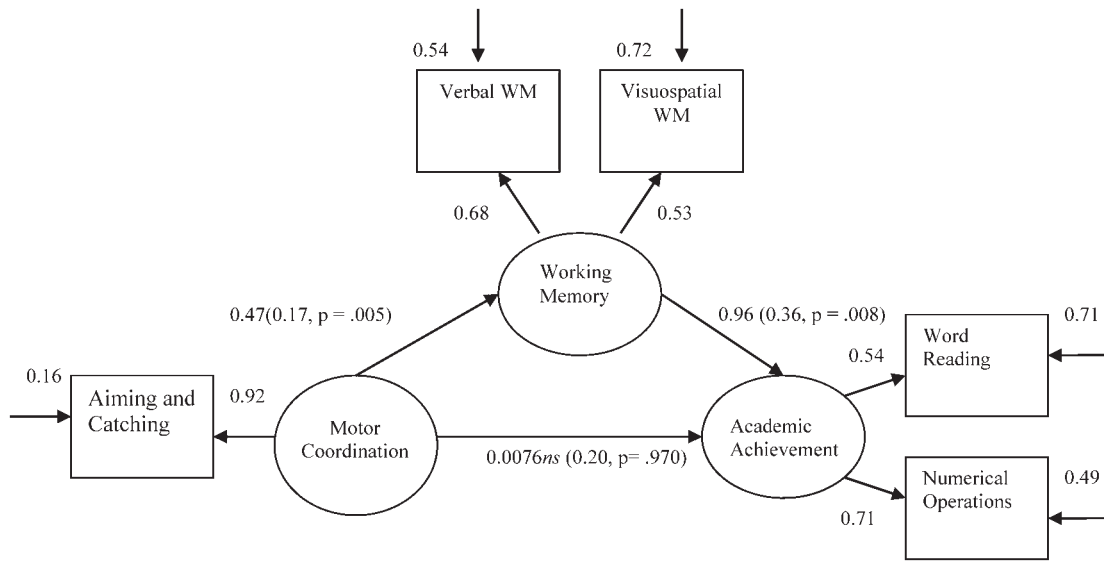*$p < .05$ (two-tailed).

**$p < .01$ (two-tailed).

Fig. 2. Parameter estimates for the saturated model.

Table 3. Summary of model fit indices for the saturated and mediator models of the relationship between motor coordination, WM, and academic achievement

Model	χ^2	df	p-value	RMSEA	CFI	SRMSR
Saturated model	5.28	3	.15	0.095	0.98	0.041
Mediator model	5.28	4	.26	0.063	0.99	0.041

Notes: CFI = Comparative Fit Index; SRMSR = Standardized Root Mean Square Residual; RMSEA = Root Square Mean Square Error of Approximation.
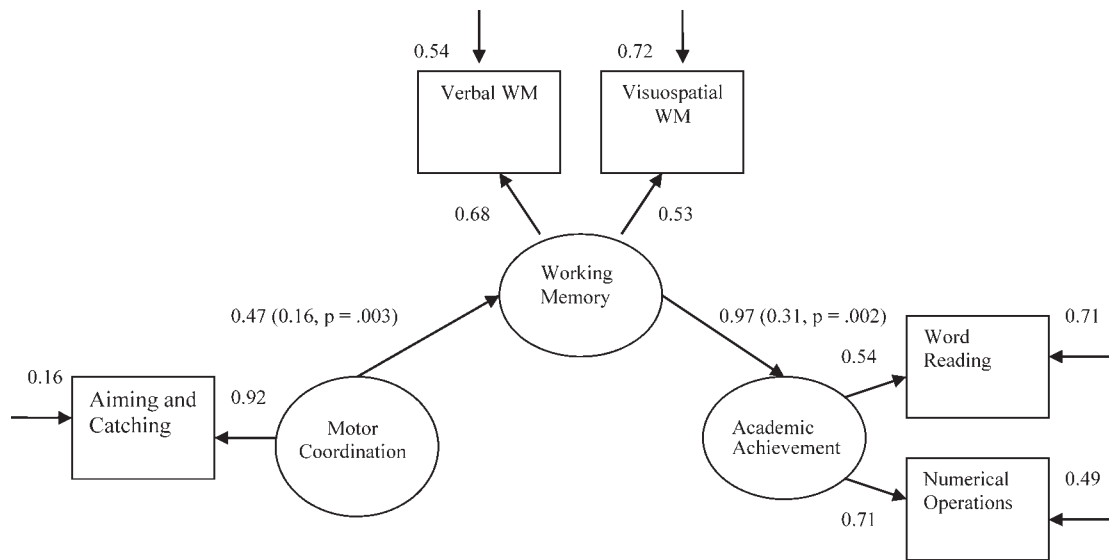
Fig. 3. Parameter estimates for the mediator model.

link between WM and academic outcomes in an adolescent normative sample. The current results also support recent research suggesting a link between WM and motor coordination (Piek et al., 2004; Wassenberg et al., 2005).

