Exploring Associations Between Motor Competence, Executive Function, and Academic Attainment in Children in England.

Abstract

Motor competence supports physical, emotional, and mental health, but its cognitive impact is understated. Motor-cognitive links remain underexplored, and motor competence's role in academic attainment, including executive functions' mediating influence, is limited. This research aimed to 1) investigate associations between motor competence and executive functions in 8-9-year-old children in England and 2) examine whether greater motor competence has a positive impact on executive function and academic attainment. Two hundred and forty seven children (51.4% girls; age 8.7 ± .4 years; 77.7% white British; 5 ± 3.1 deprivation decile; 73.3% healthy weight) across Pennine Lancashire completed a motor competence circuit, and executive function tests. Attainment across reading, writing, and mathematics assessed academic attainment. Direct effects were found between motor competence and executive function (β=-2.55, 95% CI [-4.87, -0.24]), motor competence and academic attainment (β=0.57, 95% CI [0.16, 0.98]), and executive function and academic attainment (β=-0.13, 95% CI [-0.24, -0.02]). Executive function mediated the indirect motor competence-academic attainment association (β=0.20, *p*=0.01). Multi-group analyses found a significant deprivation group effect (*p*=0.03). The motor-cognitive phenomenon is complex, requiring future research. The findings show that motor and cognitive skills intertwine to support academic achievement. Therefore, educational approaches that integrate these skills may improve attainment.

Keywords: Children, movement skills, cognition, educational performance, deprivation.

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Movement is essential for quality of life, contributing to physical, emotional, and mental health benefits such as improved strength, well-being, and reduced anxiety (Abdin et al., 2018; Adamson et al., 2015; Adsett et al., 2015; Bouchard et al., 2007). Motor competence refers to the development and performance of fundamental, combined and complex movement skills that are intended to achieve a goal in a precise and coordinated way, without error (Hulteen et al., 2018; Tyler et al., 2020). Motor competence is critical for children's development, shaping motor learning through physical and social interactions (Adolph & Hoch, 2019), and recent research has begun to explore its potential link to cognitive abilities (van der Fels et al., 2015). Although this area of research is limited (Albuquerque et al., 2022a; Fernández-Sánchez et al., 2022). Embodied cognition suggests cognitive development arises from sensory-motor interactions with the environment (Gibbs, 2005), reinforcing the idea that motor and cognitive skills are interconnected (Gandotra et al., 2022), yet empirical evidence remains scarce (Malambo et al., 2022).

Executive functions are a group of higher-order cognitive processes that form a multidimensional concept and support goal-directed behaviours and self-regulation (Diamond, 2000). While a triadic model of the 'core executive functions' (working memory, inhibitory control, and cognitive flexibility) has been proposed (Miyake et al., 2000), a broader framework including higher-order executive functions, such as planning, reasoning, and problem-solving (Lin et al., 2020), has now been highlighted (Best & Miller, 2010; Diamond, 2013). Executive functions can influence an individual's emotions, ideas, and actions, yet are only activated in goal-directed situations (Carlson et al., 2013; Huizinga et al., 2006). Thus, executive functions are crucial to necessitate effort to everyday tasks (Carlson et al., 2013; Huizinga et al., 2006). The present study adopts a multidimensional perspective to demonstrate this developmental hierarchy, including five components: working memory, inhibition, cognitive flexibility, planning, and problem-solving. This approach recognises that middle childhood often highlights the integration of the core executive function components into higher-order executive function processes and thus should be included in future research on this population (Best & Miller, 2010; Diamond, 2013).

Executive functions develop rapidly during childhood, and extends throughout the lifespan, and have thus drawn interest (Diamond & Ling, 2016). In particular, the middle and late childhood periods are crucial for executive function development, since there are key changes in the development of the prefrontal cortex (Carlson et al., 2013). In combination, these processes can predict children's learning and successes, whilst providing a substantial foundation for children to absorb and process academic material (McClelland & Cameron, 2019). However, while some frameworks (Miyake et al., 2000) present executive functions as individual entities, others suggest a more unitary construct (Wiebe et al., 2008). Middle childhood presents a key transitional stage whereby executive functions begin to differentiate, yet inter-correlations among executive functions measures may remain high, therefore making it difficult to assess discrete executive functions (Carlson et al., 2013).

Few studies have examined motor competence-executive function associations within children (Albuquerque et al., 2022a; van der Fels et al., 2015), often using product-based measures like the KörperKoördinationsTest für Kinder (Kiphard & Schiling, 1974) or process-based measures such as the Test of Gross Motor Development Two/Three (Ulrich, 2000). The KörperKoördinationsTest für Kinder (Kiphard & Schiling, 1974) has been criticised in terms of the tendency to overestimate the number of individuals with motor coordination issues, and the comparison of data with standardised values may be outdated (Iivonen et al., 2015). Given that the KörperKoördinationsTest für Kinder (Kiphard & Schiling, 1974) is a product-orientated measure, there is no assessment of motor-skill quality, and thus would need to be combined with a process-based measure to provide a coherent assessment of motor competence (Ré et al., 2018). The Test of Gross Motor Development Two/Three (Ulrich, 2000) prevents motor skills to be modified to adjust to real-world contexts and instead are defined by environment-specific instructions (Hulteen et al., 2023). This fails to provide a holistic understanding of motor competence, since it abandons stability skills (Lopes et al., 2013a). The Test of Gross Motor Development Two/Three (Ulrich, 2000) has been criticised for the lack of applicability across cultures, despite its suitability to assess a wide variety of motor skills (Hulteen et al., 2023). Therefore, these assessments focus on isolated skills (Ulrich, 2000) or the outcome of movements (Kiphard & Schiling, 1974), and thus warrants more comprehensive motor competence measures.

