O'Callaghan, L, Foweather, L, Crotti, M, Opicci, L, Pesce, C, Boddy, L, Fitton Davies, K and Rudd, J

Associations of physical activity dose and movement quality with executive functions in socioeconomically disadvantaged children aged 5–6 years

Associations of Physical Activity Dose and Movement Quality with Executive Functions in Socioeconomically Disadvantaged Children Aged 5-6 Years

Laura O'Callaghan[1], Lawrence Foweather[1], Luca Oppici[4] Caterina Pesce[2], Matteo Crotti[1], Lynne Boddy[1], Katie Fitton-Davies[1] and James Rudd*[4,5]

[1] Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool L2
[2] Department of Movement, Human and Health Sciences, University of Rome
[3] Research Centre for Sport, Exercise, and Life Sciences, Coventry University, Coventry, UK
[4] Department of Teacher Education and Outdoor Studies, Norwegian School of Sports Sciences, Oslo, Norway
[5] Department of Sport, Food and Natural Sciences, Faculty of Education, Arts and Sports, Western Norway University of Applied Sciences, Sogndal, Norway

* Corresponding author James Rudd: Jrudd@nih.no

Declaration of Interest: None

School of Sport Sciences

ABSTRACT

Background: Growing up in areas of high deprivation can negatively impact children's movement behaviours and cognitive development. Enhancing the quantity and quality of children's movement experiences is believed to enhance cognitive development. This study investigated the association of three different modes of movement assessment, movement proficiency and divergent movement ability (collectively understood as motor competence) and PA dose with executive function in a low socio-economic demographic. Demographics, motor competence, and a combination of motor competence and physical activity were hypothesised to be significantly predictor of executive functions. Method: In this cross-sectional study, 360 children aged 5-6 years from deprived areas were assessed using three movement assessments: wrist-worn accelerometery for physical activity dose, Test of Gross Motor Development-3 for movement proficiency, and divergent movement assessment. Executive function, including inhibitory control, working memory, and cognitive flexibility, was measured using the NIH Toolbox on an iPad. Multiple linear regression models were designed to evaluate the independent and combined association of demographics, movement competence and physical activity variables with executive function. Results: The regression analysis, with demographic factors only, explained 12% of EF variance (r^2 = 0.12 95%CI 0.06-0.18). In addition to this demographics the model with divergent movement explained 19% of EF variance (r^2= 0.19 95% CI = 0.12-0.28), the model with movement proficiency explained 16% of EF variance (r^2= 0.16 95% CI = 0.08-0.26) and the model with PA dose explained 13% of EF variance (r^2= 0.13 95% CI = 0.07-0.20). In these models both divergent movement and proficiency were significant predictors, whilst physical activity variables were not. The final models, combining motor competence and physical activity variables, explained 24% and 23% of EF variance (r^2= 0.24 CI = 0.14-0.33 and r^2= 0.23 CI = 0.14-0.32). In these models, motor competence variables were significant predictors, and only vigorous physical activity and

Euclidean Norm Minus One emerged as significant PA dose predictors. Discussion: These findings emphasise that motor competence and physical activity variables better predict executive functions when they are combined. When considered individually both motor competence variables were significant predictors of executive function whilst physical activity variables were not. Importantly, among the two movement competence facets, divergent movement assessment exhibited the strongest association with executive function. Future interventions should consider how to facilitate both movement and cognitive development in children. Future interventions should consider both the interplay of movement quality and quantity and the importance of environments that invite children's exploratory movement behaviour.

Key Words: cognition, movement competence, divergent movement capability, executive function, physical activity, measurement

Associations of Physical Activity Dose and Movement Quality with Executive Functions in Socioeconomically Disadvantaged Children Aged 5-6 Years