Importantly, the results from this study suggest that the relationship between motor coordination and academic achievement can be understood in terms of a mechanism whereby motor coordination has an indirect impact on learning outcomes via WM.

Table 4. Summary of model fit indices for alternative measurement models of the WISC-IV WMI and the ZN-back

Model	χ^2	df	p-value	RMSEA	CFI	SRMSR	Model AIC
Model 1							
1BACK–4BACK = VSWM							
DSF DSB LNS = VWM	16.90	13	.20	0.058	0.95	0.070	46.90
Model 2							
2BACK–4BACK DSB LNS = WM							
1BACK DSF = STM	26.97	13	.013	0.120	0.85	0.084	59.97

Note: CFI = Comparative Fit Index; SRMSR = Standardized Root Mean Square Residual; RMSEA = Root Square Mean Square Error of Approximation; Model AIC = Akaike's Information Criterion (smaller is better); VSWM = Visuospatial Working Memory; VWM = Verbal Working Memory; WM = Working Memory; STM = Short-Term Memory.

Alloway and Warner (2008) provided evidence that learning outcomes may not be directly impacted by motor skills in children with DCD, but rather, it is difficulties with combined processing and storage of information that may underlie learning outcomes in these children. This argument is consistent with a mediation model in which motor coordination impacts on learning via WM. The present study extends from these findings by establishing the viability of this model in an adolescent normative sample.

It is important to note that in the present study, "motor coordination" was operationalized with just one of the three MABC-2 motor skill components, namely, Aiming and Catching. The three models (i.e., Aiming and Catching, Manual Dexterity, and Balance) were initially examined separately given that the association between Aiming and Catching and Manual Dexterity subscales was found to be non-significant for this sample of adolescents. This result is in line with Haga, Pedersen, and Sigmundsson's (2007) study which found weak correlations among the MABC motor tasks in a sample of 4-year-old children. The authors of the study explained their findings in terms of task-specific skills and argued for the importance of identifying the skills that are necessary and important for children to learn (Haga et al., 2007).

In the present study, the models with Manual Dexterity and Balance were subsequently dropped because they failed to demonstrate significant correlations with the mediator and the outcome measures. This is consistent with Gaysina and colleagues (2010) study, which did not find any significant association between fine motor skills and academic difficulties in the reading domain at age 15. Similarly, Michel and colleagues (2011) found that "motor impaired" children, identified by having Manual Dexterity difficulties, did not perform worse on a WM task of Backwards Color Recall when compared with those without motor impairment. In another study, Backwards Color Recall did not significantly correlate with fine motor skills as measured by a pegboard task in a normative sample of 7-year olds (Roebers & Kauer, 2009). However, significant correlations were found with a postural flexibility task (Roebers & Kauer, 2009).

The current study demonstrates an important relationship between Aiming and Catching games, WM, and academic achievement (specifically, Word Reading and Numerical Operations), supporting previous research of a specific relationship between aspects of motor coordination and these cognitive areas. The specific relationship found between the Aiming and Catching games, WM, and academic outcomes may be explained by shared underlying neural processes. Ball games such as those used in the current study (e.g., throwing a ball against a wall and then catching it with one hand upon return) require the control of independent limb movements, including rapid skilled movements. Carlson (2010) notes that the lateral zone of the cerebellum is important in calculating the complex, closely timed sequences of muscular contractions required for such rapid skilled movements. Consequently, it is possible that the specific associations found in the current study may be explained by cerebellar mechanisms, specifically, involvement from the lateral cerebellum. Therefore, the current results provide some support for the cerebellar deficit hypothesis proposed by Nicolson and colleagues (2001). Their framework suggests a causal relationship between cerebellar dysfunction and reading problems, which may be understood in terms of the cerebellar contributions to automation of skills and production of inner speech. An important link between the cerebellum and verbal WM is also suggested which is important when understanding the resulting reading problems (Nicolson et al., 2001). The results of the current study also provide support for previous evidence which demonstrates the role of the lateral cerebellum in developmental dyslexia (e.g., Rae et al., 1998). The present results also support other studies implicating the cerebellum in WM (Ravizza et al., 2006) and in other academic areas such as mathematics (Feng et al., 2008).

In addition, the basal ganglia may also play a role in the present findings as it has it been associated with the ability to modulate force of movement (Lundy-Ekman, Ivry, Keele, & Woollacott, 1991) which is a skill needed for the fast, goal-directed movements involved in ball throwing activities. The basal-ganglia forms part of the extrapyramidal system (along with the cerebellum) and has also been implicated in cognitive functions such as WM (Voytek & Knight, 2010).

However, it is also important to note the complex interactions between the motor areas of the brain and other parts of the central nervous system such as the cerebellum, resulting in continuous interplay among these structures (Piek, 2006). Diamond (2000) highlighted the close co-activation of the cerebellum (specifically, the neocerebellum which forms part of the lateral cerebellum) and prefrontal cortex when understanding the relationship between complex motor and cognitive domains. In addition to the important role of the cerebellum, it is possible that the complex nature of ball skills assessed in the current study co-activates greater prefrontal cortex activity than the tasks assessing solely fine motor (Manual Dexterity tasks) or Balance skills. The prefrontal cortex plays an important role in WM (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006) and has been implicated in both mathematics (Ansari & Dhital, 2006; Rivera, Reiss, Eckert, & Menon, 2005) and reading performance (Backes et al., 2002; Maguire, Frith, & Morris,1999). This may, in part, explain the specific links found in the current study.