The Dragon Challenge (Tyler et al., 2018) encompasses both skill technique and outcome, yet to date, its use has been limited in motor competence research (Morley et al., 2021; Richards et al., 2023; Tyler et al., 2018, 2022). Most studies also overlook higher-order executive functions such as problem solving and planning (Fernández-Sánchez et al., 2022). The Tower of Hanoi (Byrnes et al., 1979), a key measure of these skills remains unexplored in motor competence research. Therefore, studies are needed to expand the understanding of the link between motor competence and higher-order executive functions.

Education is critical for an individual's well-being, quality of life, and future (Farooq, 2011). Academic attainment alludes to the long-term impact on personal goals, career outlooks, and educational successes (Pizzolato et al., 2011). While physical activity's link to academic attainment is well-documented (Ahamed et al., 2007; Fox et al., 2010; Rasberry et al., 2011), the motor competence-academic attainment association in primary school-aged children remains underexplored (Lopes et al., 2013b). Research suggests executive functions may mediate this association (Cadoret et al., 2018; Rigoli et al., 2012; Schmidt et al., 2017), as they are key predictors of academic attainment (Lopes et al., 2013a). The speed-accuracy trade-off is a common explanation for this, given that it is an essential component of both motor coordination and executive function tasks (Roebers & Kauer, 2009). The cognitive stimulation hypothesis (Best, 2010; Pesce, 2012a) and the skill acquisition approach (Tomporowski & Pesce, 2019) also highlight that cognitively challenging physical activity will engage the same brain regions for both learning and executive functions. However, few studies have investigated executive functions as mediators between motor competence and academic attainment in primary school-aged children (Cadoret et al., 2018; Rigoli et al., 2012; Schmidt et al., 2017).

Therefore, the current study aimed to 1) investigate associations between motor competence, executive functions, and academic attainment of 8-9-year-old children in England, and determine whether they differ between sex and deprivation groups and 2) examine whether greater motor competence has a positive impact on an individual's executive function (working memory, inhibitory control, cognitive flexibility, planning, and problem-solving) and academic attainment. It was hypothesised that (i) greater motor competence ability would be associated with higher performance on executive function tests and academic attainment, (ii) a positive indirect association will exist between motor competence and academic attainment through executive function, and (iii) higher executive function scores would be associated with greater academic attainment. Accordingly, this quantitative cross-sectional study was in partnership with 'Together an Active Future', a Sport England-funded Place-Based Partner for physical activity promotion in Pennine Lancashire, northwest England.

Method

Participants

Opportunity sampling recruited 247 participants (51.4% girls; age 8.7 ± .43 years; 77.7% white British; 5 ± 3.1 English Indices of Multiple Deprivation decile; 73.3% healthy weight) who were physically able to participate in physical activity, within Pennine Lancashire. Children aged 8-9 years were selected as this represents a key developmental window for executive functions and fundamental movement skills (Best & Miller, 2010; Gallahue et al., 2012). This population also represents Key Stage 2 within the UK National Curriculum, of which presents increased demands across literacy and mathematics (Department for Education, 2013). This therefore requires enhanced attention regulation, problem solving (Best & Miller, 2010). The study of motor competence and executive function is particularly relevant for this population, since both domains undergo rapid development during this period (van der Fels et al., 2015). This study was ethically approved by the Edge Hill University Research Ethics Committee (REC- ETH2223-0207). Written informed consent was obtained from the School headteachers and the children's guardians. Written assent was obtained from the children, and the children were asked on the day of data collection whether they were happy to participate, ensuring verbal assent was also obtained. Children were made aware that they could withdraw at any time without penalty, and there was no pressure applied to participate. Participant's home postcode, ethnicity, and date of birth were obtained. Socio-economic status was determined via English Indices of Multiple Deprivation deciles (Ministry of Housing, Communities, and Local Government, 2019). The Indices of Multiple Deprivation deciles combine information from seven domains: income, employment, education, health and disability, crime, barriers to housing and services, and the living environment, to provide an overall score for each Lower-layer Super Output Area (Ministry of Housing, Communities, and Local Government, 2019). The Lower-layer Super Output Areas are then ranked and grouped into Deciles, whereby decile 1 represents the most deprived 10% of areas and Decile 10 represents the least deprived 10% (Ministry of Housing, Communities, and Local Government, 2019; Noble et al., 2006).

Anthropometric Data

Stature and body mass were measured to the nearest 0.1cm and 0.1kg following standard procedures (Lohman et al., 1991), using a portable stadiometer and seca 761 digital scales (seca, Birmingham, UK), respectively. Body mass index and body mass index z-scores were calculated (Cole et al., 1995) and used to classify participants as normal, overweight, or obese according to the sex and age International Obesity Task Force BMI cut-off points (Cole, 2000).

Academic Attainment

National Curriculum attainment across reading, writing, and mathematics were categorised as (1) ‘working towards’ (a score of 80-99 - working below expected for their age), (2) ‘expected’ (a score of 100 - working at the expected level), and (3) ‘greater depth’ (a score of >110 - working above expected). This reflects the National Curriculum for key stage two scaled scores (Standards and Testing Agency, 2023). For analysis purposes, attainment for reading and writing were combined to form an overall literacy score.

Executive Functions

A battery of cognitive tests was administered online via the Psytoolkit software (version 3.4.6) (Stoet, 2010, 2017)- (https://www.psytoolkit.org/c/3.4.0/survey?s=B6JvP), on laptops/desktop computers, in which the lead researcher was adequately trained and competent in for use (Gilmour et al., 2023). Each executive function task was administered at a fixed difficulty and entry level, which remained consistent throughout the test and across all participants, regardless of performance.