ABSTRACT

Background: Growing up in areas of high deprivation can negatively impact children's movement behaviours and cognitive development. Enhancing the quantity and quality of children's movement experiences is believed to enhance cognitive development. This study investigated the association of three different modes of movement assessment, movement proficiency and divergent movement ability (collectively understood as motor competence) and PA dose with executive function in a low socio-economic demographic. Demographics, motor competence, and a combination of motor competence and physical activity were hypothesised to be significantly predictor of executive functions. Method: In this cross-sectional study, 360 children aged 5-6 years from deprived areas were assessed using three movement assessments: wrist-worn accelerometery for physical activity dose, Test of Gross Motor Development-3 for movement proficiency, and divergent movement assessment. Executive function, including inhibitory control, working memory, and cognitive flexibility, was measured using the NIH Toolbox on an iPad. Multiple linear regression models were designed to evaluate the independent and combined association of demographics, movement competence and physical activity variables with executive function. Results: The regression analysis, with demographic factors only, explained 12% of EF variance (r^2 = 0.12 95%CI 0.06-0.18). In addition to this demographics the model with divergent movement explained 19% of EF variance (r^2= 0.19 95% CI = 0.12-0.28), the model with movement proficiency explained 16% of EF variance (r^2= 0.16 95% CI = 0.08-0.26) and the model with PA dose explained 13% of EF variance (r^2= 0.13 95% CI = 0.07-0.20). In these models both divergent movement and proficiency were significant predictors, whilst physical activity variables were not. The final models, combining motor competence and physical activity variables, explained 24% and 23%

of EF variance (r^2= 0.24 CI = 0.14-0.33 and r^2= 0.23 CI = 0.14-0.32). In these models, motor competence variables were significant predictors, and only vigorous physical activity and Euclidean Norm Minus One emerged as significant PA dose predictors. Discussion: These findings emphasise that motor competence and physical activity variables better predict executive functions when they are combined. When considered individually both motor competence variables were significant predictors of executive function whilst physical activity variables were not. Importantly, among the two movement competence facets, divergent movement assessment exhibited the strongest association with executive function. Future interventions should consider how to facilitate both movement and cognitive development in children. Future interventions should consider both the interplay of movement quality and quantity and the importance of environments that invite children's exploratory movement behaviour.

Key Words: cognition, movement competence, divergent movement capability, executive function, physical activity, measurement

INTRODUCTION

Child poverty is multidimensional and encompasses more than just material and economic deprivation; it also leads to educational poverty and developmental deprivation (Save the Children, 2016). Nurturing and protecting children's brain development is crucial (Luby, 2015), however growing up in disadvantaged communities negatively affects the growth of neural networks and related academic and development outcomes (Hair et al, 2015). Recent evidence emphasises how the motor cortex that coordinates complex movements is strongly connected with other parts of the brain responsible for goal-driven action planning, critical thinking, and other tasks such as regulating blood pressure and pain (Gordon, Chauvin, Van., et al, 2023). These core functions are termed executive functions and they are a key aspect of neural development in childhood, that enable complex processing, inhibiting responses, manipulating information, and shifting attention (Diamond, 2013). Living in areas of high deprivation is associated with poorer performance of certain executive functions, reduced overall development and health outcomes (Rakesh et al., 2021; Diamond 2014; Blair 2002, Blair & Razza 2007; Rosen et al., 2020; Cortes Pascual et al., 2019). Environmental inequalities in deprived areas of Western countries can also result in reduced physical activity (PA) due to fewer opportunities for children to be active, and have been shown to increase time spent engaging in sedentary activities (Noonan, et al., 2017; Strife & Downey, 2009). The negative impacts of poverty on cognitive development and PA could be intertwined, with a substantial body of literature suggesting that PA may benefit cognitive development (Donnelly et al., 2016). However, recent reviews and meta-reviews reveal inconsistent conclusions of the beneficial effect of PA interventions on cognition (Singh et al., 2019; Wassenaar et al., 2020); highlighting the need to understand whether these inconsistencies result from specific moderators of the PA-cognition relationship (Lubans et al., 2021; Ludyga et al., 2020; Pesce et al., 2021).

