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

Daniela Rigoli[1], Jan P. Piek[1], Robert Kane[1], & Jaap Oosterlaan[2]

[1] School of Psychology and Speech Pathology

Curtin Health Innovation Research Institute (CHIRI)

Curtin University, Perth, Western Australia

[2] VU University Amsterdam, Department of Clinical Neuropsychology, Amsterdam, The

Netherlands

Correspondence to:

Daniela Rigoli

School of Psychology and Speech Pathology

Curtin University

GPO Box U1987

Perth 6845

Western Australia

Tel: +618-9266 2286

Fax: +618 9266 2464

Email: d.rigoli@curtin.edu.au

Abstract

The aim of the current study was to examine whether the relationship between motor coordination and academic achievement is mediated by working memory in a normative adolescent sample. Participants included 93 adolescents aged 12 to 16 years. The Movement Assessment Battery for Children-2 provided three indicators of motor coordination (manual dexterity, aiming and catching, balance), the Working Memory Index of the Wechsler Intelligence Scale for Children-IV and the N-back paradigm provided two indicators of working memory, and the Wechsler Individual Achievement Test-II provided three indicators of academic achievement (word reading, spelling, and numerical operations). Structural equation modelling, 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 working memory. 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. **Key words:** motor coordination; working memory; academic achievement; adolescents; normative sample

1. 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 et al., 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, and learning outcomes (Alloway).

Working memory 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, working memory comprises four components. The central executive controls resources and monitors information processing, as well as being responsible for various regulatory functions (Baddeley & Hitch). 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 working memory and long-term memory (Baddeley). A substantial body of research now suggests that working memory capacity is a reliable predictor of various cognitive skills such as general fluid intelligence (Engle et al.,

1999) as well as academic skills such as reading and mathematics (Alloway, 2009), and language comprehension (Nation et al., 1999).

Recently, working memory has been linked with motor coordination. For example, Piek and colleagues (2004) found that after controlling for age, gender and verbal IQ, motor coordination was significantly associated with working memory in children aged 6 to 15 years. In this study, motor coordination was operationalised 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 working memory and certain aspects of motor coordination were not examined. In a later study (Piek et al., 2007), children with developmental coordination disorder (DCD) were slower than ADHD and control groups on the same working memory task used in Piek et al.'s (2004) study, but also performed less accurately on another measure of working memory. 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 which identified 'motor impaired' children by using a cut-off below the 10th percentile on the Movement Assessment Battery for Children 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 working memory task of Backwards Color Recall when compared to those without motor impairments (Michel et al., 2011). Furthermore, correlations revealed that although the working memory 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.). These results suggest the possibility of specific relationships between working memory and

certain aspects of motor coordination. For example, manual dexterity may not have an important association with working memory.

In a normative study investigating the relationship between different aspects of motor coordination and cognitive control in seven year old children, a significant association was found between Backwards Color Recall and postural flexibility (Roebers & Kauer, 2009), whereas, no significant association was found between Backwards Color Recall and a fine motor pegboard task (Roebers & Kauer). Longitudinal research examining the predictive ability of motor skills on later working memory has also revealed an important relationship between gross motor skills and working memory. 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 working memory 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 working memory. Similarly, in relation to the link between academic outcomes and certain aspects of motor coordination, Gaysina and colleagues (2010) did not find any significant association between fine motor skills and academic difficulties in the reading domain at age 15 years.

Evidence suggesting important links between certain aspects of motor coordination and outcomes of cognitive functioning (namely, working memory 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). 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). 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). Furthermore, certain parts of the cerebellum are said to be associated with specific aspects of motor control for example, the vermis has been linked with postural reflexes (important for balance) whereas the lateral zone of the cerebellum has been linked with the control of independent limb movements particularly rapid, skilled movements (Carlson) 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, Fawcett 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 automatisation, 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, specifically, verbal short-term or working memory. 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 working memory difficulties, through its impact on subvocal rehearsal. It is further suggested that the resulting problems of cerebellar dysfunction, that is, 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.). Thus providing a framework for the involvement of the cerebellum in reading difficulties, as well as in working memory.

Other studies have also implicated the cerebellum in working memory (Ravizza et al., 2006) and other academic areas such as mathematics (Feng et al., 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 working memory 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 working memory) in functional neuroimaging (Diamond, 2000) provides further evidence for a relationship between motor coordination and cognitive outcomes including working memory.

Ultimately, in light of the increasing evidence of a link between motor coordination and cognitive outcomes such as working memory and academic achievement, what role does working memory 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 working memory tasks) and found that

the low visuospatial memory ability group performed significantly worse on literacy and

numeracy compared to 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). 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 working memory showed

improvement, but there was no improvement in verbal working memory or reading and math

scores. Firstly, the results suggest that motor coordination may be more important in predicting

visuospatial working memory than verbal working memory 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 characterising DCD (Wilson &

McKenzie, 1998). The improvement in visuospatial working memory in Alloway and Warner's

intervention study may be understood in terms of the movement planning and control

components of such visuospatial working memory tasks, which can be improved by movement

training. However, given that neither verbal working memory nor reading and maths 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

8

with DCD (Alloway & Warner). 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., working memory ability).

