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Disentangling the relationships between motor control and cognitive control in young children with symptoms of ADHD

Cameron Ferguson [a,b], Christopher Hobson [c,d], Craig Hedge [e], Cerith Waters [c,d], Kate Anning [d] and Stephanie van Goozen [d]

[a]School of Psychological Science, University of Bristol, Bristol, United Kingdom; [b]Community Neurological Rehabilitation Service, Aneurin Bevan University Health Board, NHS Wales, Newport, United Kingdom; [c]South Wales Doctoral Programme in Clinical Psychology, Cardiff and Vale University Health Board, NHS Wales, Cardiff, United Kingdom; [d]Neurodevelopment Assessment Unit, Cardiff University, Cardiff, United Kingdom; [e]School of Psychology, Aston University, Aston, United Kingdom

ABSTRACT

Children with ADHD experience difficulties with motor and cognitive control. However, the relationships between these symptoms are poorly understood. As a step toward improving treatment, this study investigated associations between specific aspects of motor control and cognitive control in children with varying levels of hyperactive-impulsive symptoms. A heterogeneous sample of 255 children of 4 to 10 years of age (median = 6.50, MAD = 1.36) completed a battery of tests probing motor generation, visuomotor fluency, visuomotor flexibility, cognitive inhibition, verbal and visuospatial working memory, and cognitive flexibility. Their caregivers were interviewed regarding their hyperactive-impulsive symptoms. 25.9% of the main sample met diagnostic criteria for ADHD. Multiple linear regression analysis was used to determine whether specific aspects of motor control were associated with specific aspects of cognitive control, and whether any associations were moderated by hyperactive-impulsive symptoms. Additionally, cognitive modeling (the drift diffusion model approximated with EZ-DM) was used to understand performance on a cognitive inhibition task. Visuomotor fluency was significantly associated with cognitive inhibition. Visuomotor flexibility was significantly associated with cognitive flexibility. There were no significant moderation effects. Cognitive modeling was inconclusive. In conclusion, the ability to fluently perform visually guided continuous movement is linked with the ability to inhibit the effects of distracting information. The ability to spontaneously use visual information to flexibly alter motor responses is related to the ability to cognitively shift from one frame of mind to another. These relationships appear to be quantitatively and qualitatively similar across the childhood hyperactive-impulsive continuum as rated by parents.

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Motor control; Cognitive control; Attention deficit hyperactivity disorder; Hyperactivity-impulsivity; Cognitive modelling; Drift diffusion model

Children with attention deficit hyperactivity disorder (ADHD) experience difficulties with controlling movement and controlling thought. In addition to hyperactivity, which is a core

CONTACT Cameron Ferguson hu18869@bristol.ac.uk School of Psychological Science, University of BristolPriory Road, Bristol BS8 1TU

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feature of hyperactive-impulsive and combined ADHD (American Psychiatric Association, 2013; World Health Organisation, 2019), children with ADHD can experience several other motor difficulties (see Kaiser et al., 2015, for a review). These include challenges with fine motor skills (e.g., Mokobane et al., 2019; Polderman et al., 2011), motor timing (e.g., Rosch et al., 2013; Rubia et al., 2003; van der Meer et al., 2016; Zelaznik et al., 2012), motor overflow (e.g., Denckla & Rudel, 1978; Mostofsky et al., 2003), motor generation (e.g., Rommelse et al., 2008), and visuomotor control (e.g., Fabio et al., 2022; Tirosh et al., 2006). Typically, children with ADHD display increased response variability and reaction time variability as well as decreased overall accuracy of motor functioning (e.g., Demers et al., 2013; Kalff et al., 2005; Klotz et al., 2012; Rommelse et al., 2008). Motor control difficulties are associated with greater social problems (Goulardins et al., 2018) and poorer social, psychosocial, emotional, and overall quality of life in childhood with ADHD (Goulardins et al., 2011). Cognitively, children with ADHD often have difficulties with inhibition, working memory, cognitive flexibility, planning and organization as well as in overall cognitive ability (Pievsky & McGrath, 2017). Cognitive control in childhood is predictive of educational, occupational, and health outcomes in adulthood (Moffit et al., 2011). Subsequently, it is important to identify and capitalize on opportunities for early intervention regarding cognitive control. Improving our understanding of the relationship between motor control and cognitive control early in development has the potential to inform timely intervention.

The relationship between motor control and cognitive control

The growth of the cognitive control system is entwined with the refinement of the motor system in typical development (Diamond, 2000; van der Fels et al., 2015). Faster (slower) acquisition of motor milestones is strongly predictive of greater (poorer) cognitive control abilities in adulthood (Murray et al., 2006, 2007; Ridler et al., 2006). While motor and cognitive issues co-occur in childhood ADHD, the potential relationships between them are poorly understood. Koziol et al. (2013) argue that motor and cognitive difficulties co-occur in childhood ADHD because of abnormal functioning in overlapping neural substrates. It is known that frontostriatal (Diamond, 2013; Frank & Badre, 2015) and corticocerebellar (Bellebaum & Daum, 2007; Blaedel & Bracha, 1997; Diamond, 2000; Ramnani, 2006) circuits are important for the control of thought as well as the control of movement (Koziol et al., 2012, 2014; Middleton & Strick, 2000). Indeed, childhood ADHD is associated with delayed maturation in these structures as well as in the prefrontal cortex (Sharma & Couture, 2014). As the development of motor control begins before the development of cognitive control (Njiokiktjien, 2007; Piek et al., 2008), difficulties in motor control may underly difficulties in cognitive control (Koziol et al., 2013). Treating motor difficulties might therefore benefit cognitive control and life outcomes for children with symptoms of ADHD. Indeed, research that clarifies the relationship between cognitive and motor control may be helpful for developing more effective and informed targets for cognitive remediation interventions (e.g., Meyer et al., 2020; Pauli-Pott et al., 2021).

For children without ADHD, performance on various tasks involving motor control is associated with cognitive inhibition (Livesey et al., 2006; Rigoli et al., 2012; Stöckel & Hughes, 2016), working memory (Rigoli et al., 2012; Stöckel & Hughes, 2016; Wassenberg et al., 2005), and cognitive flexibility (Fang et al., 2017) in some but not all studies. For children with ADHD, one study suggests that motor control is most consistently associated with cognitive inhibition (Tseng et al., 2004). Together, these studies suggest that there is not a general relationship between motor control and cognitive control, which implies that efforts should be focused on understanding associations between specific abilities. Unfortunately, associations between motor control and specific aspects of cognitive control are not well replicated across existing studies. The most consistent finding is that motor control and cognitive inhibition are related (e.g., Livesey et al., 2006; Rigoli et al., 2012; Stöckel & Hughes, 2016), but evidence for associations with other aspects of cognitive control (e.g., working memory, cognitive flexibility) should not be dismissed.

Motor control skills

One factor that makes it difficult to understand the relationship between motor and cognitive control is that they are complex, multifaceted constructs. Many existing studies assessed general motor competence and motor-related activities (e.g., running, throwing, and catching). Motor control can refer to a wide array of underlying abilities, including motor generation, visuomotor fluency, and visuomotor flexibility (de Sonneville, 2022; Njiokiktjien, 2007). *Motor generation* refers to the ability to voluntarily generate consistent motor output over time, such as tapping with one's finger for a prolonged period. Motor generation is important for initiating and continuing to perform practically all tasks with a physical element. It can therefore be considered a foundational motor ability (de Sonneville, 2022, p. 271). *Visuomotor fluency* involves controlling movement in relation to unchanging visual stimuli, such as tracing a circle. Visuomotor fluency is important for writing between or coloring within the lines, for example. It is a less demanding skill than *visuomotor flexibility*, which involves controlling movement in unpredictable visual situations, such as when a target to be followed moves in an unexpected way (de Sonneville, 2022, p. 213). Visuomotor flexibility is likely important for playing computer games and taking part in sport where children must visually track moving stimuli (e.g., a football) and alter their movement (e.g., the motion of their feet) accordingly.

Cognitive control skills

Similarly, cognitive control is an umbrella term which can be separated into three related components in young children. These are *cognitive inhibition*, which involves withholding automatic responses and/or resisting the effect of distracting information; *working memory*, which involves holding and manipulating information temporarily held in the mind; and *cognitive flexibility*, which involves switching between different frames of mind (Henry & Bettenay, 2010; Miyake & Friedman, 2012; Miyake et al., 2000). These variables have been identified as three separable factors in factor analytic studies in children (Anderson, 2010; Fisk & Sharp, 2004; Garon et al., 2008; Henry & Bettenay, 2010; Lehto et al., 2003), with a tendency toward increased differentiation with age (Best & Miller, 2010; Karr et al., 2018); although, it is debatable whether inhibition reflects a unique process or general executive functioning (Friedman & Miyake, 2017). Previous relevant studies have fractionated cognitive control along these lines (e.g., Rigoli et al., 2012), but they have generally not also considered specific aspects of motor control.

Associations between specific aspects of motor control and cognitive control

Understanding of links between specific motor control and cognitive control skills can inform the development of motor and cognitive remediation programmes by identifying which specific functions should be targeted in early childhood. As an initial effort toward this goal, we tested plausible hypotheses about associations between specific aspects of motor control (motor generation, visuomotor fluency, and visuomotor flexibility) and cognitive control (cognitive inhibition, working memory, and cognitive flexibility). Due to the lack of previous research, these hypotheses were developed through considering limited prior work in this area, logical reasoning, and necessary speculation (Swedberg, 2021). Our hypotheses were pre-registered (https://osf.io/nphb9) prior to analysis. We summarise our rationale for our hypotheses below.

Motor control and cognitive inhibition

Being able to produce sufficient motor output (motor generation) and fluidly perform visually guided movement in predictable situations (visuomotor fluency) may be necessary to respond quickly and accurately in visual situations involving cognitive inhibition (Rigoli et al., 2012). Accordingly, we hypothesised that motor generation and visuomotor fluency would be positively associated with cognitive inhibition. (We did not hypothesise that visuomotor flexibility would be associated with cognitive inhibition because cognitive inhibition is often invoked in fast-paced tasks, which do not provide sufficient time for flexible cognition.)

Motor control and working memory

Because motor generation involves maintaining persistent motor output over time (de Sonneville, 2022; Njiokiktjien, 2007) and working memory involves the maintenance of information over time (Baddeley, 2012; Barrouillet & Camos, 2007), we hypothesised that motor generation would be positively associated with working memory. Additionally, because being able to continually adjust visually guided movements in predictable (visuomotor fluency) and unpredictable (visuomotor flexibility) settings is akin to manipulating information held in the mind's eye in response to persistent and changeable environmental demands (working memory manipulation), we hypothesized that visuomotor fluency and visuomotor flexibility would be positively associated with working memory manipulation.