Inhibition

The Eriksen Flanker Test (Eriksen & Eriksen, 1974) assessed inhibition, a voluntary control over goal-irrelevant stimuli and responses to behaviours (Diamond, 2013). Five letters appeared on a blank screen. In congruent trials, all letters were identical, i.e., XXXXX, while in the incongruent trial, the middle letter differed, i.e., XXVXX. Participants pressed “A” if the centre letter was an X or C and “L” if it was a V or B. To familiarise participants, four practice trials (two congruent, two incongruent) were included. The test consisted of 25 trials (16 congruent, 9 incongruent) in pseudorandom order to minimise fatigue effects (Eriksen & Eriksen, 1974). The flanker effect was calculated by subtracting the average reaction time (ms) in congruent trials from incongruent trials. Reaction times <150ms were excluded to account for anticipatory responses (Bedard et al., 2021; Viviani et al., 2024). In instances where the mean incongruent and congruent reaction times were equal, resulting in a Flanker effect of zero, a value of 2000ms was imputed to reflect an invalid or atypical response, and to ensure consistency. This decision assumed that a zero difference in reaction times across conditions is unlikely to reflect true performance and therefore may result from an outlier behaviour or task disengagement. This test was implemented following a validation study for the Flanker test in children aged between 3-15-years (Zelazo et al., 2013). A higher flanker effect indicated weaker inhibition.

Visuospatial Working Memory

The Corsi-block test (Corsi, 1972) assessed visuospatial working memory, the temporary retention of information that is no longer available perceptibly (Baddeley & Hitch, 1974). This is a valid and reliable measure (Siddi et al., 2020). This presents nine squares, with some illuminating in an increasing sequence per trial. Participants reproduced the sequence by clicking the squares in order. The test was terminated after three consecutive errors, and block-span was determined by the final correct sequence. To ensure this output aligned with the other executive function measures, the score was reversed, and thus a lower score represented a greater performance.

Cognitive Flexibility

The Wisconsin Card Sorting Task (Grant & Berg, 1948) assessed cognitive flexibility, the shifting of thoughts, perspectives, actions, and attentional focus (Diamond, 2000), as this is the most used neurocognitive test of cognitive flexibility (Johnco et al., 2014; Tchanturia et al., 2012) and is widely accepted (Cragg & Chevalier, 2012; Figueroa & Youmans, 2013). Participants matched a response card to one of four multidimensional stimulus cards based on number, colour, or shape (Miles et al.). The matching rule changed after 10 consecutive correct responses, marking one ‘completed category’. The task ended after six categories or 60 trials. The total number of errors included perseveration (applying the old rule) and non-perseveration errors (Miles et al.). Fewer perseveration errors indicated greater cognitive flexibility.

Planning and Problem Solving

The Tower of Hanoi (Byrnes et al., 1979) is a multidimensional assessment that predominantly measured planning and problem solving, while also indicating working memory ability. Planning can be understood as the organising of behaviour and considering the future to ensure success of pre-determined goals (Corbo & Casagrande, 2022). Problem solving highlights the capability to successfully achieve an end-goal via a series of cognitive operations (Lin et al., 2021). The Tower of Hanoi demonstrated high reliability through internal consistency (Humes et al., 1997). The participants were tasked to rearrange a set of disks, of varying size, across three pegs in the fewest moves possible (Mitani et al., 2022). Fewer moves indicated greater planning ability.

Motor Competence

The Dragon Challenge (Tyler et al., 2018) is a valid and reliable measure of motor competence (Tyler et al., 2018) and was administered and assessed in accordance with the Dragon Challenge manual (Tyler et al., 2018). The Dragon Challenge took place within a school sports hall or outdoors and required children to wear sports footwear and light clothing. The Dragon Challenge also requires children to illustrate movement skills and characteristics that are representative of an individual with a good level of physical fitness (Tyler et al., 2018). The Dragon Challenge is a nine-station time trialled circuit of predominantly object-control (basketball dribbling, overarm throw, underarm throw and catch), stability (wobble sport, balance bench, core agility), and locomotor (jumping pattern, T-run, sprint) skills. The assessors achieved 90% agreement with an experienced Dragon Challenge assessor, prior to assessment in accordance with the Dragon Challenge manual (Tyler et al., 2018) . Performance was assessed through (1) time taken to complete the circuit, (2) three criterions (two technical (process) and one outcome (product)). Each construct, technique (scored out of 18), outcome (scored out of 9 multiplied by 2), and time (scored out of 18) provided an overall score out of 54. Time taken for participants to complete the Dragon Challenge was recorded in minutes and seconds, via a stopwatch, and converted to a score whereby a faster time receives a higher score. Time completion was recorded from the word ‘go’ and stopped when the participant crossed the finish line of the sprint task. The scoring calculation is available in the original studies (Tyler et al., 2018, 2020). Additionally, technique and outcome for each task were summed to provide Dragon Challenge cumulative task scores (Tyler et al., 2020).

Analysis

Descriptive statistics (mean and standard deviation) were calculated for all measured variables using SSPS/Amos software, v29 [IBM SPSS Statistics Inc., Chicago, IL, USA]. Little’s missing completely at random test assessed the missing at random pattern of missing values. Data transformation included reversing the Corsi span (Corsi, 1972) score and converting Flanker scores (Eriksen & Eriksen, 1974) into absolute values, whereby a score of zero indicated the greatest performance. It should be noted that while children’s executive function is assessed, detailed psychometric properties for this specific population are limited. Therefore, task performance was interpreted with caution, and confirmatory factor analyses were used to support evidence of construct validity of the overall executive function construct.

A confirmatory factor analysis assessed the fit of two measured variables into three hypothesised latent variables: motor competence (Dragon Challenge cumulative task scores), executive function (Flanker effect, reversed Corsi-span, perseveration errors, Tower of Hanoi step count), and academic attainment (literacy and mathematics). Comparative fit index (CFI), Goodness of fit index (GFI), Incremental fit index (IFI), Root Mean Squared Error of Approximation (RMSEA; threshold of ≤ 0.08), and Standardised Root Mean Square Residual (SRMR; cut off value < 0.05) acted as criterion for good model fit, with CFI, GFI, and IFI >0.90 and RMSEA of <0.05 demonstrated good fit (Hu & Bentler, 1999). The confirmatory factor analysis also examined structural validity evidence for all executive function tests prior to further data analyses. Structural equation modelling explored relationships between motor competence, executive function, and academic attainment, with direct effects assessed via path coefficients. An indirect effect was assessed by using the product of two direct effects between the three latent factors. Model fit was assessed again using CFI, GFI, IFI, AGFI, SRMR, and RMSEA fit indices (Hu & Bentler, 1999). A multi-group analysis (Chi-squared difference test) examined moderation by sex (boys vs. girls), weight status (healthy weight vs. overweight), and deprivation (low-medium deprivation (decile ≥ 6) vs. medium-high deprivation (decile ≤ 5)). Non-significant paths were removed from the final structural equation model.