Although preliminary evidence provides important insights into the relationship between motor coordination, working memory, and learning outcomes, a number of issues need to be addressed. Firstly, the current study controls for the confounding influence of ADHD symptomatology. This is important given that ADHD has been linked with motor problems (Pitcher, Piek, & Hay, 2003), working memory (Martinussen et al., 2005), and learning outcomes (Semrud-Clikeman et al., 1992). Also, previous research investigating motor coordination, working memory, 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). In addition, research in the area has involved younger samples aged 5 to 11 years (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 cognitive domains differ across age cohorts of 3 to 14 years of age (Dyck et al., 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 current study examined a mediating model of the relationship between motor coordination, working memory, and academic achievement in adolescents from a normative

sample whilst controlling for potentially confounding factors such ADHD symptoms, verbal

ability, SES, age, and gender. It was hypothesised 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 working memory (as measured by verbal and

visuospatial working memory) through a direct path; working memory would have a positive

direct effect on academic achievement; and motor coordination would have a positive effect on

academic achievement through an indirect path with working memory mediating this

relationship. Figure 1 provides a diagrammatic representation of the proposed mediating model.

<div style="text-align:center">Insert Figure 1 about here</div>

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 et al., 2008). Studies have provided initial evidence that motor coordination predicts performance on complex cognitive tasks including working memory (Murray et al.; Piek et al.). 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), 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 working memory 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.

2. Method

2.1 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 to 16 years. 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 parent report). The final sample included ninety three adolescents, 38 girls and 55 boys, with a mean age of 14.2 years (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 mothers' and father's occupation was used as the SES score (M =3.77, SD = 1.00, range = 1.80-6.60).

2.2 Measures

Movement Assessment Battery for Children-2 (MABC-2; Henderson, Sugden, & Barnett, 2007)

The three subscales from the MABC-2 were utilised to provide the observed variables for the construct motor coordination. The MABC-2 is a standardised 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; 11-16 years) and tasks are grouped into the subscales: Manual Dexterity, Aiming & 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 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 1-5)

indicates significant movement difficulty (≤ 5th percentile). The age-standardised Manual

Dexterity, Aiming & Catching, 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

favourable psychometric properties (Henderson et al., 2007). Reliability coefficients range from

.73 to .84 for the subscale scores and .80 for the MABC-2 TTS. There is also evidence

demonstrating criterion-related and discriminative validity (Henderson et al.). 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 (that is, age band 11-16 years).

Wechsler Individual Achievement Test-II (WIAT-II – Australian; Wechsler, 2007)

The WIAT-II Australian is an individually administered test of achievement in

individuals aged 4 to 85 years, assessing academic skills in the domains of reading, writing,

mathematics, and oral language. In the current study, the age- standardised 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, working memory, 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 .98, and test-retest reliabilities varying from .80 to .96 for subtests (Wechsler, 2007). The WIAT-II-Australian also has good content, construct and criterion-related validity (Wechsler).

Wechsler Intelligence Scale for Children-IV (WISC-IV) – Australian (Wechsler, 2003)

The WISC-IV measures cognitive ability in children aged 6 to 16 years 11 months. The 10 core subtests yield a Full Scale IQ and are organised to yield four composite scores (*M*= 100, *SD*= 15), namely: VCI, Perceptual Reasoning (PRI), Working Memory (WMI), and Processing Speed (PSI). 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-standardised WMI score (comprising Digit- Span and Letter-Number-Sequencing subtests to assess verbal working memory) was used to provide an observed measurement for the construct, working memory. 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 working memory and was used to provide the second observed variable for the construct working memory. This task involves a visuospatial variant of the N-back task, designed after Gevins and Cutillo (1993) and Jansma et al. (2000), and has been adapted to make it more attractive and appropriate for children (van Leeuwen et al., 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

14

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 one second 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 working memory thereby capturing the full dimension of visuospatial working memory performance. For the purposes of the current 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 working memory and in a study examining a sample of adolescents with the current version of the N-back task, test-retest (carried out two to three weeks after initial assessment) reliabilities of .70 and .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 .7 or higher are considered satisfactory, whereas reliabilities of .5 and .6 may be considered as modest (Kunsti et al., 2001; van Leeuwen et al.).

Strengths and Weaknesses of ADHD Symptoms and Normal Behaviour (SWAN; Swanson et al., 2001)

The parent-rated SWAN scale is based on the ADHD symptoms listed in the Diagnostic and Statistical Manual of Mental Disorders-IV (DSM-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, whilst the second nine items relate to hyperactive/impulsive behaviours. Items are phrased in order to sample the full dimension of a particular behaviour. 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 current study, the raw overall SWAN score was converted to a z-score. Hay et al. (2007) found the SWAN to be an accurate reflection of the ADHD phenotype, and Polderman et al. (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. Cronbach alpha for current study was .97, demonstrating excellent internal reliability.

Australian Prestige Scale (Daniel, 1983)

Daniel's Prestige Scale rates occupational status on a scale of one (representing higher prestige) to seven (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 et al., 1997).

2.3 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

16

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 standardised instructions. Testing time was 4.5 hours 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.

2.4 Data Analysis

Structural equation modelling (SEM), with maximum likelihood estimation, was used to determine the degree to which working memory mediates the relationship between motor coordination and academic achievement. The analysis was implemented through LISREL (Version 8.54; Jöreskog & Sörbom, 2003). For relatively simple models such as our 1-mediator model, sample sizes between 100 and 150 have been recommended (Hair et al., 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.