Motor control and cognitive flexibility

To switch between different frames of mind, cognitive flexibility depends on the cognitive inhibition of distracting information and the maintenance and manipulation of information in working memory (Cragg & Chevalier, 2012). We already hypothesised that motor generation would be positively associated with cognitive inhibition and working memory, and that visuomotor fluency and visuomotor flexibility would be positively associated with working memory manipulation. Additionally, both visuomotor flexibility and cognitive flexibility involve adaptation to unpredictable changes in the environment, albeit in different domains. Subsequently, we hypothesized that motor generation, visuomotor fluency, and visuomotor flexibility would be positively associated with cognitive flexibility.

The moderating effect of hyperactive-impulsive symptoms

J. A. Sergeant (2005), J. Sergeant (2000) theorised that activation (i.e., physiological readiness to respond) can influence cognitive processing. Specifically, both too much and too little physiological activation can undermine cognition, implying a u-shaped relationship, and hence there is an optimal window to support cognitive task performance. Children with ADHD typically exhibit excessive activation (Burley et al., 2021; Murillo et al., 2015). Therefore, we hypothesised that greater motor generation in children with higher levels of hyperactive-impulsive symptoms would be associated with poorer cognitive control skills. Specifically, any associations between motor generation and cognitive inhibition, working memory, and cognitive flexibility would be moderated by hyperactive-impulsive symptoms by changing the positive sign of the associations to negative for children at the high end of the hyperactive-impulsive continuum (Hayes, 2017).

Additionally, we speculatively hypothesised that children with higher hyperactive-impulsive symptoms and poorer visuomotor fluency and visuomotor flexibility would display even poorer working memory manipulation. In other words, positive associations between visuomotor fluency and visuomotor flexibility and working memory manipulation would be moderated by hyperactive-impulsive symptoms through increasing the strength of the aforementioned association (Hayes, 2017).

A process approach to understanding cognitive control

Another barrier to understanding links between specific aspects of motor and cognitive control is that tests of cognitive inhibition, working memory, and cognitive flexibility are not-process specific, despite purporting to measure a particular element of cognitive control. For example, regarding cognitive inhibition, a child's performance on a flanker task (in which they must quickly select a target stimulus that is flanked by either congruent or incongruent stimuli on either side) can depend on how efficiently they process information, whether they prioritise speed or accuracy, and how long it takes them to encode stimuli and prepare for motor actions (Ratcliff & McKoon, 2008).

By separating overall performance into subcomponents, cognitive modeling can highlight specific difficulties and qualitatively different cognitive approaches (e.g., a speed-accuracy trade-off). Cognitive modeling can help us move beyond a deficit approach, which focuses solely on what is wrong, to a process approach (e.g., Bernstein, 2013), which clarifies *why* children are struggling. Knowing *how* children achieve a score (e.g., by prioritizing accuracy over speed) as well as what they score compared to normative data, could improve understanding of their strengths and difficulties and inspire personalised treatment plans. Also, because cognitive modeling can facilitate an appreciation of individual differences, its use is consistent with contemporary dimensional approaches to understanding ADHD symptoms in childhood (e.g., Musser & Raiker, 2019).

Several studies have used the Drift Diffusion Model (DDM; Ratcliff & McKoon, 2008), which models processing efficiency, the speed-accuracy trade-off, and stimuli encoding and motor response execution time, to understand cognitive differences in children with ADHD. Generally, studies suggest that children with ADHD process information less efficiently than their typically developing peers (Haller et al., 2021; Huang-Pollock et al., 2017, 2020; Karalunas et al., 2012). Studies have generally not found evidence for group differences in the speed-accuracy trade-off (Feldman & Huang-Pollock, 2021; Haller et al., 2021; Karalunas et al., 2012) or for associations between continuously measured ADHD symptoms and the speed-accuracy trade-off (Feldman & Huang-Pollock, 2021); although, one study found evidence of increased caution in a group of children with ADHD (Fosco et al., 2019). Evidence for differences in stimuli encoding and motor response execution time is mixed. One study reported that children with ADHD take less time to encode stimuli and prepare and execute motor responses (Metin et al., 2013) while other studies did not report any differences (Fosco et al., 2019; Karalunas et al., 2012). Overall, these findings are equivocal. This may be because the studies used a variety of tasks probing various cognitive and perceptual abilities. It is unclear whether DDM parameters are best considered task-invariant latent constructs (Schmiedek et al., 2007) or whether differences in them arise from differing task demands (Koziol, 2014). In the current study, we focused our cognitive modeling on flanker task performance as a prototypical measure of cognitive inhibition (Zelazo et al., 2013), which, in comparison with other aspects of cognitive control, has been more frequently linked with motor control in children with and without ADHD (Livesey et al., 2006; Rigoli et al., 2012; Stöckel & Hughes, 2016).

Previous studies have not considered whether the processing efficiency, speed-accuracy trade-off, and time for encoding stimuli and motor response execution underlying cognitive inhibition are influenced by motor control abilities and moderated by hyperactive-impulsive symptoms. We tentatively hypothesised that motor generation would be positively associated with stimuli encoding and motor response time underlying cognitive inhibition, as at face value both involve the execution of motor actions. We also hypothesised that visuomotor fluency would be associated with the speed-accuracy trade-off, but we did not make a directional hypothesis because children who are better able to control their movement in response to visual stimuli could feasibly show more liberal (i.e., prioritizing speed) or more conservative (i.e., prioritizing accuracy) approaches in the speed-accuracy trade-off underlying cognitive inhibition. Additionally, we hypothesised that motor generation and visuomotor fluency would be positively associated with processing efficiency, because the ability to generate consistent, prolonged motor output and to adjust movement in response to consistent visual information might lead to increased processing efficiency underlying cognitive control. Finally, we explored whether these associations would be moderated by hyperactive-impulsive symptoms, but we did not make any specific hypotheses in this domain.

The current study

In summary, childhood ADHD involves difficulties with both motor and cognitive control. Indeed, motor control difficulties may contribute to cognitive control difficulties. However, current findings are equivocal. A key challenge is that motor control and cognitive control encompass several skills. To better understand and treat children's difficulties, it is important to clarify the relationship between motor control and cognitive control. The primary aims of our study were to investigate which aspects of motor control (motor generation, visuomotor fluency, and visuomotor flexibility) are associated with which aspects of cognitive control (cognitive inhibition, working memory, and cognitive flexibility) and whether these relationships are moderated by hyperactive-impulsive symptoms. We focused on the moderating role of hyperactive-impulsive ADHD symptoms, rather than inattentive or combined ADHD symptoms, because of the overlapping neural bases for motor control, trait hyperactivity-impulsivity, and cognitive control; namely, cortico-striatal loops (Diamond, 2013; Sharma & Couture, 2014). Recent research suggests inattentive symptoms are linked with abnormal functioning of the default mode network, which is associated with (internally focussed) cognitive processing (Bozhilova et al., 2018) but not directly linked with motor functioning in childhood. Subsequently, we decided to focus on proximal neurocognitive constructs in this initial study. We also used cognitive modeling to indicate *how* motor control might influence cognitive inhibition in terms of processing efficiency, the speed-accuracy trade-off, and encoding of stimuli and motor execution time underlying cognitive inhibition. We anticipated that our study would provide foundational knowledge, which may highlight potential avenues for early intervention for children with motor and cognitive issues, such as cognitive remediation programmes.

Methods

Our hypotheses, methods, and analyses were pre-registered after data collection had begun: https://osf.io/nphb9. Our methods section is a near reproduction of our preregistration document. Deviations from the pre-registered analysis plan are stated below.

Participants

Recruitment and sample

Data were collected from 399 children between 4 to 10 years of age who were referred to the Neurodevelopment Assessment Unit at Cardiff University. Ethical approval was gained from the University (EC.16.10.11.4592GRA5). Children were referred for a range of cognitive and socio-emotional problems at school. Recruitment was from schools across South Wales who referred children for assessment with parental consent. The referrer received a report describing the child's strengths/needs on a battery of standardised tasks including tests of cognitive inhibition, cognitive flexibility, working memory, episodic memory, sustained attention, verbal and nonverbal reasoning, emotion recognition, and theory of mind alongside recommended compensatory strategies (the reports were overseen by an Educational Psychologist). Data for 255 children were available following the exclusion of missing data. Children in this sample were 6.5 years old on average ($SD = 1.1$). Approximately 31% of this sample were female and 64% male; sex data were unavailable for 5% participants. 25.9% met criteria for combined ADHD, 6.3% met criteria for hyperactive-impulsive ADHD, and 4.3% met criteria for inattentive ADHD as assessed by the Development and Well-Being Assessment (DAWBA; Goodman et al., 2000). On average, children were missing data for 2.7 variables; 60% children were missing data for at least one variable. The number of missing data points for model variables per child was weakly but significantly correlated with age ($r_\tau = -0.20$, $p < .001$), suggesting that younger children had greater difficulty completing the motor and cognitive tasks.

Data for a subset of 150 children were used for cognitive modeling (inclusion/exclusion criteria are described below). Approximately, 31% this subsample were female and 68% were male; sex data were unavailable for 0.7% participants. In the subsample, 2.7%

children met criteria for hyperactive-impulsive ADHD, 4.0% met criteria for inattentive ADHD, and 12% met criteria for combined ADHD. Further characteristics of the sample(s) are summarised in Table 1.

Inclusion/exclusion criteria

It was intended that children would be excluded if they had estimated general cognitive functioning below a scaled score of 70 (where $M = 100$, $SD = 15$) on the Lucid Ability Test (Singelton, 2001), to ensure that individual differences in motor and cognitive control ability were investigated, rather than the effects of very low general cognitive ability and possible intellectual disability. However, no children scored below this criterion. Levels of anxiety, low mood, or developmental co-ordination disorder were not exclusion criteria.

Power analysis

An a priori power calculation using G*Power (Faul et al., 2009) indicated that a sample of at least 153 children was needed to confer at least 80% power to detect a relatively small

Table 1. Descriptive statistics for the main sample and the cognitive modelling subsample.