Among individual, task, and context-related moderators (Pesce et al., 2021), research about PA and cognition has emphasized the importance of PA dose (volume [frequency, duration] and intensity) across the lifespan (Erickson et al., 2019; Lubans et al., 2016; Hillman et al., 2009) and specifically in childhood (Donnelly et al., 2016). In this literature, PA dose often refers to quantitative parameters of exercise, a subset of planned, structured, and repetitive PA, and its physical fitness outcomes, defined as health or skill-related attributes (Caspersen et al., 1985). The heterogeneity in dose parameters limits the ability to draw general conclusions on the optimal dose for enhancing cognition (Erickson et al., 2019). No single exercise parameter seems to result in simple dose-response relationships, but rather reciprocal relationships between different dose parameters emerges (Ludyga et al., 2020). Understanding the relationship between PA dose and cognition in children may be limited by the focus on PA dose or intensity, and the neglect of other important movement qualities that might provide insight into executive function activation and development. In contrast to children living in deprived areas of Western countries, who exhibit low levels of PA (Noonan et al., 2017), there is some evidence from low-income settings in developing countries showing children engaging in high amounts of PA but mostly low-intensity, free-living PA, and active commuting (e.g., Cook et al., 2021; Craig et al., 2013). These high amounts of low-intensity free-living PA do not appear to benefit cognition and are even negatively related to executive function (Cook et al., 2019) and related self-regulation skills (Cook et al., 2019). Therefore, the PA-executive function relationship in children appears to be more complex due to the moderation by socio-economic status, PA level, intensity, type, and quality.

It is possible that the inconsistency in conclusions regarding the relationship between PA dose and cognition is not only due to moderators that constrain the generalisability of results but also to the PA constructs that are investigated. A common device-based measure often employed in these studies to measure PA is accelerometry. The most prevalent method of accelerometer data analysis is to classify accelerations into different PA intensities (e.g., sedentary, light, moderate, vigorous) using thresholds or cut-points (Rowlands et al., 2019). To avoid solely focusing on the number of minutes spent in moderate-vigorous PA (MVPA), intensity gradient and average acceleration have recently been proposed as novel metrics that may indicate the intensity distribution of PA across a 24-hour day. This method demonstrates whether volume and intensity have independent or interactive effect on a variable under investigation (Rowlands et al., 2019). Investigating average acceleration and intensity gradient could help understand whether PA volume (i.e., average acceleration) or the interaction between PA volume and intensity (i.e., intensity gradient) are associated with executive function (Ludyga et al., 2020).

An alternative perspective suggests that the beneficial adaptations for healthy brain development during childhood are not mainly driven by a threshold of PA quantity, but rather by the degree of control and effort exerted by brain processes during movement tasks (Best, 2010; Pesce, 2012). Emotional investment and complexity of the task dynamics are proposed to be key features of children's PA to manipulate the required challenge to support brain development through 'higher-order' control (Diamond & Ling 2019; Tomporowski & Pesce 2019). Tomporowski and Pesce (2019) suggested that the cognitive effort required during skill acquisition, independently or in combination with the level of physical effort, is an essential mechanism explaining the cognitive benefits of PA. The hypothesis of a motor skill acquisition mechanism shifts the focus toward motor competence, which has been shown to be strongly associated with cognitive development in children aged 4-12 years (Van der Fels et al., 2015; Zeng et al., 2017).

Motor competence is typically defined as the proficient performance of fundamental movement skills (Bardid & Utesch, 2018). Its measurement mainly consists of predefined fundamental movement skill patterns that children must reproduce (Hulteen et al., 2020, Bolger et al., 2020In the widely used Test of Gross Motor Development-3 (TGMD), children's locomotor and object control skills are assessed using 13 different activities (Ulrich, 2013). In the TGMD, a point scoring system identifies the position of body parts at different stages of a skill. A child is measured against how well they conform to the optimal movement template of each skill in isolation, in a closed environment, based on the verbal and visual example provided by a trained instructor (Ulrich, 2013).

To move beyond the conventional view of movement as decontextualized fundamental movement skills, it is essential to consider alternative forms of movement assessment that focus on how a child interacts with the task and the environment, rather than reproducing a predefined movement pattern (Hulteen et al., 2022). Such an ecological perspective of movement assessment would not prescribe a movement; instead, it would standardize an informationally rich task and environment in which children explore functional outcomes (Rudd et al., 2020; Adolph, 2019). This approach reflects how children typically play and captures motor proficiency as an adaptive process, where a child explores the movement solutions that a task offers and adapts their movement to changes in the environment. An exploratory movement task could also develop an understanding of cognition as part of an active system adapting to constant change (Adolph, 2019; Raja, 2019). This approach to movement assessment – termed 'divergent movement' assessment - focuses on executive functions' involvement in behavioural adaptability and flexibility when diverging from habitual behaviours and routines (Hulteen et al., 2023; Pesce et al., 2021; Tocci et al., 2022).