In addition, it is likely that children who experience difficulty in executing the complex combination of motor skills involved in ball games will subsequently avoid participating in such tasks (Cairney et al., 2005). Children also typically require partners to practice with in order to develop ball skills which may be a problem for individuals with movement difficulties given the associated difficulties in the social domain (Smyth & Anderson, 2000). It is possible that the resulting lack of opportunity to learn and practice the skills needed for ball games may play a significant role in understanding the current findings.

Best (2010) highlighted the protracted period of cognitive and brain development into adolescence and argued that since executive functions and the underlying neural circuitry are still immature during this time, complex cognitive functions (such as WM) may be sensitive to the effects of a child's experiences and plausibly enhanced by certain experiences (Best, 2010). In fact, there is increasing research demonstrating the positive impact of physical activity on cognitive and academic functioning (Tomporowski, Davis, Miller, & Naglieri, 2008). Sibley and Etnier (2003), in their meta-analysis, suggest that the mechanisms underlying the relationship between physical activity and cognition may be explained by two broad categories including physiological and learning/developmental mechanisms. Physiological mechanisms, induced by exercise, include physical changes such as increased cerebral blood flow, structural changes in the central nervous system, alterations in brain neurotransmitters, and arousal levels (Sibley & Etnier, 2003). Conversely, learning/developmental mechanisms suggest that movement and physical activity provide learning experiences which enhance, and may be essential for, cognitive development (Sibley & Etnier, 2003). For example, active games may require similar cognitive processes to those involved in EF tasks such as strategic and goal-directed behavior when faced with a novel game experience. Thus, the skills gained during participation in such games may also transfer to EF tasks (Best, 2010).

Research has also suggested that the more complex forms of physical exercise, requiring greater cognitive engagement as well as coordination of complex bodily movements, are more likely to enhance EF than simpler exercises (Budde, Voelcker-Rehage, Pietrabyk-Kendziorra, Ribeiro, & Tidow, 2008; Pesce, Crova, Cereatti, Casella, & Bellucci, 2009). Therefore, it is likely that games involving Aiming and Catching motor skills (e.g., basketball) require this complex cognitive engagement which may prove important in transferring to and enhancing EF skills. Ultimately, individuals with motor coordination difficulties may not be provided with the same opportunity to enhance these areas given their tendency to withdraw from physical participation.

This study has some limitations. It is important to note that the current study investigated the academic domains of Word Reading, Numerical Operations, and Spelling only. Consequently, it is possible that motor areas, such as Manual Dexterity, may be important in predicting other academic outcomes in adolescence such as writing. The present study did not include other potential mediating variables, such as processing speed or motivation, which may also be important in understanding the nature of the relationship between motor coordination and academic achievement. Furthermore, an important area of future research appears to be addressing the potential mediating influence of physical participation/fitness levels in the relationship between motor coordination and academic outcomes. Examining the role of individual factors may be important in attempting to further understand the relationship between motor functioning, WM, and academic achievement. For example, it would be interesting to study children with motor coordination difficulties who show significant strengths in WM and academic achievement. It should also be noted that although researchers made effort to minimize all distractions in the testing setting, those sessions conducted at the family home (according to family preference) may have been more susceptible to such distractions, potentially confounding the results (particularly, on cognitive measures). However, despite these limitations and to the best of our knowledge, this is the first study to reveal the important relationship between motor coordination, WM, and academic achievement in an adolescent normative sample, highlighting the significance of these findings. Additionally, the present study is cross-sectional in nature and cannot conclude the directional relationships between the motor and cognitive domains. Further research is needed to elucidate the directional nature of the relationships. Finally, given that our findings provide some support for Unsworth and Engle (2007) who argue against the notion that STM and WM are different constructs, it is recommended that future studies attempt to further examine this notion and compare it with Baddeley's model which argues for a domain independent central executive.

Conclusion

Overall, the results of this study suggest that the association between motor coordination and academic achievement in an adolescent normative sample can be best understood in terms of a mechanism whereby motor coordination, specifically Aiming and Catching skills, has an indirect impact on learning outcomes via WM. These findings have important implications for the early assessment and treatment of motor coordination and learning difficulties. For children with movement difficulties, for example, strategies aimed at reducing excessive WM loads in the classroom may prove useful in enhancing their capacity to achieve in these academic areas. Finally, the current results revealing an important association between Aiming and Catching skills, WM, and academic outcomes (specifically Word Reading and Numerical Operations) suggest that the association between motor coordination and such cognitive outcomes may be understood in terms of common underlying mechanisms in the lateral cerebellum.

Conflict of Interest

None declared.

Acknowledgements

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