	Main sample ($N = 255$)		Cognitive modelling subsample ($n = 150$)	
	Mean (*SD*)	Median (MAD)	Mean (*SD*)	Median (MAD)
Contextual variables				
Age (years)	6.5 (1.1)	6.50 (1.4)	6.6 (0.9)	6.6 (1.1)
IQ (estimated)	98.3 (12.0)	98.0 (11.9)	99.9 (12.0)	99.0 (13.3)
Anxiety	63.4 (12.2)	62.0 (15.6)	62.8 (11.5)	61.0 (13.3)
Low mood	62.8 (9.9)	60.0 (11.9)	62.4 (9.7)	60.0 (11.9)
Coordination	45.5 (13.3)	45.0 (14.8)	46.6 (13.4)	47.0 (13.3)
ADHD Symptoms				
Hyperactive-Impulsive	11.0 (6.7)	13.0 (6.2)	10.8 (6.0)	13.0 (5.9)
Inattentive	10.8 (6.0)	12.0 (5.9)	10.5 (5.9)	11.0 (5.9)
Motor control tasks				
Tapping (motor generation)	−1.0 (1.7)	−0.39 (1.1)	−1.2 (1.8)	−0.6 (1.4)
Tracking (visuomotor fluency)	−2.4 (3.3)	−1.40 (2.1)	−2.1 (2.7)	−1.3 (1.9)
Pursuit (visuomotor flexibility)	−2.1 (5.4)	−0.30 (1.7)	−1.5 (3.4)	−0.5 (1.5)
Cognitive control tasks				
Flanker (cognitive inhibition)	93.0 (14.9)	94.0 (11.9)	99.1 (11.1)	100.0 (14.8)
DCCS (cognitive flexibility)	95.5 (14.1)	96.0 (10.4)	95.6 (14.2)	97.5 (8.2)
BDR (verbal working memory)	98.7 (16.5)	98.0 (16.3)	101 (16.5)	100 (14.8)
Mr X (visuospatial working memory)	106.1 (17.2)	104.0 (17.8)	111 (17.0)	111 (14.8)
Mr X Processing (working memory manipulation)	103.8 (16.6)	99.0 (13.3)	108 (17.0)	104 (17.8)
Cognitive modelling parameter estimates				
Drift rate (processing efficiency)	-	-	0.14 (0.0)	0.14 (0.0)
Boundary separation (speed-accuracy trade-off)	-	-	0.22 (0.0)	0.23 (0.0)
Nondecision time (stimuli encoding and motor execution)	-	-	0.73 (0.3)	0.70 (0.3)

Note: Statistics are based on untransformed data. Anxiety and low mood data are T scores from the Child Behaviour Checklist, with higher scores representing greater severity (Achenbach & Rescorla, 2000). Coordination data reflect total score on the Developmental Coordination Disorder Questionnaire (Wilson et al., 2009). ADHD symptoms reflect raw scores from the DAWBA. Motor control task data are z scores. Cognitive control task data are standardise scores with a mean of 100 and a standard deviation of 15. ADHD: Attention Deficit Hyperactivity Disorder. BDR: Backwards Digit Recall. DCCS: Dimensional Change Card Sort Task. IQ: Overall cognitive ability estimated with the Lucid Ability Test. MAD: Median absolute deviation. Mr X: Mister X. *SD*: Standard deviation.

relationship of $f^2 = 0.065$ between motor control and cognitive control, given the inclusion of seven predictors in a linear multiple regression model with R^2 increase. The anticipated effect size was selected from Rigoli et al. (2012) who observed that motor control significantly predicted a small portion of the variance (equivalent to $f^2 = 0.065$) on a test of inhibition in a sample of adolescents.

Measures

Motor control

Motor generation. The Amsterdam Neuropsychological Tasks (ANT; de Sonneville, 1999) Tapping task is a measure of self-generated motor output without internal or external cues (Rommelse et al., 2008). Children must click a computer mouse button with their dominant hand as many times as possible within a 60-second time limit. The task was validated in a convenience sample of 913 children (de Sonneville, 2022). The task generates a z-score for the number of taps generated, which is referenced to an age-stratified normative sample. Tapping shows high test-retest reliability in children (Njiokiktjien, 2007, p. 195).

Visuomotor fluency. ANT Tracking is a test of visuomotor fluency (Slaats-Willemse et al., 2005). Children must trace a circle with a computer mouse and cursor with their dominant hand. Thus, movement follows a predefined trajectory during the task. Validity was established in a convenience sample of 1,789 children (de Sonneville, 2022). Tracking provides norm-referenced z-scores for accuracy (i.e., the mean distance from the midline averaged across equal-sized segments of the circle) and variability (i.e., the standard deviation of the mean distance from the midline averaged across equal-sized segments of the circle) of movement. As accuracy and variability were very strongly related ($r = 0.91$), only the z-scores for accuracy were included in statistical models to guard against multicollinearity. Scores were reversed so that higher values represented better performance.

Visuomotor flexibility. ANT Pursuit is a test of visuomotor flexibility (Slaats-Willemse et al., 2005). Children must follow an on-screen target, which moves in an unpredictable manner, with a computer mouse and a cursor. Thus, movement during the task is spontaneous. Validity was established in a convenience sample of 1,789 children (de Sonneville, 2022). Pursuit also provides norm-referenced z-scores for accuracy (i.e., the mean distance from the trajectory of a target moving in an unpredictable manner) and variability (i.e., the standard deviation of the mean distance from the trajectory of a target moving in an unpredictable manner) of movement. However, due to a very strong correlation between accuracy and variability ($r = 0.90$), only the accuracy z-scores were included in models. Scores were reversed so that higher values signified better performance.

Hyperactive-impulsive symptoms

Development and wellbeing assessment ADHD hyperactivity symptom score. The Hyperactivity score from the Development and Well-Being Assessment (DAWBA) Attention and Activity scale was used as a measure of hyperactive-impulsive ADHD symptoms (Goodman et al., 2000). The DAWBA is a structured interview with a parent as the informant. The score was entered as covariate in the regression analyses described below.

Cognitive control

Cognitive inhibition. The National Institute of Health (NIH) Toolbox Flanker is a test of cognitive inhibition (Zelazo et al., 2013). Children must selectively attend to a central target stimulus while inhibiting attention to laterally placed stimuli. Children aged 3–7 years old are initially presented with 20 trials of fish stimuli (12 congruent, 8 incongruent). If a child aged 3–7 scores ≥90% on the fish stimuli, 20 additional trials with arrows are presented (12 congruent, 8 incongruent). Children aged 8+ are presented with 20 trials of arrow stimuli (12 congruent, 8 incongruent). The task provides a single combined score for accuracy and, for participants who achieve more than 80% accuracy, reaction times. This score is age-corrected by reference to normative data. Test-retest reliability is .92 (Zelazo et al., 2013). Individual trial data for accuracy and reaction time were used for cognitive modeling (see below).

Cognitive flexibility. The NIH Toolbox Dimensional Change Card Sort (DCCS) task is a test of cognitive flexibility (Zelazo, 2006). Children must sort a series of cards according to one rule (by color or shape) before this rule changes and they must sort the series of cards according to a new rule. The DCCS task provides a single combined score for accuracy and, for participants who achieve more than 80% accuracy, reaction times. This score is age-corrected by reference to normative data stratified by year of age. Test-retest reliability is .92 (Zelazo et al., 2013).

Verbal working memory. The Automated Working Memory Assessment (AWMA) Backwards Digit Recall is a test of verbal working memory (Alloway et al., 2006). Children hear a sequence of digits, which increases in length on subsequent trials, and must recall the numbers in backwards order. The score is age-corrected by reference to normative data stratified by year of age. Test-retest reliability is .64 (Alloway et al., 2008).

Visuospatial working memory. AWMA Mister X is a test of visuospatial working memory (Alloway et al., 2006). Children are presented with two figures with different colored hats who are holding a ball in one of two hands. One of these figures is rotated. Children are asked whether the two figures are holding the ball in the same or different hands and then to recall where the figure with the blue hat was holding the ball. Two metrics are generated, an accuracy score (which reflects foundational visuospatial working memory abilities such as capacity and maintenance) and a processing score (which reflects the manipulation aspect of visuospatial working memory). Each measure is expressed as a standard score ($M = 100$, $SD = 15$) which is age-corrected by reference to normative data. Test-retest reliability is .77 (Alloway et al., 2006).

Statistical analyses

Multiple linear regression analyses

Several multiple linear regression analyses were used to examine individual differences in motor control, cognitive control, and hyperactive-impulsive ADHD symptoms. The model terms were pre-registered in accordance with the study hypotheses. Post-hoc simple slope analyses were also planned to understand any moderation effects, but these were not necessary (as all moderation terms were non-significant). Children were excluded from an analysis if they were missing data for the variables included in that analysis. A data imputation strategy was not used. Two outliers were removed from Tracking task data (z scores of −22.4 and −22.5) and a single outlier was removed from data for the Pursuit (a z score of − 63.0) task after inspecting pre-transformation histograms (see Appendix A). Deviating from the preregistration, data were transformed using non-paranormal transformation (Liu et al., 2009) prior to analysis to better meet the assumptions of multiple linear regression. This transformation method maintains ordinality and therefore preserves the interpretability of variables while meeting model assumptions (Epskamp & Fried, 2018). Following transformation, data approximated all assumptions for multiple linear regression analysis (see Appendix B). An overall alpha level of 0.05 was set as the threshold for statistical significance. Holm-Bonferroni correction was used when there were multiple models that could each support the same hypothesis (i.e., models for Backward Digit Recall and Mister X could both support the hypothesis that motor generation was associated with working memory).

Cognitive modelling

The EZ-DM method (Wagenmakers et al., 2007, 2008) was used to estimate a basic Drift-Diffusion Model (DDM; Ratcliff & McKoon, 2008) of performance on the NIH Flanker task for a pragmatically selected subset of 150 children (see inclusion/exclusion criteria below). The DDM assumes that while making a binary decision (e.g., whether to click left or right on a flanker task), information is continuously sampled, in a noisy diffusion-like process, from the displayed stimuli array until enough evidence has accumulated to make a response (Ratcliff & McKoon, 2008). A response occurs once one of two thresholds has been crossed. The accuracy of the response depends on which threshold was hit during the decision process.

The EZ-DM method provides parameter estimates for drift rate, boundary separation, and non-decision time parameters based on mean reaction time, the variance of reaction time, and the percentage of correct responses on the Flanker task. Drift rate is the average slope of the diffusion process and reflects the efficiency with which information is sampled. Boundary separation refers to the distance between the two decision thresholds. Larger values lead to longer decision processes on average, whereas smaller values lead to shorter decision processes on average. A larger (smaller) boundary separation value implies a more conservative (liberal) decision-making style as more (less) evidence is needed for a decision to be made. Non-decision time refers to the time before and after the decision process (which is characterised by drift rate and boundary separation) and reflects the time needed for stimuli encoding and motor response execution (Ratcliff & McKoon, 2008). Congruent and incongruent Flanker trials were modeled in parallel and then the EZ-DM parameter estimates were averaged, giving rise to combined estimates which were statistically analyzed.