The aim of this study was to investigate, in children living in disadvantaged areas, the relationship between three assessments of movement quantity and quality: PA dose, reproduction of fundamental movement skills (movement proficiency), exploration and production of divergent movement solutions in an exploratory movement task and executive functions (inhibitory control, working memory, and cognitive flexibility). Specifically, according to previous literature (Last et al., 2018, Wade et al., 2022), we examined how demographic factors are associated with EF in this specific cohort, and a significant association is hypothesized. Second, we investigated the association of each individual predictor (PA dose, movement proficiency, exploration and production of divergent movement solutions) with EF. Children's exploratory and divergent movements are hypothesized to demonstrate a stronger association than fundamental movement proficiency or PA dose with children's EF. Lastly, we examined how the combination of PA and motor competence variables predict EF, hypothesizing a significant added value when these predictors are combined.

This study is novel for two reasons. First, is an extension of movement assessment that, along with PA dose and motor proficiency, encompasses a measurement of a child's exploration of divergent movement solutions. Secondly, we aim to fill a gap in the literature regarding children growing up in poverty, which mostly considers the negative consequences of these disadvantages for PA levels (Chang & Kim, 2017), motor competence (Barnett et al., 2016), and executive function (Haft & Hoeft, 2017) in isolation, largely neglecting their interrelation with few exceptions (e.g., Cook et al., 2019).

By adopting this approach, researchers and practitioners may be better equipped to identify the unique contributions of different movement aspects to cognitive development in children living in disadvantaged areas. This understanding could inform interventions aimed at promoting cognitive development and overall well-being in these populations. Additionally, the ecological approach to movement assessment may provide a more comprehensive and accurate picture of the complex relationship between movement and cognitive development, allowing for more effective, tailored interventions that target both cognitive and motor skill development.

METHOD

Design

This cross-sectional study utilised baseline data (collected between January and February 2018) from the SAMPLE-PE Randomized Controlled Trial (Rudd et al., 2020), which investigated how pedagogical approaches in primary physical education could support various aspects of physical literacy in children aged 5-6 years old. The trial is registered at ClinicalTrials.gov (identifier: NCT03551366) and received institutional research ethics committee approval (Reference 17/SPS/031).

Participants

A total of 360 children (5.95 ± 0.3 years old; 55% female) were recruited from 12 eligible government-funded primary schools in a large city in North West England. This sample size was calculated for the broader project SAMPLE-PE (for details, see Rudd et al., 2020), and it provides an adequate statistical power for the design, analysis, and expected effect sizes of this current study. Previous literature with a design and analysis similar to the current study showed a small-to-moderate association of physical activity and motor proficiency with executive functions, with *shifting* showing the smallest association ($r^2 = 0.181$; $\Delta r^2 = 0.031$) (Cook et al., 2019). A-priori sample size calculation with $\alpha = 0.05$ and power $(1 - \beta) = 0.80$ revealed that 293 participants were required to detect such small association ($f^2 = 0.038$), also in line with a recent umbrella review of RCTs showing small effects of PA on executive functions (Ciria et al., 2023).

Each school was ranked within the most deprived tertile for the English population, based on the schools' postcode as ranked by the 2015 English Indices of Deprivation index (Gov.UK, 2018). After an information meeting with the research team, where headteachers were provided with an in-depth overview of the project, gatekeeper consent was obtained for recruitment and data collection. Year 1 children (aged 5-6 years) were then invited to participate in the study via a parent/carer and child invitation pack, which included information sheets, parental consent forms, parent and child characteristics questionnaires, child medical information forms, and child assent forms. If information gathered from parents indicated that children had special education needs (SEN), this was verified by the class teacher. Children who did not return consent and assent forms, signed by both the parent and child, respectively, were excluded from all assessments. Additionally, children who were unable to participate in Physical Education (e.g., due to medical conditions) were excluded from data analysis.

Assessments

Cognitive Functions

The NIH Toolbox is a comprehensive set of neuro-behavioural measurements that assess executive functions using an iPad and has well-established validity and reliability for use with children aged 3-15 years (Weintraub et al., 2013). The first author and an independent research assistant who helped collect the data completed the online training videos provided by Northwestern University for each of the NIH Toolbox assessments. To evaluate the three components of executive function, the first author and the independent research assistant worked one-on-one with each child in a quiet space outside the classroom (e.g., library). Each child was asked to complete three age-appropriate activities from the NIH Toolbox, lasting approximately 15 minutes in total (Northwestern University, 2018).