Results

Descriptive statistics of the final analytical sample are provided in table 1. The final sample included two hundred and forty seven children (51.4% girls), with a mean age of 8.7 ± 0.4 years. The average Indices of Multiple Deprivation (IMD) decile was 5.0 ± 3.1, indicating a broad socioeconomic distribution. The majority of participants were of white British ethnicity (77.7%), and 26.7% were classified as overweight. The overall Dragon Challenge average score was 30.2 ± 7.8. executive function scores indicated considerable variability, particularly in the Flanker effect (76.8 ± 231.7ms). Literacy and mathematics attainment were within the expected range for the sample's age. The rate of missingness ranged from 0% (age, sex and ethnicity) to 5% (agility score). Little's missing completely at random test was administered (χ^2 = 254.9, df= 722, *p*= 1.00). Overall, 1.5% of the data were missing completely at random. The median scores for the Dragon Challenge were imputed for the missing values and multiple imputation was used for all continuous variables (Schafer, 1999; Sterne et al., 2009).

Table 1 Descriptive Characteristics of the participants (M (SD) unless indicated otherwise).

Variables	**All**	**Sex**	
		Boys	**Girls**
n	247	120	127
Age (years)	8.7 (0.4)	8.7 (0.4)	8.7 (0.4)
Girls *n* (%)	127 (51.4)	-	-
Boys *n* (%)	120 (48.6)	-	-
Indices of Multiple Deprivation decile	5.02 (3.1)	4.8 (3.1)	5.2 (3.1)
Ethnicity *n* (%)			
White British	192 (77.7)	95 (79.2)	97 (76.4)

Asian	6 (2.4)	5 (4.2)	1 (0.8)
Mixed	9 (3.6)	3 (2.5)	6 (4.7)
Other White	1 (0.4)	0 (0)	1 (0.8)
Pakistani	35 (14.2)	14 (11.7)	21 (16.5)
Bangladeshi	2 (0.8)	2 (1.7)	0 (0)
Indian	1 (0.4)	1 (0.8)	0 (0)
Other	1 (0.4)	0 (0)	1 (0.8)
Weight Status *n* (%)			
Healthy Weight	181 (73.3)	92 (76.7)	89 (70.1)
Overweight	66 (26.7)	28 (23.3)	38 (29.9)
Motor Competence			
Balance Bench (0-4)	2.2 (1.6)	2.2 (1.7)	2.3 (1.6)
Core Agility (0-4)	2.0 (1.5)	1.6 (1.4)	2.3 (1.5)
Wobble Spot (0-4)	1.7 (2.0)	3.1 (0.9)	1.9 (2.0)
Overarm Throw (0-4)	2.1 (1.2)	2.3 (1.3)	1.9 (1.1)
Basketball Dribble (0-4)	1.3 (1.6)	1.9 (1.7)	0.8 (1.2)
Catch (0-4)	1.5 (1.6)	1.8 (1.6)	1.1 (1.3)
T-agility (0-4)	2.2 (1.4)	2.2 (1.3)	2.2 (1.5)
Jumping Patterns (0-4)	2.4 (1.6)	2.2 (1.7)	2.6 (1.6)
Sprint (0-4)	3.0 (0.9)	3.1 (0.9)	3.0 (0.9)
Process Score	9.3 (3.6)	9.5 (3.7)	9.0 (3.5)
Product Score	9.2 (3.6)	9.5 (3.6)	9.0 (3.6)
Time Score	11.8 (2.1)	12.2 (2.4)	11.4 (1.8)
Overall Dragon Challenge score	30.2 (7.8)	30.9 (8.1)	29.4 (7.4)
Executive Function			
Flanker Effect (seconds)	76.8 (231.7)	43.7 (242.4)	108.0 (217.5)
Corsi-Span	3.2 (2.0)	3.1 (2.0)	3.2 (1.9)
Wisconsin Card Sorting Task Perseveration Error Count	14.4 (4.2)	14.5 (4.1)	14.3 (4.2)
Tower of Hanoi Steps Taken	18.4 (9.3)	19.4 (9.5)	17.5 (9.0)
Academic Attainment			
Literacy Attainment (2-6)	3.7 (1.2)	3.6 (1.2)	3.8 (1.3)
Mathematics Attainment (1-3)	2.0 (0.7)	2.0 (0.7)	1.9 (0.7)

Associations between three latent variables (motor competence, executive function, and academic attainment) and their indicators were examined via a three-factor measurement model via confirmatory factor analysis. After the addition of four correlations between.

The confirmatory factor analysis unstandardised beta values indicate that the Flanker effect (λ = -0.63, SE = 8.5, *p*= 0.48) did not significantly contribute to the executive function latent variable and was removed. The chi-square difference test indicated no significant difference between models ($\Delta\chi^2 = 30.4$, $\Delta df = 26$, $p > 0.05$), but removing the Flanker effect improved model fit (CFI, 0.96; GFI, 0.95; IFI, 0.96; AGFI, 0.93; SRMR, 0.05; RMSEA, 0.03) (Figure 1).