Inclusion/exclusion criteria for cognitive modelling. Children who attempted the full 40 trial version of the task and who had available trial by trial data necessary for modeling were eligible for inclusion. Children who only completed a 20-trial version of the NIH Flanker task were excluded in order to maximise trial numbers and therefore the accuracy of EZ-DM parameter estimates. Trials featuring non-physiologic anticipation responses (RT ≤150 ms) were excluded from cognitive modeling (as in Haller et al., 2021). Slow responses of ≥3 seconds were also excluded (Ratcliff, 2008).

Robustness checks. Prior to inferential analysis, two checks were performed to ensure that the EZ-DM parameter estimates were robust. First, a parameter recovery routine was used to assess the relative fit of EZ-DM estimates to the empirical data. Second, a comparison of empirical and simulated summary statistics was used to assess the absolute fit of EZ-DM modeling. Both checks suggested acceptable robustness. Additionally, correlational analysis was used to check whether all EZ-DM parameters were associated with the NIH Flanker score. Full details of these checks are presented in Appendix D.

Results

Descriptive statistics

Descriptive statistics are presented in Table 1. The descriptive statistics reveal that, on average, children performed within normal limits (±1 *SD*) on tests of cognitive control and general cognitive ability. This suggests that, as a sample, the children did not display marked cognitive control difficulties. However, children performed considerably poorer on standardised tests of motor functioning, indicating that they experienced difficulties with motor control. As a sample, the children scored particularly low on visuomotor fluency. Parent ratings of motor coordination suggested elevated levels of difficulties (Wilson et al., 2009), consistent with the performance of the children on motor tasks. Anxiety and low mood levels were slightly elevated in comparison to a typically developing normative sample but were in keeping with a group of children with a diagnosis of ADHD (Redmond & Ash, 2014).

Bivariate Pearson's correlations amongst transformed variables, which were used in the inferential analyses, are displayed in Table 2. In these preliminary analyses, Tracking

Table 2. Correlations amongst transformed variables.

	Background variables		Motor control tasks			Sx	Cognitive control tasks			
	Age	IQ	TP	TR	PU	HI	FL	DC	BD	MX
IQ	−.11									
TP	−.11	**.14**								
TR	**.27**	**.23**	**.24 (.21)**							
PU	**.33**	**.27**	**.13** (.01)	**.52 (.51)**						
HI	**.26**	.07	−.01	**.13**	.11					
FL	.05	**.26**	.00	**.23**	**.27**	.12				
DC	−.07	**.44**	.12	**.14**	**.19**	.08	**.35 (.32)**			
BD	−.10	**.37**	.11	.10	**.21**	.00	**.14** (.03)	**.30 (.25)**		
MX	−.08	**.24**	.05	.00	.08	**.37**	.08 (.05)	.11 (.00)	**.31** (.06)	
MP	−.08	**.24**	.03	.06	.10	**.36**	.06 (.04)	.11 (.00)	**.22 (.13)**	**.83 (.82)**

Note: Correlations outside of brackets are bivariate, correlations within brackets are partial correlations controlling for other variables in their category (e.g., other motor control tasks). Correlations in bold are significant at the 0.05 level. ADHD: Attention Deficit Hyperactivity Disorder. BD: Backwards Digit Recall (verbal working memory). DC: Dimensional Change Card Sort (cognitive flexibility). FL: Flanker (cognitive inhibition). HI: Hyperactive-Impulsive Symptoms. IQ: Lucid Ability Test (overall cognitive ability). MX: Mister X (visuospatial working memory). MX P: Mister X Processing (visuospatial working memory manipulation). PU: Pursuit (visuomotor flexibility). Sx: Symptoms. TP: Tapping (motor generation). TR: Tracking (visuomotor fluency).

(visuomotor fluency) and Flanker (cognitive inhibition) performance (r = 0.23, 95% CI = 0.11, 0.34, $p < .001$) and Tracking and Dimensional Change Card Sort (cognitive flexibility) performance (r = 0.14, 95% CI = 0.02, 0.26, $p = .02$) were significantly correlated. Tracking was also significantly related to Hyperactive-Impulsive Symptoms (r = 0.13, 95% CI = 0.00, 0.25, $p = .04$). Additionally, Pursuit (visuomotor flexibility) and Flanker (r = 0.27, 95% CI = 0.15, 0.38, $p < .001$), Pursuit and Dimensional Change Card Sort (r = 0.14, 95% CI = 0.07, 0.30, $p < .001$), and Pursuit and Backwards Digit Recall (verbal working memory) performance (r = 0.21, 95% CI = 0.09, 0.33, $p < .001$) were significantly associated. Hyperactive-Impulsive Symptoms and Mister X (working memory) performance (r = 0.37, 95% CI = 0.26, 0.47, $p < .001$) and Hyperactive-Impulsive Symptoms and Mister X Processing (working memory manipulation) performance (r = 0.36, 95% CI = 0.25, 0.46, $p < .001$) were significantly correlated. Finally, Tapping (motor generation) was not significantly associated with any cognitive control variable.

Inferential analyses

All inferential analyses were conducted in accordance with the pre-registered analysis plan. The results for all multiple linear regression analyses are shown in Table 3. All statistically significant results remained as such after including age in each model (see Appendix C).

Table 3. Multiple linear regression analyses of motor control and cognitive control tasks.

Hyp.	Dependent and predictor variables	Adj. R^2	β	SE	t	*p*
A1	Flanker (cognitive inhibition)	0.05				**.002**
	Intercept		−0.00	0.06	−0.01	.99
	• Tapping (motor generation)		−0.07	0.07	−1.07	.29
	• Tracking (visuomotor fluency)		0.21	0.06	3.32	**.001**
	• Hyperactive-Impulsive Sx		0.10	0.06	1.52	.13
	• Tapping * Hyperactive-Impulsive Sx		0.08	0.07	1.05	.29
A2	Backwards Digit Recall (verbal working memory)	0.01				.13
	Intercept		0.00	0.06	0.04	.96
	• Tapping (motor generation)		0.08	0.07	1.17	.24
	• Hyperactive-Impulsive Sx		0.01	0.06	0.13	.90
	• Tapping * Hyperactive-Impulsive Sx		0.12	0.07	1.61	.11
A2	Mister X (visuospatial working memory)	0.13				**< .001**
	Intercept		−0.00	0.06	−0.03	.98
	• Tapping (motor generation)		0.07	0.06	1.06	.29
	• Hyperactive-Impulsive Sx		0.38	0.06	6.34	< **.001**
	• Tapping * Hyperactive-Impulsive Sx		−0.05	0.07	−0.74	.46
A3	Mister X Processing (working memory manipulation)	0.12				< **.001**
	Intercept		−0.02	0.06	−0.28	.78
	• Tracking (visuomotor fluency)		−0.04	0.07	−0.57	.57
	• Pursuit (visuomotor flexibility)		0.06	0.07	0.86	.39
	• Hyperactive-Impulsive Sx		0.36	0.06	5.87	**< .001**
	• Tracking * Hyperactive-Impulsive Sx		0.08	0.08	0.96	.34
	• Pursuit * Hyperactive-Impulsive Sx		0.05	0.08	0.61	.54
A4	Dimensional Change Card Sort (cognitive flexibility)	0.03				**.029**
	Intercept		0.00	0.06	0.01	.99
	• Tapping (motor generation)		0.09	0.07	1.38	.17
	• Tracking (visuomotor fluency)		0.04	0.07	0.48	.63
	• Pursuit (visuomotor flexibility)		0.15	0.07	2.09	**.037**
	• Hyperactive-Impulsive Sx		0.06	0.06	0.94	.35
	• Tapping * Hyperactive-Impulsive Sx		−0.01	0.08	−0.13	.90

Note: Bold text denotes statistically significant results. The alpha level was 0.05 for each model. Hyp: Relevant hypothesis. Sx: Symptoms.

Part A: hypotheses regarding associations between specific aspects of motor and cognitive control

Hypothesis 1: motor generation and visuomotor fluency would be positively associated with cognitive inhibition

A multiple linear regression model containing Tapping (motor generation), Tracking (visuomotor fluency), Hyperactive-Impulsive Symptoms, and Tapping/Tracking and Hyperactive-Impulsive Symptoms interaction terms significantly predicted 5% of the variance in Flanker (cognitive inhibition) performance (Adjusted $R^2 = 0.08$, $F(4, 250) = 4.40$, $p = .002$). Only Tracking was a significant predictor of Flanker (cognitive inhibition) performance within the model ($\beta = 0.21$, 95% CI = 0.09, 0.34, $p = .001$).

Hypothesis 2: motor generation would be positively associated with working memory

A model containing Tapping (motor generation), Hyperactive-Impulsive Symptoms, and a Tapping and Hyperactive-Impulsive Symptoms interaction term did not significantly predict Backwards Digit Recall (verbal working memory) performance (Adjusted $R^2 = 0.01$, $F(3,251) = 1.91$, $p = 0.13$). However, a model containing identical terms did significantly explain 13% of the variance in Mister X (visuospatial working memory) performance (Adjusted $R^2 = 0.13$, $F(3.251) = 13.86$, $p < .001$); although, only Hyperactive-Impulsive Symptoms was a significant predictor within the model ($\beta = 0.38$, 95% CI = 0.26, 0.5, $p = <.001$).

Hypothesis 3: visuomotor fluency and visuomotor flexibility would be positively associated with working memory manipulation

A model containing Tracking (visuomotor fluency), Pursuit (visuomotor flexibility), Hyperactive-Impulsive Symptoms and Tracking/Pursuit and Hyperactive-Impulsive Symptoms interaction terms collectively accounted for 12% of the variance in Mister X Processing (visuospatial working memory manipulation): Adjusted $R^2 = 0.12$, $F(5,249) = 8.14$, $p < .001$). Only Hyperactive-Impulsive Symptoms were a significant predictor within the model ($\beta = 0.36$, 95% CI = 0.26, 0.50, $p < .001$). Tracking (visuomotor fluency)/Pursuit (visuomotor flexibility) by Hyperactive-Impulsive Symptoms moderation terms were not significant predictors (see Table 3.)