Inhibitory Control: Assessed using the Flanker Test, which required the child to focus on the central arrow appearing on the iPad screen while inhibiting attention to the arrows on either side of the centre. On congruent trials, all arrows point in the same direction, while on incongruent trials, the middle arrow points in the opposite direction of the other arrows. The child was instructed to choose one of two buttons on the screen that corresponded to the direction in which the middle arrows were pointing as quickly as possible. The child performed four practice trials and 20 trials in the test. The software recorded the child's response accuracy (i.e., number of correct responses) and response time (from stimulus appearance to a button being pressed), combined them, and provided an arbitrary outcome measure, which ranged from 0 to 10. The software computed the score using a 2-vector scoring method (vectors ranged from 0 to 5 in both accuracy and response time) and considered accuracy first; if accuracy level was less than, or equal to, 80% (i.e., vector = 4), the outcome measure was equal to the accuracy score. When accuracy was higher than 80%, reaction time and accuracy were combined.

Working Memory: Assessed via the List Sorting Task, which required a child to memorise, manipulate, and recall a series of pictures of animals and food presented on the iPad screen. At the end of each series, a blank screen appeared, and the child was required to verbally list the pictures in order of size, from smallest to largest. There were two conditions: 1-list and 2-list condition. In the 1-list condition, only one category of pictures (food or animals) is presented in each series, whereas both picture categories are presented in the 2-list condition in each series. In each condition, the number of pictures increased with each series to progressively overload a child's working memory. Prior to the test, participants performed 10 practice trials before each condition. The software provided an outcome variable of the number of correct recalls.

Cognitive Flexibility: Assessed through the Dimension Change Card Sort, which required the child to match two target pictures with a reference picture by either color or shape. Prior to the appearance of the reference stimulus, a cue – shape or color – appeared visually and audibly on the screen, indicating to the child what dimension the target should be matched by. The child was instructed to choose as quickly as possible between which of the two target items matched the dimension, indicated by touching the screen with their index finger. The software recorded the score in the same way as the Flanker Test detailed above.

Physical activity

Children wore ActiGraph GT9X Link triaxial accelerometers (ActiGraph, USA) on their non-dominant wrist for 7 days, removing them only for showers, baths, or swimming. The accelerometers had a sampling frequency of 30Hz and a dynamic range of ±8 g. Acceleration data were downloaded using ActiLife software (ActiGraph, USA) in 1 s epochs files and then exported in .csv format. GGIR version 1.11–0 from R software version 4.02.5 was used to process data, complete auto-calibration procedures (Van Hees et al., 2014), and convert raw triaxial accelerometer signals into Euclidean Norm Minus One (ENMO) acceleration data (van Hees et al., 2013). PA data were analysed within a standardized waking time window between 06:00 and 23:00, and non-wear was scored using the moving window method described by Van Hees et al. (2013). To obtain a valid day, children had to wear the accelerometer for at least 10h. To be including within analysis, children had to wear the monitor for a minimum of three valid weekdays and one valid weekend day. Children not meeting the valid week criterion were invited to wear the monitor for another 7 days. ENMO data were classified into time spent in MVPA using age-appropriate validated cut-points (Crotti et al., 2020). Intensity gradient was calculated using GGIR, following the method described by Rowlands et al., (2019), which is based on the relationship between log values for intensity (0-25mg, 25-50mg, etc.) and time at each intensity bin. Average acceleration, expressed in milligravitational units (mg), was computed using ENMO values1s.

Motor Proficiency

Locomotor and object control motor proficiency was assessed using the Test of Gross Motor Development-3 (TGMD-3) (Ulrich, 2013). Specifically, six locomotor (run, gallop, hop, skip, horizontal jump, slide) and seven object-control (two-hand strike, one-hand strike, one-hand dribble, two-hand catch, kick, overhand throw, underhand throw) skills were assessed. The children received a verbal explanation and single demonstration from the trained assessor and were given one practice attempt before undertaking two trials of each skill. Proficiency of stability skills was assessed using the Test of Stability Skills (TSS) (Rudd et al., 2015). The stability test involves three tasks (log roll, rock, and back support) where children received a verbal explanation and single demonstration from the assessor and were then given one practice attempt before undertaking two trials of each skill. The validity and reliability of these assessments have been well established (Maeng et al., 2016; Rudd et al., 2015). All skill performance trials across the two measures of motor proficiency were video recorded for future analysis, prior to video coding all inter- rater reliability was conducted.