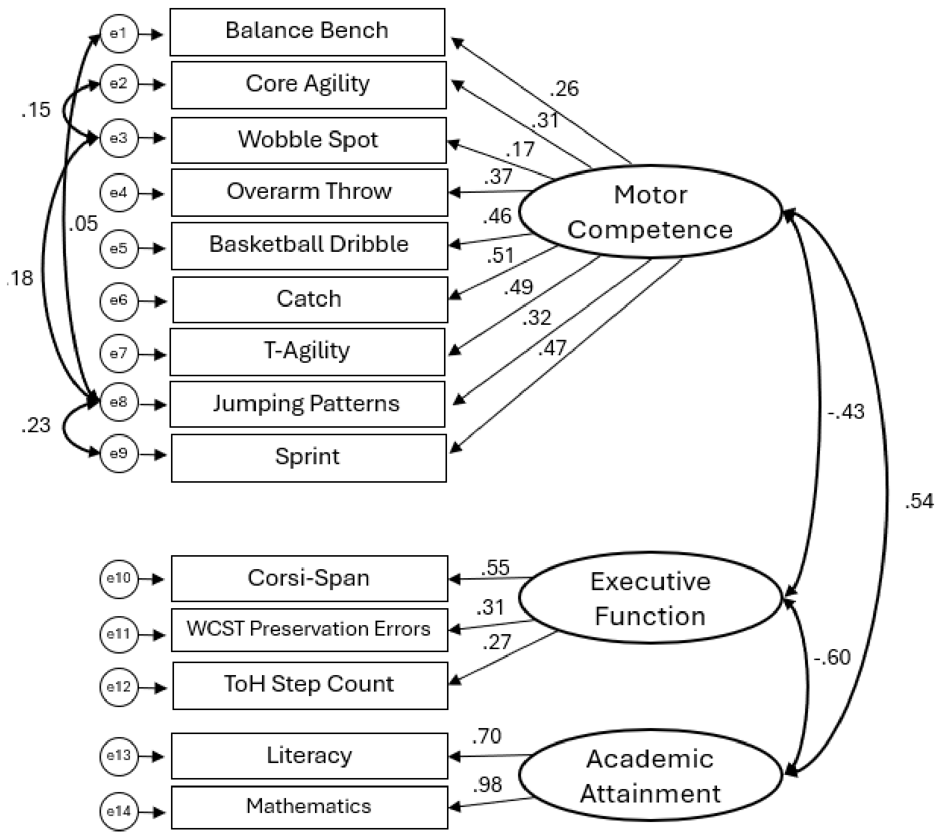

Figure 1- Final Confirmatory Factor Analysis of the measured variables into three hypothesised latent factors

The hypothesised structural equation model revealed a significant chi-square value of χ^2 (84) = 218.637, p <0.01, indicating a good model fit. A further assessment of model fit revealed CFI, 0.70; GFI, 0.87; IFI, 0.72; AGFI, 0.82; SRMR, 0.10; RMSEA, 0.08, which also highlighted poor to adequate model fit.

Prior to further analyses, intraclass correlation coefficients were calculated to account for school nesting. These results highlighted minimal statistical dependency within school clusters (< 0.1), indicating that majority of the variance is attributed to the participants.

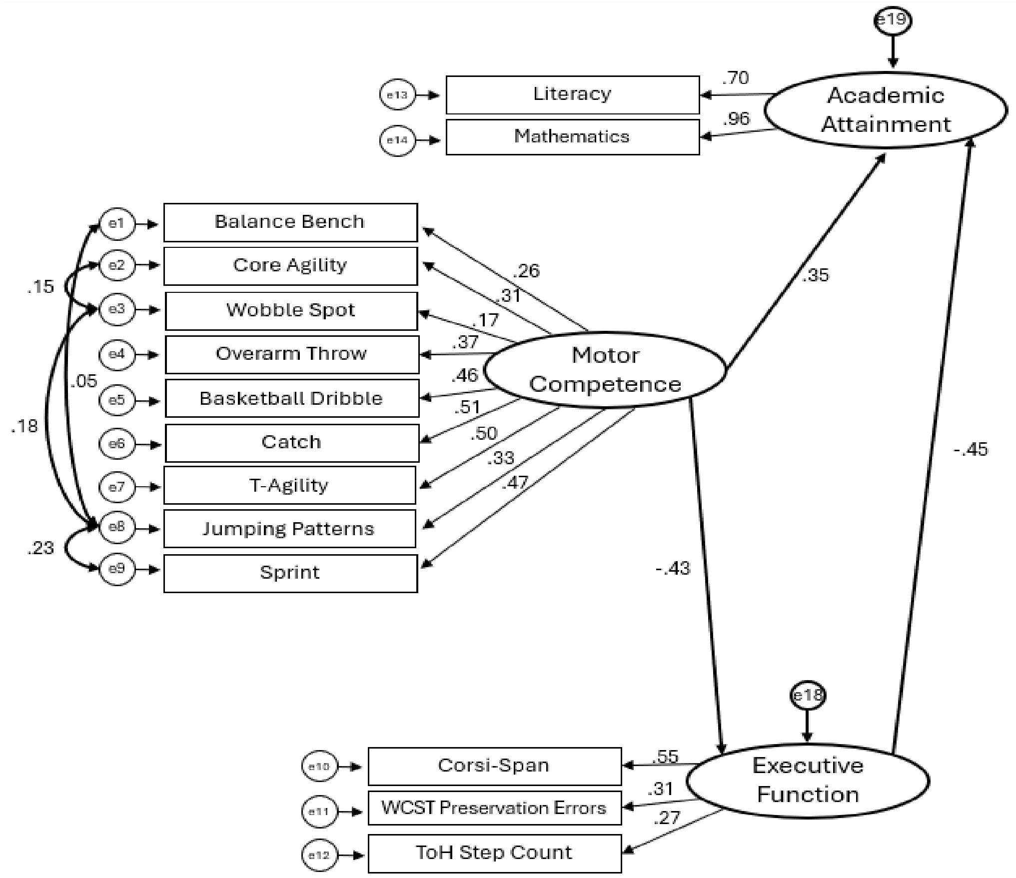

Figure 2- Final SEM evaluating relationships between motor competence, executive function, and academic attainment

The final structural equation model (figure 2) highlights the standardised beta values, and an excellent model fit on a global level ($\chi^2(70) = 88.652$, $p = 0.07$; CFI, 0.96; GFI, 0.95; IFI, 0.06; AGFI, 0.93; SRMR, 0.05; RMSEA, 0.03), indicating a significant improvement in model fit. A chi-square difference test confirmed this improvement ($\Delta\chi^2 = 129.9$, $\Delta df= 14$, $p < 0.05$). Overall, the fit indices highlight that the final structural equation model fits the data well.