Hypothesis 4: motor generation, visuomotor fluency, and visuomotor flexibility would be positively associated with cognitive flexibility

A model containing Tapping (motor generation), Tracking (visuomotor fluency), Pursuit (visuomotor flexibility), Hyperactive-Impulsive Symptoms and Tapping/Tracking/Pursuit and Hyperactive-Impulsive Symptoms interaction terms predicted 3% of the variance on the Dimensional Change Card Sort task (Adjusted $R^2 = 0.03$, $F(5,249) = 2.55$, $p = 0.029$). Only Pursuit was a significant predictor within the model ($\beta = 0.15$, 95% CI = 0.01, 0.30, $p = .037$).

Hypothesis 5: greater motor generation in children with higher levels of hyperactive-impulsive symptoms would be associated with poorer cognitive inhibition, working memory, and cognitive flexibility

The Tapping (motor generation) by Hyperactive-Impulsive Symptoms moderation terms in models for all cognitive inhibition (β = 0.08, 95% CI = −0.07, 0.20, p = .29), verbal working memory (β = 0.12, 95% CI = −0.03, 0.27, p = .11), visuospatial working memory (β = −0.05, 95% CI = −0.19, 0.09, p = .46), and cognitive flexibility (β = −0.10, 95% CI = −0.16, 0.14, p = .90) were all non-significant (see Table 3). Accordingly, post-hoc simple slopes analysis was not used.

Hypothesis 6: children with higher hyperactive-impulsive symptoms and poorer visuomotor fluency and visuomotor flexibility would display even poorer working memory manipulation

The Tracking (visuomotor fluency) and Pursuit (visuomotor flexibility) by Hyperactive-Impulsive Symptoms moderation terms in the Mister X Processing (working memory manipulation) multiple linear regression model were both non-significant (β = 0.08, 95% CI = −0.08, 0.23, p = .34and β = 0.05, 95% CI = −0.10, 0.20, p = .54; see Table 3), meaning post-hoc simple slopes analysis was not used.

Part B: hypotheses regarding specific processes underlying cognitive inhibition

Multiple linear regression analyses regarding our hypotheses that 1) motor generation ability would be positively associated with stimuli encoding and motor response execution time underlying cognitive inhibition, 2) visuomotor fluency would be associated with the speed-accuracy trade-off underling cognitive inhibition, and 3) motor generation and visuomotor fluency would be positively associated with processing efficiency underlying cognitive inhibition are reported in Table 4. In summary, these analyses revealed that the hypothesised motor control variables did not significantly predict component processes of NIH Flanker (cognitive inhibition) performance. Correlational analysis did not reveal any significant associations amongst cognitive modeling variables and NIH Flanker performance (see Appendix E); we consider potential explanations for this in our discussion.

Table 4. Multiple linear regression analyses of motor control and cognitive modelling variables.

Hyp.	Dependent and predictor variables	Adj. R^2	Est.	SE	t	p
B1	Drift rate (processing efficiency)	0.00				.39
	Intercept		0.00	0.08	−0.04	.97
	• Tapping (motor generation)		−0.06	0.08	−0.75	.46
	• Tracking (visuomotor fluency)		0.16	0.08	1.88	.06
	• Hyperactive-Impulsive Sx		−0.05	0.08	−0.55	.58
	• Tapping * Hyperactive-Impulsive Sx		−0.06	0.11	−0.55	.59
	• Tracking * Hyperactive-Impulsive Sx		0.09	0.09	0.96	.34
B2	Boundary separation (speed-accuracy trade-off)	0.00				.51
	Intercept		0.00	0.08	0.00	1
	• Tracking (visuomotor fluency)		−0.11	0.08	−1.33	0.18
	• Hyperactive-Impulsive Sx		−0.06	0.08	−0.75	0.45
	• Tracking * Hyperactive-Impulsive Sx		−0.02	0.09	−0.18	0.86
B3	Nondecision time (stimuli encoding and motor response execution)	0.01				.17
	Intercept		−0.02	0.08	−0.19	.85
	• Tapping (motor generation)		0.11	0.08	1.33	.18
	• Hyperactive-Impulsive Sx		−0.09	0.08	−1.12	.26
	• Tapping * Hyperactive-Impulsive Sx		−0.16	0.10	−1.58	.12

Note: The alpha level was set at 0.05. Hyp: Hypothesis. Sx: Symptoms.

Discussion

Motor and cognitive control difficulties co-occur in childhood ADHD. Indeed, difficulties with motor control may contribute to difficulties with cognitive control across the ADHD continuum (Koziol et al., 2013). Accordingly, motor control is a candidate target for early intervention to improve cognitive outcomes. However, the relationship between motor control and cognitive control is poorly understood. We sought to clarify which specific aspects of motor and cognitive control are related in children, and to test if these relationships are moderated by hyperactive-impulsive symptoms.

Our hypothesis that children's cognitive inhibition would be associated with their motor generation and visuomotor fluency was partly supported. Our analyses revealed that performance on a test of visuomotor fluency predicted a small portion of the variance in performance on a measure of cognitive inhibition. Children with better visuomotor fluency displayed better cognitive inhibition, which is consistent with the hypothesis that cognitive inhibition relies on this motor skill, although our cross-sectional analyses are not sufficient to demonstrate a causal relationship. In contrast, no evidence was found in favor of an association between motor generation and cognitive inhibition. Together, our findings imply that the ability to visually control movement in relation to predictable visual stimuli is associated with the ability to mentally inhibit the effects of distracting information. This interpretation is broadly consistent with previous research suggesting that manual dexterity is positively associated with cognitive inhibition (Livesey et al., 2006; Rigoli et al., 2012; Stöckel & Hughes, 2016). Moreover, our findings imply that it is the visual control of motor responses (i.e., visuomotor fluency) rather than the generation of motor actions that is linked with cognitive inhibition.

Additionally, our hypothesis that children's cognitive flexibility is associated with their motor generation, visuomotor fluency, and visuomotor flexibility abilities, was partially supported. A test of visuomotor flexibility was significantly associated with performance on the Dimensional Change Cart Sort task, which is a measure of cognitive flexibility. By contrast, cognitive flexibility was not associated with tests of motor generation or visuomotor fluency. Our findings suggest that being able to visually control movement in response to unpredictable visual stimuli is associated with the ability to change focus from one frame of mind to another. These results are consistent with a previous study which reported that visuomotor integration and motor coordination are positively associated with cognitive flexibility measured by an adapted Dimensional Change Card Sort Task (Fang et al., 2017). Moreover, our findings indicate that it is the ability to visually control movement in unpredictable situations, but not the ability to generate consistent movements over time or visually control movement in predictable situations, that underlies the association between visuomotor control and cognitive flexibility.

Our results did not support our other hypotheses. For example, we reasoned that children's ability to generate persistent motor output over time would support their ability to maintain information in working memory over time. However, neither verbal nor visuospatial working memory performance were associated with a test of motor generation. Additionally, visuospatial working memory manipulation was not associated with tests of visuomotor fluency and visuomotor flexibility, despite our theorizing that performing predictable and spontaneous visually guided movements was akin to manipulating information held in working memory. While the absence of evidence is not the same as evidence of absence, our findings indicate that motor generation, visuomotor fluency, and visuomotor flexibility are not strongly associated with working memory. Here, our findings contrast those from previous studies which found that motor skills are weakly but positively associated with verbal working memory manipulation (Wassenberg et al., 2005) and visuospatial working memory capacity (Rigoli et al., 2012; Stöckel & Hughes, 2016). One potential reason for this discrepancy is that working memory, like cognitive inhibition and cognitive flexibility, is a broad construct encompassing several dissociable subprocesses (Baddeley, 2012). It is possible that only certain working memory subprocesses depend on motor control and that these elements were better tapped by the measures used or the association was stronger in the samples used in previous studies.

Building on Koziol et al. (2013) suggestion that motor control contributes to difficulties with cognitive control across the ADHD continuum, we hypothesised that hyperactive-impulsive symptoms would moderate associations between motor control and cognitive control. Specifically, we reasoned that associations between motor generation and several aspects of cognitive control (cognitive inhibition, working memory, and cognitive flexibility) become negative in children with higher hyperactive-impulsive symptoms. We made this hypothesis considering J. A. Sergeant (2005), J. Sergeant (2000) theorizing around levels of physiological activation having a non-linear association with cognitive processing with both too much and too little activation undermining performance. Accordingly, we expected the relationship between motor generation and executive functioning abilities to become negative in children with higher levels of hyperactive-impulsive symptoms because children with these traits can exhibit too much physiological activation (Burley et al., 2021; Murillo et al., 2015). We also suggested that children with lower visuomotor fluency and visuomotor flexibility abilities and higher levels of hyperactive-impulsive symptoms would display poorer levels of working memory manipulation than children with lower levels of hyperactive-impulsive symptoms. Contrary to our expectations, we did not find any evidence that associations between specific aspects of motor control and cognitive control were moderated by hyperactive-impulsive symptoms. This finding might be because we used a parent-informant measure of hyperactivity-impulsivity which could capture different facets of hyperactivity-impulsivity or parental distress in comparison with objective measures of hyperactivity, such as actigraphy (Burley et al., 2021). Subsequently, our results indicate that children with different levels of parent-reported hyperactive-impulsive symptoms have similar relationships between specific aspects of motor control and cognitive control.

Another aim of our study was to understand the relationship between motor control and cognitive inhibition (e.g., Livesey et al., 2006; Rigoli et al., 2012; Stöckel & Hughes, 2016) in more detail. To this end, we used cognitive modeling to break down the Flanker task performance into processing efficiency, speed-accuracy trade-off, and stimuli encoding and motor response execution time components (Ratcliff & McKoon, 2008; Wagenmakers et al., 2007). We predicted that these component processes would be differentially associated with motor generation, visuomotor fluency, and visuomotor flexibility. However, in contrast with our expectations, no aspect of motor control was significantly associated with any component processes. Paradoxically, while our cognitive modeling was acceptably robust, correlational analysis suggested that none of the component processes were significantly associated with the NIH Flanker score. One explanation is that the NIH Flanker task uses a complex scoring method (see measures section for an explanation) which can include a combination of reaction time and accuracy data or just accuracy data, depending on whether a child meets an accuracy criterion (Zelazo et al., 2013). These scores are then standardised with reference to a normative sample. By contrast, our cognitive modeling methods used raw reaction time and accuracy data from the Flanker task, with reaction times exceeded three seconds being discarded. Subsequently, the NIH Flanker score and the cognitive modeling components may have been sensitive to different aspects of Flanker task performance. To aid interpretability, future studies should use traditional task scores and cognitive models based on identical data.