Exploratory Movement Capability

Exploratory movement capability was assessed using the Divergent Movement Ability Assessment (DMA) (Cleland, 1990), which required the children to explore three rich environments. The first environment affords balancing and creating shapes with their body, the second invites the child to locomote in as many different ways as possible, and finally an object manipulation environment where children play with a ball in as many ways as possible. At the stability environment, children were asked to make as many shapes and balances on or around the bench using as many different body parts as they could. For every station, children completed two 90-second trials, during which, every 30 seconds, each child received a predefined prompt from the research assistant to support and encourage. Groups of 3 children rotated around the 3 locomotor, object, and stability stations in the DMA. This took place during school hours within the school hall and was video recorded for later analysis. The DMA was scored using a performance criterion for flexibility (the number of changes in body position for the same movement response) and fluency (the number of different movement responses). For fluency, each different movement response was names (e.g. running, catching, kicking, star shape) and elicited a score of 1. For flexibility, the changes in body position (e.g. running backwards, jumping sideways, catching with left hand, kicking with left foot, star shape on right foot) for each movement response elicited a score of 1. Exploratory Movement was a total score computed by combining the fluency and flexibility total scores.

A total of 9 research assistants supported data collection and each received 9 hours of training in the administration of the DMA, TGMD-3 and stability test. Five of the research assistants received an additional 6 hours training on coding each of the assessments. Skill data from ten children randomly selected from a previous pilot assessment study was used to ascertain inter- and intra-rater reliability of the assessors coding on the TGMD-3, DMA and stability test. One child did not partake in the DMA because they were absent from school on the day of the assessment. Intraclass correlation coefficients (ICC) were run with two-way mixed, average measures for absolute agreement, with 95% confidence intervals. Table 1 shows the inter- and intra-rater mean ICC scores for the five raters of the DMA (total fluency and flexibility scores),TGMD-3 and stability test, as well as the mean range for each outcome ICC. All mean ICC scores were "excellent" (Cicchetti, 1994).

Anthropometrics

Children's height, sitting height, waist circumference and body mass were measured with an accuracy of 0.1cm and 0.1kg, respectively. Height and sitting height were assessed with a portable stadiometer (Leicester Height Measure, SECA, Birmingham, UK) and body mass was assessed using digital scales (Tanita WB100-MA, Tanita Europe, The Netherlands). Height and weight values were used to examine weight status using the International Obesity Task Force age and sex adjusted body mass index (BMI) growth reference (Cole et al., 2000).

Data Analysis

Before conducting both preliminary and main analyses, the data were checked to ensure they met the major statistical assumptions for each statistical test, and an alpha level (p) of .05 or less was used as the criterion to reject the null hypothesis. The Shapiro-Wilks test was performed to assess the distribution of the three executive functions. Assumptions of independence of observation were tested using the Durbin-Watson statistic (1.996), and linearity between variables and homoscedasticity were examined through a visual inspection of scatterplots. To determine whether to use a composite score of executive function, an exploratory factor analysis (EFA) was employed to produce the most parsimonious factor structure for the subsequent main analysis. For factor analysis, if the assumption of multivariate normality is violated, a principal axis factor method in SPSS is recommended. The working memory raw score registered a significant outlier. To assess whether outliers affected the analysis, the factor analysis was run twice to see if the outlier influenced the number of factors. The three executive function variables measured (inhibitory control, working memory, and cognitive flexibility) were tested for suitability of structure detection using the Kaiser-Meyer-Olkin Measure of Sampling adequacy (>0.5) and Bartlett's test of sphericity test (0.001). In the EFA, principal axis factoring (PAF) was selected as the extraction method with a direct oblimin rotation. An eigenvalue above 1 was used to determine the number of factors, guided by the interpretation of the scree plot. The preliminary factor analysis grouped the variables within one factor, and thus, the executive functions scores were combined into a total score (EF).