The unstandardised beta values of this model demonstrated a negative direct effect of motor competence on executive function (β= -2.55, 95% CI [-4.87, -0.24]), indicating that higher motor competence performance was associated with lower executive function scores (more efficient executive function abilities). Motor competence was also significantly associated with academic attainment (β= 0.57, 95% CI [0.16, 0.98]). An indirect association between motor competence and academic attainment, mediated by executive function, was found (β= 0.20, p = 0.01), demonstrating that motor competence’s association with academic attainment was partly explained by its influence on executive function. Finally, the direct effect of executive function on academic attainment was negative (β= -0.13,95% CI [-0.24, -0.02]), which revealed that better executive function (lower scores) was associated with higher academic attainment.

There was no significant difference in models and paths for sex (p = 0.38) and weight status (p = 1.00). However, a significant difference was found for deprivation (p = 0.03), and for the path between motor competence and academic attainment (p = 0.04).

The final structural equation model for deprivation groups revealed an excellent model fit for individuals within low-medium deprivation areas (see supplementary material S1) ($\chi^2(70)$ = 70.448, p = 0.46; CFI, 1.00; GFI, 0.91; IFI, 1.00; AGFI, 0.87; SRMR, 0.07; RMSEA, 0.01). A significant positive direct effect of motor competence on academic attainment was found (β= 1.15,95% CI [0.29, 2.01]), yet the paths between motor competence and executive function (β= -0.25,95% CI [-1.35, 0.85]) and between executive function and academic attainment (β= -0.18,95% CI [-0.79, 0.43]) were not significant. The indirect path between motor competence and academic attainment, mediated by executive function, presented a significant association (β= .021, p = 0.01).

The final structural equation model revealed a good model fit for individuals within high-medium deprivation areas (supplementary material S2) ($\chi^2(70)$ = 88.031, p = 0.07; CFI, 0.94; GFI, 0.92; IFI, 0.94; AGFI, 0.88; SRMR, 0.06; RMSEA, 0.04). A significant direct negative effect was highlighted for the motor competence-executive function path (motor competence was associated with better executive function (lower scores)) (β +6= -4.43,95% CI [2.55, 9.45]), yet the paths between motor competence and academic attainment (β= -

1.00,95% CI [-2.23, 0.23]) and executive function and academic attainment (β= -0.21,95% CI [-0.48, 0.06]) were not significant. The indirect path between motor competence and academic attainment, mediated by executive function, was also not significant (β= 0.63, p = 0.88).

Discussion

This novel study is amongst the first to report the direct and indirect relationships between motor competence, executive function, and academic attainment in 8-9-year-old children using path analyses. The confirmatory factor analysis demonstrates that the fit of the measured variables into three hypothesised latent factors was good, highlighting that the measures in this study were positively associated with the given latent factors. The final structural equation model displayed significant associations between motor competence, executive function, and academic attainment, and thus the interconnectedness between the motor and cognitive domains within primary school-aged children within England.

The association between motor competence and executive function observed in this study aligns with previous findings (Cook et al., 2019a; Fernández-Sánchez et al., 2022; Gandotra et al., 2022; Oberer et al., 2018; Piek et al., 2008), and is supported by a recent systematic review (Bao et al., 2024), and the findings of this study. However, there are inconsistencies within this area. For instance, (van der Veer et al., 2024) reported no significant association in a younger sample (three-five-years), using the Movement Assessment Battery for Children-Second Edition (MABC-2) (Henderson et al., 2010). This is a tool that primarily assesses static motor skills, and so fails to capture motor competence in dynamic, ecological tasks, which often impose greater cognitive load, task complexity and executive function demands (Carlson et al., 2013; Diamond, 2000; Ludyga et al., 2019; Wilson et al., 2013). This may partially explain the mixed findings across existing literature. For example, (Albuquerque et al., 2022a) implemented the KörperKoördinationsTest für Kinder (Kiphard & Schiling, 1974) and the Test of Gross Motor Development Two (Ulrich, 2000), which does not consider stability skills (Lopes et al., 2013b), while (Davis et al., 2011) implemented the Bruininks-Oseretsky Test of Motor Proficiency-2^{nd} Edition (Bruininks & Bruininks, 2012), which emphasises fine motor skills but lacks ecological validity (Larkin & Cermack, 2002). Therefore, such variations in motor competence measures and a wider age range, than that of this study, complicate direct comparison across studies.

Furthermore, while this study has acknowledged the heterogeneity of motor competence assessments, it is also important to consider the variability in executive function measurements across existing literature. Previous studies that have explored the association between motor competence and executive function (Albuquerque et al., 2022b; Cook et al., 2019a; Davis et al., 2011; Fernández-Sánchez et al., 2022; Gandotra et al., 2022; Oberer et al., 2018; Piek et al., 2008) have employed a range of executive function tasks that target different domains and utilised various scoring systems, task complexity, and administrative protocols. There is potential for the lack of consistency in executive function measurement to partially explain the mixed findings across existing studies, as well as individual differences in general processing playing a role (Löffler et al., 2024). Thus, future research should consider standardised, multi-domain EF batteries that also present strong psychometric properties (Löffler et al., 2024).