3. Results

3.1 Descriptives

Table 1 provides the means, standard deviations and ranges for the variables measuring motor coordination, working memory, 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 ($\leq$ 5th percentile) was 5.4%, which is comparable to previous estimates of 6% (APA, 2000). The numbers of adolescents scoring below the 25th percentile (Shafir & Siegal, 1994) on the word reading, numerical operations, and spelling subtests of the WIAT-II were seven, twelve, and five, respectively. Two participants with significant movement difficulty ($\leq$ 5th percentile) also demonstrated learning difficulties ($\leq$ 25th percentile on the WIAT-II). One participant demonstrated spelling and math difficulties, the other, reading and math difficulties.

Insert Table 1 about here

3.2 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-standardised 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 working memory 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 (chi-square [36] = 35.03, $p = .51$), gender was ignored in all further analyses of these partial correlations.

Indicators that are 'driven' by the same latent construct will necessarily correlate. In the current 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 (working memory) 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 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, pp. 286).

Finally, spelling was removed because, unlike 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.

Insert Table 2 about here

3.3 LISREL Analysis

Pearson's correlations (controlling for ADHD symptoms, VCI, and SES) were input to LISREL for structural equation modelling. The parameter estimates and standard errors for the saturated

model are given in Figure 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 working memory was significant, as was the path from working memory to academic achievement. This indirect pathway was significant (p = .003) indicating that motor coordination has an indirect effect on academic achievement through working memory.

Insert Figure 2 about here

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 chi-square value (p >= .05) (Kline, 2005); the χ^2/df ratio is below 2 (Kline); the Comparative Fit Index (CFI) is greater than .90 (Kline); and the Standardised Root Mean Square Residual (SRMSR) is less than .10 (Kline). Although the Root Square Mean Square Error of Approximation (RMSEA) for the saturated model is above the desired .05 level and above the more liberal cut-off of .08 (i.e., .092), Tabachnick and Fidell (2001) note that this index may be less preferable with smaller samples due to the tendency to overreject the true model. Overall, the results indicate good data-model fit.

Insert Table 3 about here

The test of the saturated model indicated that, when working memory 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 (χ^2_{diff} [1] = 0.00, $p = .99$) or changing parameter estimates (see Figure 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 Figure 3.

Insert Figure 3 about here

There is a plausible alternative model in which motor coordination mediates the impact of working memory 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 – 4 back) are presumed to load on a visuo-spatial working memory factor; while the digit-span forward (DSF), digit-span backward (DSB), and letter-number-sequencing (LNS) tasks from WISC-IV Working Memory Index are presumed to load on a verbal working memory factor. Previous research has argued for separation of short-term memory and working memory (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 working memory 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 2back - 4back, DSB, & LNS load on working memory; while 1-back & DSF load on short-term memory) with the proposed measurement model (in which 1back - 4back load on visuo-spatial working memory; while DSF, DSB, & LNS load on verbal working memory). 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., 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

21

similar in magnitude (Unsworth & Engle, 2007). Unworth and Engle argue against the notion that STM and WM are different constructs.

Insert Table 4 about here

4. 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, working memory (verbal and visuospatial working memory) 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 working memory.

There is extensive evidence demonstrating working memory 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 link between working memory and academic outcomes in an adolescent sample from a normative sample. The current results also support recent research suggesting a link between working memory 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 working 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 working memory. The current 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 operationalised 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 and colleagues' (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.).

In the current 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, Maughan et al.'s (2010) study, which did not find any significant association between fine motor skills and academic difficulties in the reading domain at age 15 years. Similarly, Michel and colleagues (2011) found that 'motor impaired' children, identified by having manual dexterity difficulties, did not perform worse on a working memory task of Backwards Color Recall when compared to 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).

The current study demonstrates an important relationship between aiming and catching games, working memory, 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, working memory 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. Consequently, 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 working memory is also suggested which is important when understanding the resulting reading problems (Nicolson et al.). 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 working memory (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 et al., 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 working memory (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 CNS 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 working memory (Crone et al., 2006) and has been implicated in both mathematics (Rivera, Reiss et al., 2005; Ansari & Dhital, 2006) and reading performance (Backes et al., 2002; Maguire, Frith et al., 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 to develop their ball skills may play a significant role in understanding the current findings.

Best (2010) highlighted the protracted period of brain and cognitive 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 working memory) may be sensitive to the effects of a child's experiences and plausibly enhanced by certain experiences (Best). In fact, there is increasing research demonstrating the positive impact of physical activity on cognitive and academic functioning (Tomporowski, Davis et al., 2008). Sibling 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 as well as arousal levels (Sibling & Etnier). Conversely, learning/developmental mechanisms suggest that movement and physical activity provide learning experiences which enhance, and may be essential for, cognitive development (Sibling & Etnier). For example, active games may require similar cognitive processes to those involved in EF tasks such as strategic and goal-directed behaviour when faced with a novel game experience. Thus, the skills gained during participation in such games may also transfer to EF tasks (Best).

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 et al., 2008; Pesce et al., 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, those 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, working memory, and academic achievement. For example, it would be interesting to study children with motor coordination difficulties who show significant strengths in working memory and academic achievement. It should also be noted that although researchers made effort to minimise 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, working memory, and academic achievement in an adolescent normative sample, highlighting the significance of these findings.

Additionally, the present study is cross-sectional in nature and consequently, 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 & 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 working memory. 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 working memory 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, working memory, and academic outcomes (specifically reading and math) suggest that the association between motor and such cognitive outcomes may be understood in terms of common underlying mechanisms in the lateral cerebellum.