R software and RStudio software were used to complete subsequent data handling and statistical analysis. The normality distribution of each continuous variable was assessed using the Shapiro-Wilk test, the distribution of the data was checked using boxplots and histograms, linearity relations were inspected, and potential heteroscedasticity in paired variables was examined using scatterplots. Rosner's test was used to identify potential outliers. Each statistical analysis was run both including and excluding outliers to ensure they did not affect the results, and in the end outliers were not excluded as their inclusion did not affect the results. Variance Inflation Factors (VIF) test was used to check for multicollinearity. Initially, correlation tests and multiple linear regression analysis were performed using complete cases analysis, and then the same regression analyses were run after imputing missing data.

Depending on variable distribution, either Pearson or Spearman correlation tests were run to check correlations.

The following analysis was comprised of four steps, building from simple to more complex models: i) a multiple regression analysis with all demographic factors, ii) a multiple regression analysis adding motor competence and PA variables individually to the previous model, considering demographic factors, wear time and weather conditions as covariates, iii) backward elimination process to eliminate the covariates that did not improve the model, and iv) the final multiple regression analysis combining the motor competence and PA variables that were not multicollinear.

To test the first hypothesis, a multiple regression analysis was run with demographic factors (i.e., age, sex, SEN, deprivation, and ethnicity). To test the second hypothesis, separate multiple regression analysis models were designed with EF as the dependent variable, including the variables in the previous models as covariates, and adding the independent variables of interest one at a time: exploratory movement capability (DMA), motor proficiency, MVPA, MPA, VPA, intensity gradient (IG), and ENMO. Then, through a backward elimination process, ethnicity, accelerometer wear-time, and weather conditions variables were excluded from the regression models because they either did not improve the explained variance in the model (assessed by comparing models using the "anova" function within the R package "stats" (Fields et al 2012)), were above the cut-off of $p = 0.1$, and did not change the significance of parameter estimates (Bursac et al. 2008) Lastly, to test the third hypothesis of a combined association of motor competence and PA variables with EF, different multiple linear regression models were designed, including both motor competence variables (i.e., motor creativity and motor proficiency) and physical activity variables (excluding MVPA and VPA because they were strongly correlated). Only variables that were not multicollinear were included. Variables with missing data were tested to assess whether the data were missing completely at random using Little's MCAR test, which confirmed the data were missing completely at random.

The whole procedure was performed on complete cases first and then the same models were run using the imputed data, to test that missing values did not influence the analysis. All the analyses were performed using the R Software. The "lm" function was used to run the regression analyses. Subsequently, the 'mice' package was used to run multiple imputations and create five different datasets with imputed data. Different multiple imputation models were designed for various multiple regression models. Lastly, the "pool" and "pool.r.squared" functions from the "mice" package was used to pool the outputs of the regressions from the imputed data. Effect sizes were calculated using r^2 and classified according to the thresholds proposed by Cohen (1988) (0.01 = small effect; 0.09 = moderate effect; 0.25 = large effect).

RESULTS

The final sample invited to participate in the study included 360 children (55% female), 56% of them being white British with a mean age of 6.0 (SD=0.3) years. However, due to various reasons (e.g., being absent from school or not wearing the accelerometer), not all children completed all assessments (executive function, n=335; exploratory movement, n=294; PA dose, n=262; motor proficiency, n=250). Table 2 includes the descriptive statistics for the demographic, executive function, PA, and motor competence variables.

Considering that data was missing at random and the similar trend of results with complete cases (see appendix), we present and discuss results obtained with imputed data. After data imputation, 360 children were included in the statistical analysis. The first multiple regression analysis showed that demographic factors explained 12% of EF variance (r^2 = 0.12) and all variables but ethnicity were significant predictors (Table 3). Subsequent multiple regression analyses, whereby DMA, motor proficiency, MVPA, MPA, VPA, IG, and ENMO were added individually to the previous model, showed that only DMA and motor proficiency were significant predictors of EF (Table 4). Further, r^2 and the fit of the model improved only in the models with DMA (r^2 = 0.19) and motor proficiency (r^2 = 0.16), and not with PA variables. The coefficient and r^2 were higher in the DMA model than the motor proficiency model. Lastly, the regression analysis with a combination of motor competence and PA variables (motor competence + VPA, and motor competence + ENMO + IG) explained the highest amount of variance in executive functions (r^2 = 0.23 and r^2 = 0.235). While DMA and motor proficiency did not meaningfully change their coefficient, VPA and ENMO became significant predictors of EF (Table 5). In these models, all PA variables were negatively associated with EF, but only VPA and ENMO were significant predictors (Appendix).