Moreover, the strength of the association between motor competence and executive function may be influenced by the motor competence assessment implemented. For example, the Dragon Challenge (Tyler et al., 2018, 2020) is a more ecologically valid and dynamic assessment of motor competence, and so is more likely to engage executive function processes more directly than static or narrowly focused assessments (Kiphard & Schiling, 1974; Ulrich, 2000). Motor skill tasks that incorporate multiple domains, such as locomotor, stability, and object control skills (Tyler et al., 2018, 2020), will also require children to utilise executive functions to plan, inhibit, and adapt their movements (Tomporowski & Pesce, 2019). Increasing the coordinative and cognitive complexity of a task, through manipulation of environmental and task constraints, reflects a stronger association between executive function and its neural substrate activity (Ludyga et al., 2019). By contrast, static motor competence assessments, such as the MABC-2, may not accurately represent these cognitive-motor interactions (Henderson et al., 2010). In addition to the methodological limitations of the MABC-2 (Henderson et al., 2010), age-related executive function development may also explain the lack of association in young children. Executive functions develop rapidly during the early school years (Li et al., 2020), yet performance on executive function tasks does not mature until adolescence (Li et al., 2020). It is thus possible that developmental variability may alter associations that stabilise as children grow older and their executive function skills consolidate. Therefore, when exploring cognitive-motor associations, it is crucial to consider that task complexity may enhance this association by inherently involving executive functions, and that executive function development may play a crucial role.

Additionally, the Dragon Challenge (Tyler et al., 2018, 2020) may also provide insight into physical fitness, especially speed, muscular strength, and cardiovascular endurance, particularly within the core agility and sprinting tasks (Ortega et al., 2008). It could therefore be suggested that overall physical fitness may play a key role in the participants performance in the Dragon Challenge tasks (Stodden et al., 2008). Nonetheless, the Dragon Challenge does include both process-orientated and product-orientated criteria, based upon developmentally appropriate motor skills, which supports a broader image of motor competence ability. The overall Dragon Challenge score reflects a multitude of domains, such as stability, locomotor, object control, and timing) (Tyler et al., 2018, 2020), which takes the focus away from any single component. Motor competence and physical fitness are distinctive concepts, yet are interrelated, and thus children with stronger physical fitness may obtain higher motor competence scores (Robinson et al., 2015). This suggests that the Dragon Challenge (Tyler et al., 2018, 2020) may capture a combined profile of both motor competence abilities and levels of physical fitness. Perhaps future research should consider the role of physical fitness levels when conducting assessments of motor competence abilities to control for their potential influence on motor competence scores.

Deprivation is an environmental constraint, which typically accounts for parental education, occupation, and income (Cook et al., 2019b), that may influence the motor competence-executive function relationship (Chang & Gu, 2018; Piek et al., 2008) (Piek et al., 2008). The ecological dynamics perspective (Button et al., 2021) purports that motor and cognitive development occur simultaneously. The environment is said to play a crucial role within this association, given that access to key resources, physical activity and educational opportunities can be restricted (Ghorbanzadeh et al., 2025). Individuals within less deprived areas often have access to greater facilities and structured physical activities, which allow for the enhancement and development of motor competence and executive functions (Barnett et al., 2016). The ecological dynamics perspective therefore underscores how these constraints may work cooperatively, framing developmental pathways and establishing how motor and cognitive skills may coexist among varying socio-cultural environments (Ghorbanzadeh et al., 2025). The final structural equation model supports this, demonstrating a significant direct effect of motor competence on executive function in medium-high deprivation areas. However, no studies using structural equation model have compared this association across different deprivation groups, rather studies have only considered the role of deprivation (Aadland et al., 2017; Ghorbanzadeh et al., 2025; O'Callaghan et al., 2024)and thus a valuable future implication is highlighted.

The structural equation model revealed a significant direct effect of motor competence on academic attainment, whereby greater motor competence performances are associated with higher academic attainment. This aligns with latent approach studies (de Bruijn et al., 2019; Lopes et al., 2013b; Rigoli et al., 2012; van der Niet et al., 2014) and wider analyses (Batez et al., 2021; Guillamón et al., 2021; Vanhala et al., 2023). This underscores the importance of developing children’s motor competence to support educational success’ (Vanhala et al., 2023), and thus may inform intervention strategies for educators and policymakers (de Greeff et al., 2018; Oberer et al., 2018).

A significant direct path between motor competence and academic attainment was found in the low-medium deprivation group, but not in medium-highly deprived areas, which is consistent with previous studies (Morley et al., 2015). This implies that in less deprived areas, greater motor competence abilities are associated with higher academic attainment. Children from low socio-economic areas often face limited movement skill development opportunities, which may contribute to weaker academic attainment (Anders et al., 2012; Morley et al., 2015). No previous studies have examined motor competence-academic attainment associations across deprivation groups. Education professionals should encourage movement skill development, and further research on socio-economic-related impacts on motor competence and academic attainment is warranted.

Beyond neurophysiological explanations for the motor competence-academic attainment relationship (Khan & Hillman, 2014; Stillman et al., 2016), research now emphasises psychological mediators over exercise-related mechanisms (Pesce, 2012b). Executive function is a frequently cited mediator, often explained by the speed-accuracy trade-off essential in both motor coordination and executive function tasks (Roebers & Kauer, 2009). The finding of a significant indirect effect of motor competence on academic attainment via executive function supports this, aligning with other studies (Fernández-Sánchez et al., 2022; Piek et al., 2008; Vanhala et al., 2023). Executive function has been found to mediate the motor competence-academic attainment relation in 10- to 12-year-olds (Schmidt et al., 2017), and in 12- to 16-year-olds (Rigoli et al., 2012), reinforcing that stronger motor competence is associated with better executive function, ultimately enhancing academic attainment.