References

Alloway, T. P. (2007). Working memory, reading, and mathematical skills in children with developmental coordination disorder. *Journal of Experimental Child Psychology, 96*, 20-36.

Alloway, T. P. (2009). Working Memory, but not IQ, predicts subsequent learning in children with learning difficulties. *European Journal of Psychological Assessment, 25* (2), 92-98.

Alloway, T. P., & Warner, C. (2008). The effect of task-specific training on learning and memory in children with developmental coordination disorder. *Perceptual and Motor Skills, 107*, 273-280.

Archibald, L. M. D., & Alloway, T. P. (2008). Comparing language profiles: children with specific language impairment and developmental coordination disorder. *International Journal of Language and Communication Disorders, 43*(2), 165–180.

American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: Author.

Ansari, D., & Dhital, B. (2006). Age-related changes in the activation of the intraparietal sulcus during nonsymbolic magnitude processing: An event-related functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience, 18*(11), 1820-1828.

Backes, W., Vuurman, E., Wennekes, R., Spronk, P., Wuisman, M., van Engelshoven, J., & Jolles, J. (2002). Atypical brain activation of reading processes in children with developmental dyslexia. *Journal of Child Neurology, 17*(12), 867-871.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*, 417-423.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews*

Neuroscience, 4 (10), 829-839.

Baddeley, A. D., & Hitch, G. J. (1974). *Working memory.* In G. A. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–89). New York: Academic Press.

Baron, R. M., & Kenny, D. A. (1986). The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality & Social Psychology, 51*(6), 1173-1182.

Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review, 30*, 331–351.

Budde, H., Voelcker-Rehage, C., Pietraßyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience Letters 441*(2), 219-223.

Cairney, J., Hay, J. A., Faught, B. E., Wade, T. J., Corna, L., & Flouris, A. (2005). Developmental coordination disorder, generalized self-efficacy toward physical activity, and participation in organized and free play activities. *Journal of Pediatrics, 147*, 515–520.

Carlson, N. R. (2010). *Physiology of behavior* (10th ed.). Boston: Allyn & Bacon.

Crone, E. A., Wendelken, C., Donohue, S., van Leijenhorst, L., & Bunge, S. A. (2006). Neurocognitive development of the ability to manipulate information in working memory. *PNAS, 103* (24), 9315-9320.

Daniel, A. (1983). *Australian studies: Power, privilege and prestige: Occupations in Australia.* Melbourne, Australia: Longman Cheshire.

Dewey, D., Kaplan, B. J., Crawford, S. G., Wilson, B. N. (2002). Developmental coordination

disorder: Associated problems in attention, learning, and psychosocial adjustment. *Human Movement Science, 21*, 905–918.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71* (1), 44-56.

Dyck, M. J., Piek, J. P., Kane, R., & Patrick, J. (2009). How uniform is the structure of ability across childhood. *European Journal of Developmental Psychology, 6*, 432-454.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*, 309-331.

Fawcett, A. J., & Nicholson, R. I. (1995). Persistent deficits in motor skill of children with dyslexia. *Journal of Motor Behavior, 27*, 235-240.

Feng, S., Fan, Y., Yu, Q., Lu, Q., & Tang, Y. (2008). The cerebellum connectivity in mathematics cognition. *BMC Neuroscience, 9*, 155.

Gaysina, D., Maughan, B., & Richards, M. (2010). Association of reading problems with speech and motor development: results from a British 1946 birth cohort. *Developmental Medicine and Child Neurology, 52*, 680- 681.

Gevins, A., & Cutillo, B. (1993). Spatiotemporal dynamics of component processes in human working memory. *Electroencephalography and Clinical Neurophysiology, 87*, 128-143.

Goodwin, R, & Plaze, S.H. (2000). Perceived and received social support in two cultures: Collectivism and support among British and Spanish students. *Journal of Social & Personal Relationships*, *17,* 282-291.

Haga, M., Pedersen, A. V., & Sigmundsson, H. (2007). Interrelationship among selected measures of motor skills. *Child: care, health and development, 34*, 245-248.

Hair, T. F., Black, W. C., Babin, B. J., Anderson, R. E., & Tatham, R. L. (2006). *Multivariate data analysis* (6th ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Hartman, E., Houwen, S., Scherder, E., & Visscher, C. (2010). On the relationship between motor performance and executive functioning in children with intellectual disabilities. *Journal of Intellectual Disability Research, 54*, 468-477.

Hay, D. A., Bennett, K. S., Levy, F., Sergeant, J., & Swanson, J. (2007). A twin study of attention-deficit/hyperactivity disorder dimensions rated by the Strengths and Weaknesses of ADHD-Symptoms and Normal-Behavior (SWAN) Scale. *Biological Psychiatry, 61*, 700–705.

Henderson, S. E., & Barnett, A. L. (1998). The classification of specific motor coordination disorders in children: some problems to be solved. *Human Movement Science, 17*, 449-469.

Henderson, S. E., & Sugden, D. A. (1992). *Movement Assessment Battery for Children*. London: The Psychological Corporation.

Henderson, S. E., Sugden, D. A., & Barnett, A. (2007). *Movement Assessment Battery for Children* (2nd ed.). London: Psychological Corporation.