Our study can inform cognitive remediation interventions for children with motor and cognitive differences (e.g., Meyer et al., 2020; Pauli-Pott et al., 2021). Specifically, our findings draw attention to difficulties in visually controlling movement as a potential target for early intervention to minimise the risk of poor cognitive control outcomes, which are predictive of poorer life outcomes (Moffit et al., 2011). Treating visuomotor control issues might improve cognitive outcomes, given that the development of motor control begins before the development of cognitive control (Njiokiktjien, 2007; Piek et al., 2008). Training on visuomotor fluency and visuomotor flexibility tasks might lead to improvement in cognitive inhibition and cognitive flexibility abilities. Improving visuomotor fluency and visuomotor flexibility might also serve as a useful adjunct to exercise-based interventions. There is systematic review evidence for exercise as an intervention to improve cognitive control in typically developing children (Bidzan-Bluma & Lipowska, 2018) and those with a diagnosis of ADHD (Den Heijer et al., 2017). Aerobic exercises (e.g., running) appear to be particularly beneficial for cognitive functioning. Emphasizing visuomotor control skills (e.g., passing a baton in a relay) during this type of exercise might result in incremental cognitive benefits.

There are at least four limitations with our study. First, while our study design enabled the investigation of individual differences in hyperactive-impulsive symptoms, it did not enable consideration of clinical versus non-clinical group differences. Such comparisons would not have been appropriate given that only a small minority of children in our sample (25.8%) met diagnostic criteria for ADHD and fewer still met criteria for the hyperactive-impulsive subtype (6.3%) where these symptoms predominate. Still, a mixed modeling approach would facilitate the investigation of relationships amongst motor control, cognitive control, and hyperactive-impulsive symptoms in the context of whether or not children cross clinical thresholds for ADHD.

Second, there are also potential limitations with the simultaneous entry multiple linear regression approach employed. Simultaneous entry regression was used instead of hierarchical regression because of the absence of prior research looking specifically at motor generation, visuomotor fluency, and visuomotor flexibility, which meant that there was not an obvious principled way to dictate which motor variables to enter in which order as part of a hierarchical approach. It has been argued that simultaneous entry is the most appropriate method for hypothesis testing (Studenmund & Cassidy, 1987) as opposed to exploratory research. However, simultaneous entry is less appropriate when there is a high number of candidate predictors (Kucuk et al., 2016); for example, our tests of hypotheses three and four involved five predictors in total, including two interaction terms. To address this limitation, future research can use our preliminary findings associating visuomotor fluency with cognitive inhibition and visuomotor flexibility with cognitive flexibility as the basis for theoretically motivated hierarchical linear regression models.

Third, while our study establishes statistical associations between specific aspects of motor control and cognitive control, it does not demonstrate causal relationships. To investigate causality, future research could use longitudinal methods to confirm that motor control differences/difficulties precede cognitive differences/difficulties and experimental method, such as increasing the motor demands of cognitive control tasks to investigate a direct effect of motor control on cognitive control. Additionally, treatment studies based on the clinical implications of our study could provide evidence of causal relationships. For example, if an intervention targeting visual control of movement in unpredictable settings led to cognitive improvements in flexibly switching between frames of mind, this would imply that motor flexibility directs cognitive flexibility.

Finally, the generalizability of our findings associating visuomotor fluency with inhibition and visuomotor flexibility and cognitive flexibility are unclear. The Flanker task involves the inhibition of attention in the context of distracting visual stimuli and the Dimensional Change Card Sort Task involves cognitive flexibility in the context of visual stimuli. Other tests of cognitive inhibition and cognitive flexibility were not used although it is known that they may probe differing neurocognitive mechanisms (Kornblum, 1994; Paap et al., 2020). It remains to be seen whether the associations established in our study generalise to other aspects of cognitive inhibition and flexibility, such as in the verbal domain (e.g., Burgess & Shallice, 1997). Additionally, future research could shed light on whether the associations seen in our study are invariant across sexes (Seymour et al., 2016).

Conclusion

In conclusion, our study identifies two links between specific aspects of motor control and cognitive control. First, the ability to fluently perform visually guided movement in predictable contexts is weakly associated with the ability to cognitively inhibit the effect of conflicting visual information. Second, the ability to flexibly perform visually guided movement in unpredictable contexts is weakly associated with the ability to flexibly shift attention from one frame of mind to another. Contrary to our hypotheses, these relationships appear to be quantitatively (i.e., of a similar strength) and qualitatively (i.e., of the same direction) similar across the hyperactive-impulsive continuum in childhood. That is, children with low and high levels of hyperactive-impulsive symptoms display similar relationships between motor and cognitive control. Unfortunately, only a small proportion of children in the sample met clinical criteria for ADHD and causal statements about the influence of motor control *on* cognitive control cannot be made as the study was cross-sectional. In addition to helping to clarify the theoretically important but poorly understood relationships between motor and cognitive control, our findings indicate that early interventions and adjunctive treatments targeting visuomotor control might incrementally benefit cognitive functioning in childhood. Moreover, our findings suggest that such interventions might be equally beneficial for children with high and low levels of parent-reported hyperactive-impulsive symptoms.

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ORCID

Cameron Ferguson http://orcid.org/0000-0001-5248-1182

References

Achenbach, T. M., & Rescorla, L. A. (2000). *Manual for the ASEBA preschool forms and profiles*. University of Vermont Department of Psychiatry.

Alloway, T. P., Gathercole, S. E., Kirkwood, H., & Elliott, J. (2008). Evaluating the validity of the automated working memory assessment. *Educational Psychology*, *28*(7), 725–734. https://doi.org/10.1080/01443410802243828

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development*, *77*(6), 1698–1716. https://doi.org/10.1111/j.1467-8624.2006.00968.x

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5thed.). American Psychiatric Association.

Anderson, P. (2010). Assessment and development of Executive Function (EF) during childhood. *Child Neuropsychology*, *8*(2), 71–82. https://doi.org/10.1076/chin.8.2.71.8724

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Psychology*, *63*(1), 1–29. https://doi.org/10.1146/annurev-psych-120710-100422

Barrouillet, P., & Camos, V. (2007). The time-based resource sharing model of working memory. In O. Naoyuki, R. H. Logie, & M. D'Esposito (Eds.), *The cognitive neuroscience of working memory* (pp. 59–80). Oxford University Press.

Bellebaum, C., & Daum, I. (2007). Cerebellar involvement in executive control. *The Cerebellum*, *6* (3), 184–192. https://doi.org/10.1080/14734220601169707

Bernstein, J. H. (2013). Process analysis in the assessment of children. In L. Ashendorf, R. Swenson, & D. J. Libon (Eds.), *The Boston Process Approach to neuropsychological assessment: A practitioner's guide* (pp. 300–313). Oxford University Press.

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child Development*, *81*(6), 1641–1660. https://doi.org/10.1111/j.1467-8624.2010.01499.x

Bidzan-Bluma, I., & Lipowska, M. (2018). Physical activity and cognitive functioning of children: A systematic review. *International Journal of Environmental Research and Public Health*, *15*(4), 800. https://doi.org/10.3390/ijerph15040800

Blaedel, J. R., & Bracha, V. (1997). Duality of cerebellar motor and cognitive functlons. *International Review of Neurobiology*, *41*, 613–634. https://doi.org/10.1016/s0074-7742(08)60373-6

Bozhilova, N. S., Michelini, G., Kuntsi, J., & Asherson, P. (2018). Mind wandering perspective on attention-deficit/hyperactivity disorder. *Neuroscience and Biobehavioral Reviews*, *92*, 464–476. https://doi.org/10.1016/j.neubiorev.2018.07.010

Burgess, P., & Shallice, T. (1997). *The Hayling and Brixton tests. Test manual*. Thames Valley Test Company.

Burley, D. T., Anning, K. L., & van Goozen, S. H. M. (2021). The association between hyperactive behaviour and cognitive inhibition impairments in young children. *Child Neuropsychology*, *3*(3), 302–317. https://doi.org/10.1080/09297049.2021.1976128

Cragg, L., & Chevalier, N. (2012). The processes underlying flexibility in childhood. *The Quarterly Journal of Experimental Psychology*, *65*(2), 209–232. https://doi.org/10.1080/17470210903204618

Demers, M. M., McNevin, N., & Azar, N. R. (2013). ADHD and motor control: A review of the motor control deficiencies associated with attention deficit/hyperactivity disorder and current treatment options. *Critical Reviews in Physical and Rehabilitation Medicine*, *25*(3–4), 231–239. https://doi.org/10.1615/critrevphysrehabilmed.2013009763

Denckla, M. B., & Rudel, R. G. (1978). Anomalies of motor development in hyperactive boys. *Annals of Neurology*, *3*(3), 231–233. https://doi.org/10.1002/ana.410030308

Den Heijer, A. E., Groen, Y., Tucha, L., Fuermaier, A. B., Koerts, J., Lange, K. W., Thome, J., & Tucha, O. (2017). Sweat it out? The effects of physical exercise on cognition and behavior in children and adults with ADHD: A systematic literature review. *Journal of Neural Transmission*, *124*(1), 3–26. https://doi.org/10.1007/s00702-016-1593-7

de Sonneville, L. (1999). Amsterdam neuropsychological tasks: A computer-aided assessment program. In B. den Brinker, P. Beek, A. Brand, F. Maarse, & L. Mulder *Cognitive ergonomics, clinical assessment and computer-assisted learning: Computers in psychology* (Eds.), (Vol. 6, pp. 204–217). Swets & Zeitlinger.

de Sonneville, L. (2022). *Amsterdam neuropsychological tasks (english version)*. Boom Test Uitgevers.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*(1), 44–56. https://doi.org/10.1111/1467-8624.00117

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Epskamp, S., & Fried, E. I. (2018). A tutorial on regularized partial correlation networks. *Psychological Methods*, *23*(4), 617–634. https://doi.org/10.1037/met0000167

Fabio, R. A., Andricciola, F., & Caprì, T. (2022). Visual-motor attention in children with ADHD: The role of automatic and controlled processes. *Research in Developmental Disabilities*, *123*, 104193. https://doi.org/10.1016/j.ridd.2022.104193

Fang, Y., Wang, J., Zhang, Y., & Qin, J. (2017). The relationship of motor coordination, visual perception, and executive function to the development of 4–6-year-old Chinese preschoolers' visual motor integration skills. *BioMed Research International*, *2017*, 1–8. https://doi.org/10.1155/2017/6264254