The final structural equation model revealed a significant direct effect of executive function on academic attainment, indicating that stronger executive function is associated with academic success in primary school children, aligning with cross-sectional studies (Gathercole, S. E. et al., 2003; Gathercole, Susan E. et al., 2004). The final structural equation model included three executive function tasks, Wisconsin Card Sorting Task (Grant

& Berg, 1948), Corsi-span Task (Corsi, 1972), and the Tower of Hanoi (Byrnes et al., 1979) to form the latent executive function variable, highlighting that executive functions contribute to mathematics (Bull & Scerif, 2001) and literacy (Yeniad et al., 2013) achievement. This aligns with other studies (St Clair-Thompson & Gathercole, 2006) who used a latent approach to assess executive function and academic attainment in 11–12-year-olds. Despite a small sample (n = 51), they examined core executive functions (working memory, inhibition, cognitive flexibility) (St Clair-Thompson & Gathercole, 2006), unlike the current study, which excluded the Flanker task (Eriksen & Eriksen, 1974) due to non-significance. While a small sample size limits statistical power (Kyriazos, 2018), this study also did not assess higher-order executive functions (St Clair-Thompson & Gathercole, 2006). Thus, the multifaceted approach of the current study offers more understanding of cognitive contributions to academic attainment.

The association between executive function and academic attainment did not vary significantly across deprivation groups, suggesting that executive function’s direct effect on academic attainment remains consistent regardless of socio-economic status. Other factors may mediate this relationship, such as self-control (Duckworth et al., 2019), school organization and teaching methods (Vermunt & Endedijk, 2011), and self-motivation (Zeegers, 2001). The complexity of cognition’s role in educational outcomes may explain why some studies support executive function’s positive influence on academic attainment (Gathercole, Susan E. et al., 2004; Yeniad et al., 2013), while others do not (Mayes et al., 2009). Although executive function is a predictor of academic attainment, it is unclear whether early academic attainment also influences executive function development (Fuhs et al., 2014; Welsh et al., 2010), suggesting a possible bidirectional relationship (Fuhs et al., 2014). Further research is needed to explore additional mediating factors.

Strengths and Limitations

This study demonstrated numerous strengths that warrant discussion. The equal gender representation (49% male and 51% female) enhances generalisability (Babbie, 2013). The structural equation model accounted for measurement error, ensuring precise associations between latent factors (Kline, 2023). Implementation of the Dragon Challenge (Tyler et al., 2018) to measure motor competence provided a comprehensive understanding of children's motor skills and their link to executive function. Core and higher-order executive functions formed a single latent executive function variable, while only one previous study (Fernández-Sánchez et al., 2022) incorporated higher-order executive functions when examining associations with motor competence. The confirmatory factory analysis revealed the significance of higher-order executive function measures, offering deeper insights into motor competence's influence on both core and higher-order executive functions, paving the way for future research.

However, this study is not without limitations. The cross-sectional design limits the inference of causal relationships between the variables. The sample was ethnically homogeneous (78% White British), limiting the generalisability to children from other ethnic backgrounds, although this is representative of the ethnic distribution in England and the United Kingdom. Implementing structural equation modelling to explore complex associations requires a large sample size (Kyriazos, 2018). A sample size of 200-299 is considered "fair" for structural equation modelling (Comrey et al., 1973). For multi-group analysis, a minimum of 100 participants per group is recommended (Kline, 2016), yet the final structural equation model could not be examined between ethnic groups due to limited ethnic representation. The current study included very few indicators for academic attainment (two) and executive function (four), yet small sample sizes with fewer indicators per latent variable can lead to improper solutions in structural equation modelling (Kline, 2016).

Currently, limited executive function tests for children exist (Anderson, 2001), and often lack standardised administrative and scoring procedures (Anderson, 2001). This warrants traditional executive function tests to be normed for children. The Flanker task (Eriksen & Eriksen, 1974) did not significantly represent executive function in 8- to 9-year-old children. As the five-letter Flanker is not widely used in children, it may be more cognitively demanding than the arrow Flanker (Richard Ridderinkhof et al.) or fish Flanker (Zelazo et al., 2013), which may be more appropriate. The current study provided four practice trials, yet other studies (Albuquerque et al., 2022b; Zelazo et al., 2013) have implemented a more beneficial criterion-based approach. In these studies, 75% accuracy on practice trials was required (Davidson et al., 2006) before proceeding to the test block. Participants could receive additional practice blocks, but the test would be terminated if the criteria were still not met (Zelazo et al., 2013). Future research should consider these practices, to enhance instruction and test performance (Collie et al., 2003). The Psytoolkit software (Stoet, 2010, 2017) used for the executive function tests also had limitations with its user friendliness. Therefore, future research should explore alternative platforms, such as The Cambridge Neuropsychological Test Automated Battery (Cambridge Cognition, 1996).

A further limitation relates to the lack of established psychometric evidence for the executive function measures employed for 8-9-year-old children. The reliability and validity evidence, and developmental appropriateness of the employed measures have not been consistently established for this age group (Zelazo & Carlson, 2012). As a result, the executive function findings in this study should be interpreted with caution, as they may reflect limited task sensitivity or age appropriateness rather than a true absence of association. Future research should therefore prioritise the validation of executive function measures for the middle-childhood population to support interpretability, reliability, and validity.

Conclusion

This study offers a comprehensive understanding of how children's motor and cognitive skills can intertwine to support academic achievement. This study adds depth to the motor-cognition phenomenon, broadening executive function research by examining motor competence's role in cognition. These findings emphasise the multifaceted nature of child development and the need for a holistic educational approach to integrating directed physical activity to improve motor skills, and cognitive training. Educators and policymakers should prioritise motor competence by incorporating structured physical activity into daily school routines and supporting teacher training in motor skill development. Embedding motor competence into education policy may enhance both physical and academic outcomes. Future research should explore these relationships longitudinally and consider mediating factors, such as mental health, socioeconomic status, and sleep quality to further unravel the motor-cognition phenomenon.

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Author Contributions:

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