Jansma, J. M., Ramsey, N. F., Coppola, R., & Kahn, R. S. (2000). Specific versus nonspecific brain activity in a parametric n-back task. *Neuroimage, 12*, 688-697.

Jöreskog, K. G., & Sörbom, D. (2004). *LISREL 8.7 for Windows [computer software]*. Lincoln, IL: Scientific Software International Inc.

Kail, R., & Hall, L. K. (2001). Distinguishing short-term memory from working memory. *Memory & Cognition, 29* (1), 1-9.

Kline, R.B. (2005). *Principles and practice of structural equation modeling* (2nd ed.). New

York: Guilford Press.

Kuntsi, J., Stevenson, J., Oosterlaan, J., & Sonuga-Barke, E. J. S. (2001). Test–retest reliability
of a new delay aversion task and executive function measures. *British Journal of Developmental Psychology*, *19,* 339–348.

Kurdek, L. A., & Sinclair, R. J. (2001). Predicting reading and mathematics achievement in
fourth-grade children from kindergarten readiness scores. *Journal of Educational Psychology, 93*, 451-455.

Lundy-Ekman, L., Ivry, R., Keele, S., & Woollacott, M. (1991). Timing and force control
deficits in clumsy children. *Journal of Cognitive Neuroscience, 3*, 367-376.

Maguire E. A., Frith, C. D., & Morris, R. G. M. (1999). The functional neuroanatomy of
comprehension and memory: the importance of prior knowledge, *Brain, 122*(10), 1839-1850.

Martin, N. C., Piek, J. P., & Hay, D. (2006). DCD and ADHD: A genetic study of
their shared aetiology. *Human Movement Science, 25*(1), 110-124.

Martinussen, R.**,** Hayden, J., Hogg-Johnson, S**.**, & Tannock, R. (2005). A meta-analysis of
working memory impairments in children with attention-deficit/hyperactivity disorder.
Journal of the American Academy of Child & Adolescent Psychiatry, 44(4), 377-384.

Michel, E., Roethlisberger, M., Neuenschwander, R., & Roebers, C. M. (2011). Development of
cognitive skills in children with motor coordination impairments at 12-month follow up.
Child Neuropsychology, 17(20), 151-172.

Miyake, A., Friedman, N., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000).
The unity and diversity of executive functions and their contributions to complex 'frontal
lobe' tasks: a latent variable analysis. *Cognitive Psychology, 41*, 49-100.

Murray, G. K., Veijola, J., Moilanen, K., Miettunen, J., Glahn, D. C., Cannon, T. D., et al. (2006). Infant motor development is associated with adult cognitive categorisation in a longitudinal birth cohort study. *Journal of Child Psychology and Psychiatry, 47*, 25-29.

Nation, K., Adams, J. W., Bowyer-Crane, C. A., & Snowling, M. J. (1999). Working memory deficits in poor comprehenders reflect underlying language impairments. *Journal of Experimental Child Psychology, 73*, 139-158.

Nicolson, R. I., Fawcett, A. J., & Dean, P. (2001). Developmental dyslexia: the cerebellar deficit hypothesis. Trends in Neurosciences, 24(9), 508-511.

Pesce, C., Crova, C., Cereatti, L., Casella, R., & Bellucci, M. (2009). Physical activity and mental performance in preadolescents: Effects of acute exercise on free-recall memory. *Mental Health and Physical Activity, 2*(1), 16-22.

Piek, J. P. (2006). *Infant motor development*. Champaign, IL: Human Kinetics.

Piek, J. P., Dawson, L., Smith, L. M., & Gasson, N. (2008). The role of early fine and gross motor development on later motor and cognitive ability. *Human Movement Science, 27*, 668-681.

Piek, J. P., Dyck, M. J., Francis, M., & Conwell, A. (2007). Working memory, processing speed, and set-shifting in children with developmental coordination disorder and attention-deficit-hyperactivity disorder. *Developmental Medicine and Child Neurology, 49*, 678-683.

Piek, J. P., Dyck, M. J., Nieman, A., Anderson, M., Hay, D., Smith, L. M., McCoy, M., & Hallmayer, J. (2004). The relationship between motor coordination, executive functioning and attention in school aged children. *Archives of Clinical Neuropsychology, 19*, 1063-1076.

Pitcher, T., Piek, J., & Hay, D. (2003). Fine and gross motor ability in males with ADHD.

Developmental Medicine and Child Neurology, 45, 525–535.

Polderman, T. J., Derks, E.M., Hudziak, J. J., Verhulst, F. C., Posthuma, D., & Boomsma, D. I. (2007). Across the continuum of attention skills: a twin study of the SWAN ADHD rating scale. *Journal of Child Psychology and Psychiatry, 48(*11), 1080- 1087.

Rae, C., Lee, M. A., Dixon, R. M., Blamire, A. M., Thompson, C. H., Styles, P., et al. (1998). Metabolic abnormalities in developmental dyslexia detected by 1H magnetic resonance spectroscopy. *Lancet, 351(*9119), 1849-1852.

Ravizza, S. M., McCormick, C. A., Schlerf, J. E., Justus, T., & Ivry, R. B. (2006). Cerebellar damage produces selective deficits in verbal working memory, *Brain, 129*, 306-320.

Rivera, S. M., Reiss, A. L., Eckert, M. A., & Menon, V. (2005). Developmental changes in mental arithmetic: Evidence for increased functional specialization in the left inferior parietal cortex. *Cerebral Cortex, 15*(11), 1779-1790.