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. -G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Feldman, J. S., & Huang-Pollock, C. (2021). Slow drift rate predicts ADHD symptomology over and above executive dysfunction. *Child Neuropsychology*, *27*(6), 1–22. https://doi.org/10.1080/09297049.2021.1902490

Fisk, J. E., & Sharp, C. A. (2004). Age-related impairment in executive functioning: Updating, inhibition, shifting, and access. *Journal of Clinical and Experimental Neuropsychology*, *26*(7), 874–890. https://doi.org/10.1080/13803390490510680

Fosco, W. D., Kofler, M. J., Alderson, R. M., Tarle, S. J., Raiker, J. S., & Sarver, D. E. (2019). Inhibitory control and information processing in ADHD: Comparing the dual task and performance adjustment hypotheses. *Journal of Abnormal Child Psychology*, *47*(6), 961–974. https://doi.org/10.1007/s10802-018-0504-9

Frank, M. J., & Badre, D. (2015). How cognitive theory guides neuroscience. *Cognition*, *135*, 14–20. https://doi.org/10.1016/j.cognition.2014.11.009

Friedman, N. P., & Miyake, A. (2017). Unity and diversity of executive functions: Individual differences as a window on cognitive structure. *Cortex*, *86*, 186–204. https://doi.org/10.1016/j.cortex.2016.04.023

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. *Psychological Bulletin*, *134*(1), 31–60. https://doi.org/10.1037/0033-2909.134.1.31

Goodman, R., Ford, T., Richards, H., Gatward, R., & Meltzer, H. (2000). The development and well-being assessment: Description and initial validation of an integrated assessment of child and adolescent psychopathology. *Journal of Child Psychology and Psychiatry*, *41*(5), 645–655. https://doi.org/10.1111/j.1469-7610.2000.tb02345.x

Goulardins, J. B., Marques, J. C., & Casella, E. B. (2011). Quality of life and psychomotor profile of children with attention deficit hyperactivity disorder (ADHD). *Arquivos de neuro-psiquiatria*, *69*(4), 630–635. https://doi.org/10.1590/s0004-282x2011000500011

Goulardins, J. B., Rigoli, D., Loh, P. R., Kane, R., Licari, M., Hands, B., Oliveira, J. A., & Piek, J. (2018). The relationship between motor skills, social problems, and ADHD symptomatology: Does it vary according to parent and teacher report? *Journal of Attention Disorders*, *22*(8), 796–805. https://doi.org/10.1177/1087054715580394

Haller, S. P., Stoddard, J., Pagliaccio, D., Bui, H., MacGillivray, C., Jones, M., & Brotman, M. A. (2021). Computational modeling of attentional impairments in disruptive mood dysregulation and attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry*, *60*(5), 637–645. https://doi.org/10.1016/j.jaac.2020.08.468

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach* (2nd ed.). Guilford Publications.

Hedge, C., Powell, G., Bompas, A., & Sumner, P. (2020). Self-reported impulsivity does not predict response caution. *Personality and Individual Differences*, *167*, 110257. https://doi.org/10.1016/j.paid.2020.110257

Henry, L. A., & Bettenay, C. (2010). The assessment of executive functioning in children. *Child and Adolescent Mental Health*, *15*(2), 110–119. https://doi.org/10.1111/j.1475-3588.2010.00557.x

Huang-Pollock, C., Ratcliff, R., McKoon, G., Roule, A., Warner, T., Feldman, J., & Wise, S. (2020). A diffusion model analysis of sustained attention in children with attention deficit hyperactivity disorder. *Neuropsychology*, *34*(6), 641–653. https://doi.org/10.1037/neu0000636

Huang-Pollock, C., Ratcliff, R., McKoon, G., Shapiro, Z., Weigard, A., & Galloway-Long, H. (2017). Using the diffusion model to explain cognitive deficits in attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology*, *45*(1), 57–68. https://doi.org/10.1007/s10802-016-0151-y

Kaiser, M.-L., Schoemaker, M. M., Albaret, J.-M., & Geuze, R. H. (2015). What is the evidence of impaired motor skills and motor control among children with attention deficit hyperactivity disorder (ADHD)? Systematic review of the literature. *Research in Developmental Disabilities*, *36*, 338–357. https://doi.org/10.1016/j.ridd.2014.09.023

Kalff, A. C., de Sonneville, L. M. J., Hurks, P. P. M., Hendriksen, J. G. M., Kroes, M., Feron, F. J. M., Steyaert, J., Zeben, T. M. C. B. V., Vles, J. S. H., & Jolles, J. (2005). Speed, speed variability, and accuracy of information processing in 5 to 6-year-old children at risk of ADHD. *Journal of the International Neuropsychological Society*, *11*(2), 173–183. https://doi.org/10.1017/s1355617705050216

Karalunas, S. L., Huang-Pollock, C. L., & Nigg, J. T. (2012). Decomposing Attention-Deficit/Hyperactivity Disorder (ADHD)-related effects in response speed and variability. *Neuropsychology*, *26*(6), 684–694. https://doi.org/10.1037/a0029936

Karr, J. E., Areshenkoff, C. N., Rast, P., Hofer, S. M., Iverson, G. L., & Garcia-Barrera, M. A. (2018). The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies. *Psychological Bulletin*, *144*(11), 1147–1185. https://doi.org/10.1037/bul0000160

Klotz, J. M., Johnson, M. D., Wu, S. W., Isaacs, K. M., & Gilbert, D. L. (2012). Relationship between reaction time variability and motor skill development in ADHD. *Child Neuropsychology*, *18*(6), 576–585. https://doi.org/10.1080/09297049.2011.625356

Kornblum, S. (1994). The way irrelevant dimensions are processed depends on what they overlap with: The case of Stroop- and Simon-like stimuli. *Psychological Research*, *56*(3), 130–135. https://doi.org/10.1007/bf00419699

Koziol, L. F. (2014). *The myth of executive functioning: Missing elements in conceptualization, evaluation, and assessment*. Springer International Publishing. https://books.google.co.uk/books?id=JUgxngEACAAJ

Koziol, L. F., Budding, D., Andreasen, N., D'arrigo, S., Bulgheroni, S., Imamizu, H., Ito, M., Manto, M., Marvel, C., Parker, K., Pezzulo, G., Ramnani, N., Riva, D., Schmahmann, J., Vandervert, L., & Yamazaki, T. (2014). Consensus paper: The Cerebellum's role in movement and cognition. *The Cerebellum*, *13*(1), 151–177. https://doi.org/10.1007/s12311-013-0511-x

Koziol, L. F., Budding, D. E., & Chidekel, D. (2012). From movement to thought: executive function, embodied cognition, and the Cerebellum. *The Cerebellum*, *11*(2), 505–525. https://doi.org/10.1007/s12311-011-0321-y

Koziol, L., Budding, D., & Chidekel, D. (2013). ADHD as a model of brain-behavior relationships. https://doi.org/10.1007/978-1-4614-8382-3 .

Kucuk, U., Kucuk, H. O., Eyuboglu, M., & Dogan, M. (2016). eComment. The importance of choosing a proper predictor variable selection method in logistic regression analyses. *Interactive Cardiovascular and Thoracic Surgery*, *22*(3), 258. https://doi.org/10.1093/icvts/ivv403

Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *The British Journal of Developmental Psychology*, *21*(1), 59–80. https://doi.org/10.1348/026151003321164627

Liu, H., Lafferty, J. D., & Wasserman, L. (2009). The nonparanormal: Semiparametric estimation of high dimensional undirected graphs. *Journal of Machine Learning Research*, *10* (80), 2295–2328.

Livesey, D., Keen, J., Rouse, J., & White, F. (2006). The relationship between measures of executive function, motor performance and externalising behaviour in 5- and 6-year-old children. *Human Movement Science*, *25*(1), 50–64. https://doi.org/10.1016/j.humov.2005.10.008

Metin, B., Roeyers, H., Wiersema, J. R., van der Meere, J. J., Thompson, M., & Sonuga-Barke, E. (2013). ADHD performance reflects inefficient but not impulsive information processing: A diffusion model analysis. *Neuropsychology*, *27*(2), 193–200. https://doi.org/10.1037/a0031533

Meyer, K. N., Santillana, R., Miller, B., Clapp, W., Way, M., Bridgman-Goines, K., & Sheridan, M. A. (2020). Computer-based inhibitory control training in children with Attention-Deficit/Hyperactivity Disorder (ADHD): Evidence for behavioral and neural impact. *Plos One*, *15*(11), e0241352. https://doi.org/10.1371/journal.pone.0241352

Middleton, F. A., & Strick, P. L. (2000). Basal ganglia and cerebellar loops: Motor and cognitive circuits. *Brain Research Reviews*, *31*(2–3), 236–250. https://doi.org/10.1016/s0165-0173(99)00040-5

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions. *Current Directions in Psychological Science*, *21*(1), 8–14. https://doi.org/10.1177/0963721411429458

Miyake, A., Friedman, N. P., 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*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., Houts, R., Poulton, R., Roberts, B. W., Ross, S., Sears, M. R., Thomson, W. M., & Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 2693–2698. https://doi.org/10.1073/pnas.1010076108

Mokobane, M., Pillay, B. J., & Meyer, A. (2019). Fine motor deficits and attention deficit hyperactivity disorder in primary school children. *The South African Journal of Psychiatry*, *25*, 1232. https://doi.org/10.4102/sajpsychiatry.v25i0.1232

Mostofsky, S. H., Newschaffer, C. J., & Denckla, M. B. (2003). Overflow movements predict impaired response inhibition in children with ADHD. *Perceptual and Motor Skills*, *97*(3_suppl), 1315–1331. https://doi.org/10.2466/pms.2003.97.3f.1315

Murillo, L. G., Cortese, S., Anderson, D., DiMartino, A., & Castellanos, F. X. (2015). Locomotor activity measures in the diagnosis of attention deficit hyperactivity disorder: Meta-analyses and new findings. *Journal of Neuroscience Methods*, *252*, 14–26. https://doi.org/10.1016/j.jneumeth.2015.03.001

Murray, G. K., Jones, P. B., Kuh, D., & Richards, M. (2007). Infant developmental milestones and subsequent cognitive function. *Annals of Neurology*, *62*(2), 128–136. https://doi.org/10.1002/ana.21120

Murray, G. K., Veijola, J., Moilanen, K., Miettunen, J., Glahn, D. C., Cannon, T. D., Jones, P. B., & Isohanni, M. (2006). Infant motor development is associated with adult cognitive categorisation in a longitudinal birth cohort study. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *47*(1), 25–29. https://doi.org/10.1111/j.1469-7610.2005.01450.x

Musser, E. D., & Raiker, J. S., Jr. (2019). Attention-deficit/hyperactivity disorder: An integrated developmental psychopathology and Research Domain Criteria (RDoC) approach. *Comprehensive Psychiatry*, *90*, 65–72. https://doi.org/10.1016/j.comppsych.2018.12.016

Njiokiktjien, C. (2007). *Developmental dyspraxias and related motor disorders: Neural substrates and assessment*. Suyi Publications.