Roebers, C. M., & Kauer, M. (2009). Motor and cognitive control in a normative sample of 7-year-olds. *Developmental Science, 12*(1), 175-181.

Schulz, J., Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2011). Structural validity of the Movement ABC-2 test: Factor structure comparisons across three age groups. *Research in Developmental Disabilities, 32*, 1361–1369.

Semrud-Clikeman, M., Biederman, J., Sprich-Buckminster, S., Lehman, B. K., Faraone, S. V., & Norman, D. (1992). Comorbidity between ADDH and learning disability: A review and report in a clinically referred sample. *Journal of the American Academy of Child and Adolescent Psychiatry, 31,* 439-448.

Shafrir, U., & Siegal, L. S. (1994) Subtypes of learning disabilities in adolescents and adults. *Journal of Learning Disabilities, 27*, 123-124.

Sibley, B. A., & Etnier, J. L. (2003). The relationship between physical activity and cognition in children: a meta-analysis. *Pediatric Exercise Science, 15*, 243–256.

Son, S., & Meisels, S. J. (2006). The relationship of young children's motor skills to later reading and math achievement. *Merrill-Palmer Quarterly, 52*, 75-778.

Smith, A. M. Owen, N., & Baghurst, K. I. (1997).Influence of socioeconomic status on the effectiveness of dietary counselling in healthy volunteers. *Journal of Nutrition Education, 29* (1), 27–35

Smyth, M. M., & Anderson, H. I. (2000). Coping with clumsiness in the school playground: Social and physical play in children with coordination impairments. *British Journal of Developmental Psychology, 18*, 389-413.

Swanson, J., Schuck, S., Mann, M., Carlson, C., Hartman, K., Sergeant, J., et al. (2001). *The SWAN rating scale*. Retrieved from http://www.adhd.net

Tabachnick, B. G., & Fidell, L. S. (2001). *Using multivariate statistics* (4th ed.). Needham Heights, MA: Allyn and Bacon.

Tomporowski, P. D., Davis, C. L., Miller, P. H., & Naglieri, J. A. (2008). Exercise and children's intelligence, cognition, and academic achievement. *Educational Psychology Review, 20*(2), 111-131.

Unsworth, N., & Engle, R. W. (2007). On the division of short-term and working memory: An examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin, 133*(6), 1038-1066.

Van Leeuwen, M., van den Berg, S., Hoesktra, R. A., & Boomsma, D. I. (2007). Endophenotypes for intelligence in children and adolescents. *Intelligence, 35*, 369- 380.

Voytek, B., & Knight, R. T. (2010). Prefrontal cortex and basal ganglia contributions to visual working memory. *PNAS, 107*(42), 18167-18172.

Wassenberg, R., Kessels, A. G. H., Kalff, A. C., Hurks, P. P. M., Jolles, J., Feron, F. J. M., et al. (2005). Relation between cognitive and motor performance in 5- to 6-year-old children: Results from a large-scale cross-sectional study. *Child Development, 76*, 1092-1103.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: The Psychological Corporation.

Wechsler, D. (2007). *Wechsler Individual Achievement Test - Australian Standardised Edition* (2nd ed.): Marrickville, NSW: Harcourt.

Wilson, P. H., & McKenzie, B. E. (1998). Information processing deficits associated with developmental coordination disorder: A meta-analysis of research findings. *Journal of Child Psychology and Psychiatry, 39*(6), 829–840.

Figure 1

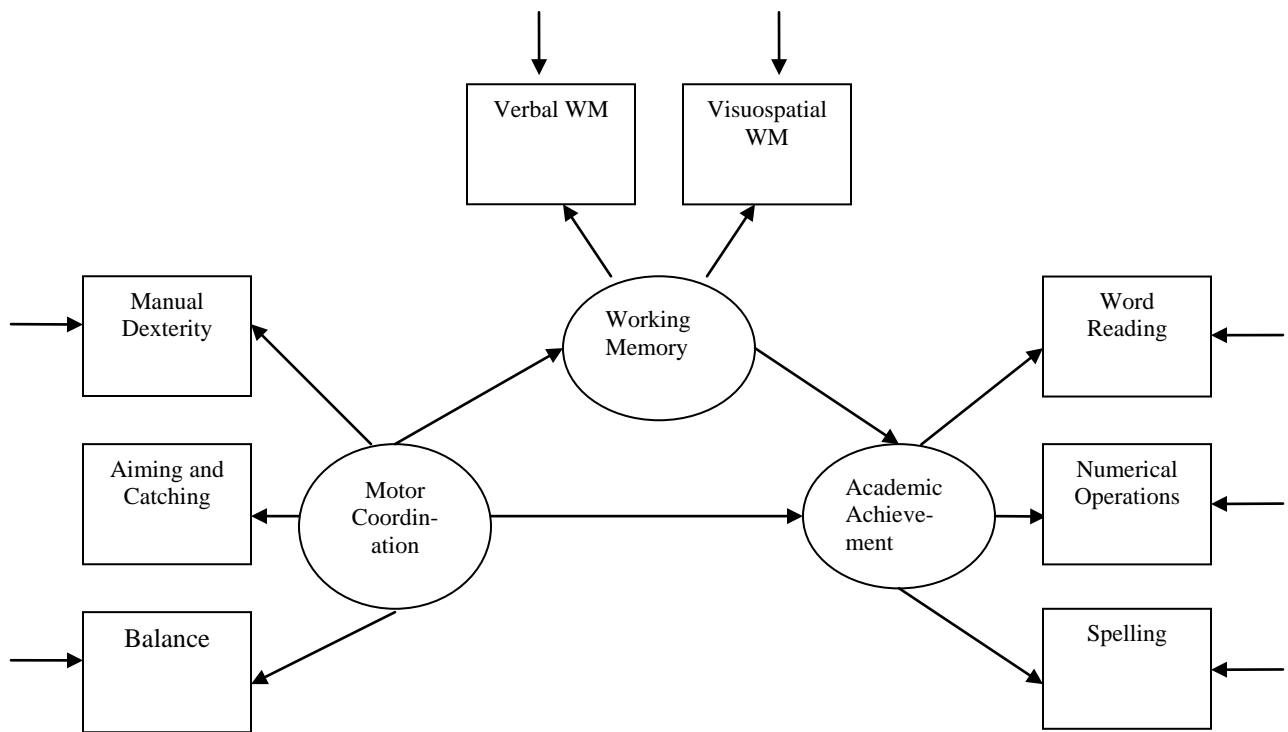*Diagrammatic Representation of the Proposed Mediating Model*

Table 1

Means, Standard Deviations (SD) and Range of Scores

	Mean	SD	Range
MABC-2 Manual Dexterity[1]	9.57	2.47	3.0 - 15.0
MABC-2 Aiming and Catching[1]	11.03	2.73	4.0 - 16.0
MABC-2 Balance[1]	11.42	2.98	4.0 - 14.0
WISC-IV Working Memory Index[1]	103.75	12.47	59.0 - 141.0
N-back[2][3]	88.17	19.69	6.0 - 124.0
Z N-back[4]	0.00	1.00	-4.17 – 1.82
WIAT-II Word Reading[1]	107.44	10.62	77.0 - 128.0
WIAT-II Numerical Operations[1]	106.85	14.73	63.0 - 139.0
Spelling[1]	107.19	11.68	67.0 – 129.0
SWAN[2][5]	-.9989	1.02	-3.0 - 1.22
Z SWAN[4]	0.00	1.00	-1.95 – 2.16
WISC-IV Verbal Comprehension Index[1]	106.63	11.25	81.0 - 132.0
SES[6]	3.77	1.00	1.80-6.60

Note: [1] = age-standardised score, [2] = raw score, [3] = total number of correct responses, [4] = z-score, [5] = scores are calculated by averaging the total of the 18 ADHD items [6] = the occupation rated as most prestigious out of mothers' and father's occupation

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[1]	1.00											
MABC-2 Aiming and Catching[1]	.071	1.00										
MABC-2 Balance[1]	.264*	.423**	1.00									
WISC-IV WMI[1]	.113	.251*	.122	1.00								
ZN-back[2]	.129	.281**	.146	.431**	1.00							
WIAT-II Word Reading[1]	.037	.280**	.128	.453**	.410**	1.00						
WIAT-II Numerical Operations[1]	.173	.229*	.146	.632**	.400**	.545**	1.00					
WIAT-II Spelling[1]	.113	.121	.164	.566**	.269**	.714**	.688**	1.00				
Gender	.235*	-.397**	-.007	-.020	-.051	-.128	-.041	.116	1.00			
WISC-IV VCI[1]	.075	.048	.155	.442**	.253*	.512**	.513**	.535**	-.018	1.00		
SES[3]	-.122	.032	-.099	-.174	-.039	-.246*	-.196	-.252*	-.083	-.384**	1.00	
ZSWAN[2]	-.179	.017	-.057	-.238*	-.196	-.208*	-.406**	-.360**	-.236*	-.324**	.110	1.00

Note. [1] = age-standardised score, [2] = z- score, [3] = the occupation rated as most prestigious out of mothers' and father's occupation,

*p< 0.05 (2-tailed), **p<0.01 (2-tailed).

Figure 2

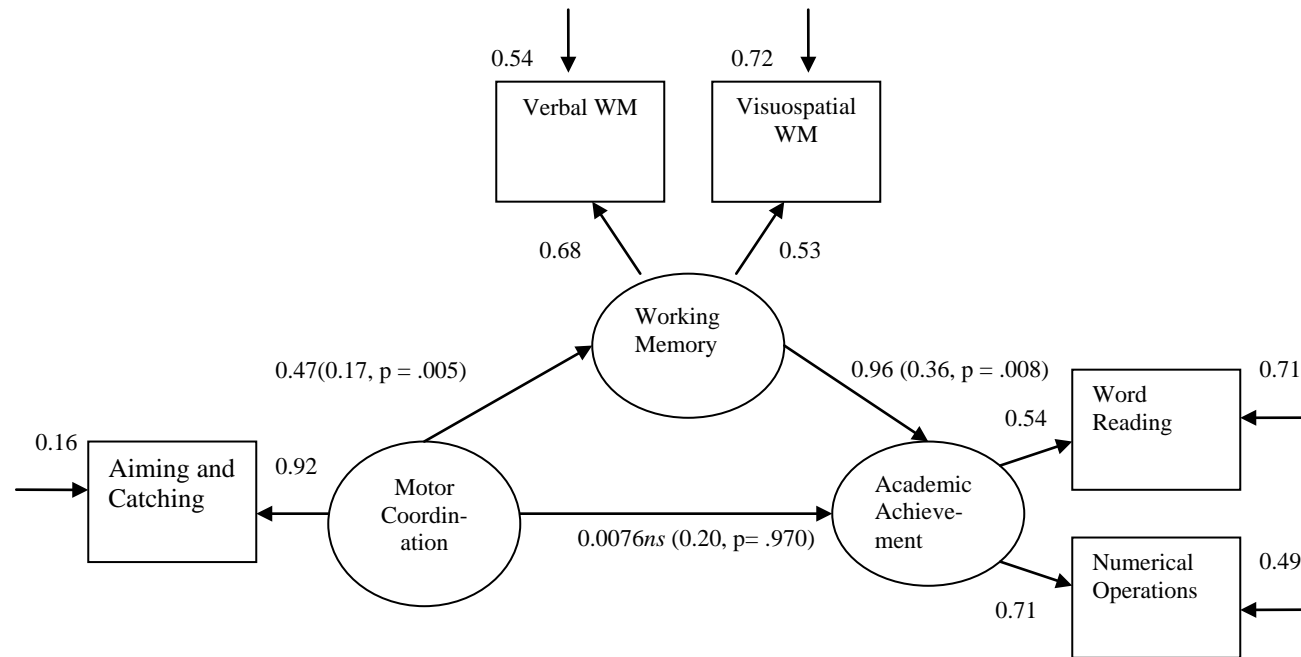*Parameter Estimates for the Saturated Model*