Paap, K. R., Anders-Jefferson, R., Zimiga, B., Mason, L., & Mikulinsky, R. (2020). Interference scores have inadequate concurrent and convergent validity: Should we stop using the flanker, Simon, and spatial Stroop tasks? *Cognitive Research: Principles and Implications*, *5*(1), 7. https://doi.org/10.1186/s41235-020-0207-y

Pauli-Pott, U., Mann, C., & Becker, K. (2021). Do cognitive interventions for preschoolers improve executive functions and reduce ADHD and externalizing symptoms? A meta-analysis of randomized controlled trials. *European Child & Adolescent Psychiatry*, *30*(10), 1503–1521. https://doi.org/10.1007/s00787-020-01627-z

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*(5), 668–681. https://doi.org/10.1016/j.humov.2007.11.002

Pievsky, M. A., & McGrath, R. E. (2017). The neurocognitive profile of attention-deficit/hyperactivity disorder: A review of meta-analyses. *Archives of Clinical Neuropsychology*, *33*(2), 143–157. https://doi.org/10.1093/arclin/acx055

Polderman, T. J. C., van Dongen, J., & Boomsma, D. I. (2011). The relation between ADHD symptoms and fine motor control: A genetic study. *Child Neuropsychology*, *17*(2), 138–150. https://doi.org/10.1080/09297049.2010.518142

Ramnani, N. (2006). The primate cortico-cerebellar system: Anatomy and function. *Nature Reviews Neuroscience*, *7*(7), 511–522. https://doi.org/10.1038/nrn1953

Ratcliff, R. (2008). The EZ diffusion method: Too EZ? *Psychonomic Bulletin & Review*, *15*(6), 1218–1228. https://doi.org/10.3758/pbr.15.6.1218

Ratcliff, R., & McKoon, G. (2008). The diffusion decision model: Theory and data for two-choice decision tasks. *Neural Computation*, *20*(4), 873–922. https://doi.org/10.1162/neco.2008.12-06-420

Redmond, S. M., & Ash, A. C. (2014). A cross-etiology comparison of the socio-emotional behavioral profiles associated with attention-deficit/hyperactivity disorder and specific language impairment. *Clinical Linguistics & Phonetics*, *28*(5), 346–365. https://doi.org/10.3109/02699206.2013.868518

Ridler, K., Veijola, J. M., Tanskanen, P., Miettunen, J., Chitnis, X., Suckling, J., Murray, G. K., Haapea, M., Jones, P. B., Isohanni, M. K., & Bullmore, E. T. (2006). Fronto-cerebellar systems are associated with infant motor and adult executive functions in healthy adults but not in schizophrenia. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(42), 15651–15656. https://doi.org/10.1073/pnas.0602639103

Rigoli, D., Piek, J. P., Kane, R., & Oosterlaan, J. (2012). An examination of the relationship between motor coordination and executive functions in adolescents. *Developmental Medicine & Child Neurology*, *54*(11), 1025–1031. https://doi.org/10.1111/j.1469-8749.2012.04403.x

Rommelse, N. N. J., Altink, M. E., Oosterlaan, J., Beem, L., Buschgens, C. J. M., Buitelaar, J., & Sergeant, J. A. (2008). Speed, variability, and timing of motor output in ADHD: Which measures are useful for endophenotypic research? *Behavior Genetics*, *38*(2), 121–132. https://doi.org/10.1007/s10519-007-9186-8

Rosch, K. S., Dirlikov, B., & Mostofsky, S. H. (2013). Increased intrasubject variability in boys with ADHD across tests of motor and cognitive control. *Journal of Abnormal Child Psychology*, *41*(3), 485–495. https://doi.org/10.1007/s10802-012-9690-z

Rubia, K., Noorloos, J., Smith, A., Gunning, B., & Sergeant, J. (2003). Motor timing deficits in community and clinical boys with hyperactive behavior: The effect of methylphenidate on motor timing. *Journal of Abnormal Child Psychology*, *31*(3), 301–313. https://doi.org/10.1023/a:1023233630774

Schmiedek, F., Oberauer, K., Wilhelm, O., Süβ, H.-M., & Wittmann, W. W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology: General*, *136*(3), 414–429. https://doi.org/10.1037/0096-3445.136.3.414

Sergeant, J. (2000). The cognitive-energetic model: An empirical approach to attention-deficit hyperactivity disorder. *Neuroscience & Biobehavioral Reviews*, *24*(1), 7–12. https://doi.org/10.1016/s0149-7634(99)00060-3

Sergeant, J. A. (2005). Modeling attention-deficit/hyperactivity disorder: A critical appraisal of the cognitive-energetic model. *Biological Psychiatry*, *57*(11), 1248–1255. https://doi.org/10.1016/j.biopsych.2004.09.010

Seymour, K. E., Mostofsky, S. H., & Rosch, K. S. (2016). Cognitive load differentially impacts response control in girls and boys with ADHD. *Journal of Abnormal Child Psychology*, *44*(1), 141–154. https://doi.org/10.1007/s10802-015-9976-z

Sharma, A., & Couture, J. (2014). A review of the pathophysiology, etiology, and treatment of Attention-Deficit Hyperactivity Disorder (ADHD). *The Annals of Pharmacotherapy*, *48*(2), 209–225. https://doi.org/10.1177/1060028013510699

Singelton, C. (2001). Computer-based assessment in education. *Educational and Child Psychology*, *18*(3), 58–74. https://doi.org/10.53841/bpsecp.2001.18.3.58

Slaats-Willemse, D., Sonneville, L. D., Swaab-Barneveld, H., & Buitelaar, J. (2005). Motor flexibility problems as a marker for genetic susceptibility to attention-deficit/hyperactivity disorder. *Biological Psychiatry*, *58*(3), 233–238. https://doi.org/10.1016/j.biopsych.2005.03.046

Stöckel, T., & Hughes, C. M. L. (2016). The relation between measures of cognitive and motor functioning in 5- to 6-year-old children. *Psychological Research*, *80*(4), 543–554. https://doi.org/10.1007/s00426-015-0662-0

Studenmund, A. H., & Cassidy, H. J. (1987). *Using econometrics: A practical guide*. Little, Brown and Company.

Swedberg, R. (2021). Does speculation belong in social science research? *Sociological Methods & Research*, *50*(1), 45–74. https://doi.org/10.1177/0049124118769092

Tirosh, E., Perets Dubrovsky, S., Davidovitch, M., & Hocherman, S. (2006). Visuomotor tracking related to Attention-Deficit Hyperactivity Disorder (ADHD). *Journal of Child Neurology*, *21*(6), 502–507. https://doi.org/10.1177/08830738060210062401

Tseng, M. H., Henderson, A., Chow, S. M. K., & Yao, G. (2004). Relationship between motor proficiency, attention, impulse, and activity in children with ADHD. *Developmental Medicine & Child Neurology*, *46*(6), 381–388. https://doi.org/10.1017/s0012162204000623

van der Fels, I. M., Te Wierike, S. C., Hartman, E., Elferink-Gemser, M. T., Smith, J., & Visscher, C. (2015). The relationship between motor skills and cognitive skills in 4-16 year old typically developing children: A systematic review. *Journal of Science and Medicine in Sport*, *18*(6), 697–703. https://doi.org/10.1016/j.jsams.2014.09.007

van der Meer, J. M. J., Hartman, C. A., Thissen, A. J. A. M., Oerlemans, A. M., Luman, M., Buitelaar, J. K., & Rommelse, N. N. J. (2016). How 'core' are motor timing difficulties in ADHD? A latent class comparison of pure and comorbid ADHD classes. *European Child & Adolescent Psychiatry*, *25*(4), 351–360. https://doi.org/10.1007/s00787-015-0734-0

Voss, A., & Voss, J. (2007). Fast-dm: A free program for efficient diffusion model analysis. *Behavior Research Methods*, *39*(4), 767–775. https://doi.org/10.3758/bf03192967

Wagenmakers, E.-J., van der Maas, H. L. J., Dolan, C. V., & Grasman, R. P. P. P. (2008). EZ does it! Extensions of the EZ-diffusion model. *Psychonomic Bulletin & Review*, *15*(6), 1229–1235. https://doi.org/10.3758/pbr.15.6.1229

Wagenmakers, E.-J., van der Maas, H. L. J., & Grasman, R. P. P. P. (2007). An EZ-diffusion model for response time and accuracy. *Psychonomic Bulletin & Review*, *14*(1), 3–22. https://doi.org/10.3758/bf03194023

Wassenberg, R., Feron, F. J. M., Kessels, A. G. H., Hendriksen, J. G. M., Kalff, A. C., Kroes, M., Hurks, P. P. M., Beeren, M., Jolles, J., & Vles, J. S. H. (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*(5), 1092–1103. https://doi.org/10.1111/j.1467-8624.2005.00899.x

Wilson, B. N., Crawford, S. G., Green, D., Roberts, G., Aylott, A., & Kaplan, B. (2009). Psychometric properties of the revised developmental coordination disorder questionnaire. *Physical & Occupational Therapy in Pediatrics*, *29*(2), 182–202. https://doi.org/10.1080/01942630902784761

World Health Organisation. (2019). *International statistical classification of diseases and related health problems* (11th ed.). World Health Organisation.

Zelaznik, H. N., Vaughn, A. J., Green, J. T., Smith, A. L., Hoza, B., & Linnea, K. (2012). Motor timing deficits in children with attention-deficit/hyperactivity disorder. *Human Movement Science*, *31*(1), 255–265. https://doi.org/10.1016/j.humov.2011.05.003

Zelazo, P. D. (2006). The Dimensional Change Card Sort (DCCS): A method of assessing executive function in children. *Nature Protocols*, *1*(1), 297–301. https://doi.org/10.1038/nprot.2006.46

Zelazo, P. D., Anderson, J. E., Richler, J., Wallner-allen, K., Beaumont, J. L., & Weintraub, S. (2013). II. NIH toolbox Cognition Battery (CB): Measuring executive function and attention. *Monographs of the Society for Research in Child Development*, *78*(4), 16–33. https://doi.org/10.1111/mono.12032