Figure 3

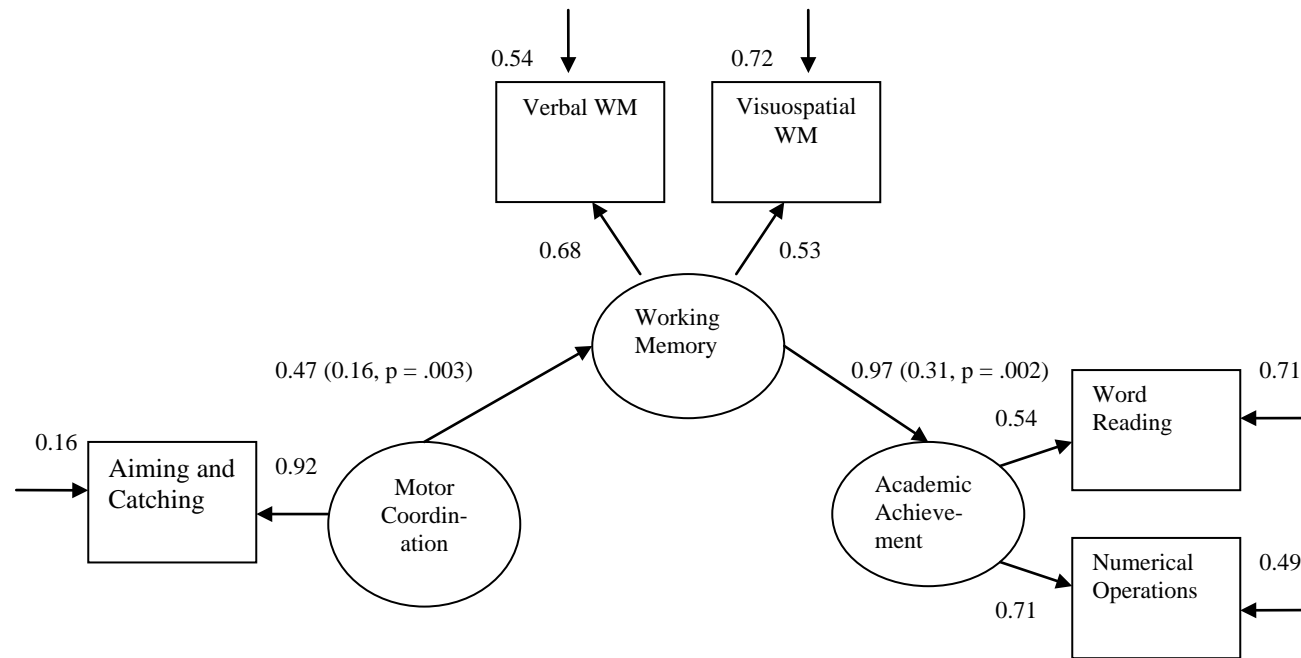*Parameter Estimates for the Mediator Model*

Table 3

Summary of Model Fit Indices for the Saturated and Mediator Models of the Relationship Between Motor Coordination, Working Memory,

and Academic Achievement

Model	Chi-Square	df	p-value	RMSEA	CFI	SRMSR
Saturated Model	5.28	3	.15	.095	.98	.041
Mediator Model	5.28	4	.26	.063	.99	.041

Note. CFI= Comparative Fit Index, SRMSR= Standardised Root Mean Square Residual, RMSEA= Root Square Mean Square Error of

Approximation

Table 4

Summary of Model Fit Indices for Alternative Measurement Models of the WISC-IV WMI and the ZN-back

Model	Chi-Square	df	p-value	RMSEA	CFI	SRMSR	Model AIC
Model 1 1BACK – 4BACK = VSWM DSF DSB LNS = VWM	16.90	13	.20	.058	.95	.070	46.90
Model 2 2BACK – 4BACK DSB LNS = WM 1BACK DSF = STM	26.97	13	.013	.120	.85	.084	59.97

Note. CFI= Comparative Fit Index, SRMSR= Standardised 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 working memory.