DISCUSSION

This study investigated the relationship between three assessments of movement (PA dose, motor proficiency, and DMA) and executive function in children aged 5-6 years from an area of socio-economic disadvantage. Regression results revealed that the model including both motor proficiency and DMA variables, as well as the most representative index of PA dose (VPA and ENMO), explained the highest amount of variance in overall executive function. However, the individual prediction by VPA and ENMO was nonsignificant, while both motor proficiency and DMA facets of motor competence were significant predictors of executive functions after controlling for demographic factors. Interestingly, among the two movement competence facets, DMA exhibited the strongest association with executive function. In summary, the results emphasise the need to consider the complexity of the different processes at play within the context in which they occur.

The main finding in this study, that movement proficiency and DMA were significant predictors of children's executive function, aligns with previous research on the association between motor competence and executive function in this age group of children (Van der Fels et al., 2015). The highest prediction of executive function specifically by DMA represents the novelty of this study, suggesting that not motor competence per se, but the capability to explore movement solutions in a divergent manner may have a potential, universal function at this stage of development in children. The fact that the participants in this study were children at the beginning of their school life (aged 5-7 years) living in an area of deprivation is especially relevant because the academic achievement gap between children growing up in advantageous or disadvantageous socio-economic conditions widens over time (von Stumm, 2017). Although the correlational nature of the present results does not allow for causal inference, this study lays the groundwork for deepening our understanding of the linkage between specific facets of motor competence and executive functions which are reliable predictors of academic achievement, especially at the early primary education age (Cortés Pascual et al., 2019).

The current results suggest the importance of capturing exploratory movement capability, as well as motor proficiency, in the linkage between motor and cognitive developmental domains. Recently, exploration has gained momentum in movement sciences, driven by both an ecological perspective on motor development (Adolph & Hoch, 2018; Adolph, 2019) and learning (Hacques et al., 2021). There is a converging interest of motor developmentalists and clinical psychologists for holistic models of child development grounded in the motor domain (Stodden et al., 2023), centered on the ecological value of exploration (Stodden et al., 2021) to find and perform functional movement solutions (Rudd et al., 2020).

The higher association found in this study between exploratory movement capability and executive function can be explained from an ecological perspective on movement and assessment, according to which cognition may be conceived as activity across a whole system (not just the brain) and attunement to ecological information (Bruineberg, Chemero & Rietveld, 2019). From this ecological perspective, executive functions can be understood as integral to the reciprocity of a child's actions and explorations through specifying affordances in the environment (E. Gibson, 1988; Adolph, 2019; Raja, 2018; Lobo et al., 2018). In this framework, executive functions will be active in different ways for the same task as a child attunes to their environment, self-regulating functional movement behavior (Hambrick et al., 2020; Chow et al., 2011; Davids & Araujo, 2010). The divergent movement capability task used to assess exploratory movement capability required children to interact with a variety of equipment, surfaces, and other environmental features (Cleland, 1990). For example, children had to find as many different ways as possible to move around an obstacle course. In this task, the nervous system is continually adjusting in context in various ways, whereby a set of neurons are equipotential for different functions in perception and behavior (Reed, 1988). It is at this intersection where higher-order executive functions are part of a dynamic system supporting the interrelation between the individual, environment, and the performance of functional movement solutions (Rudd et al., 2020).

The non-significant association, and negative association in the complex models, between PA variables and executive function must also be discussed, as it does not support the body of previous studies reporting a benefit of a child's PA dose on executive function (Donnelly et al., 2016, Hillman et al., 2019, Alvarez-Bueno et al., 2020). It must be emphasized that those reviews relied upon previous studies focused on PA dose in diverse populations that used a range of different measures and thresholds to assess PA and executive function, which restricts comparisons with our study findings. Our results are in line with recent research showing no association or negative association between PA and executive functions when habitual PA is considered (as in our study) and not PA interventions (Cook et al., 2019).

Further, these results are based on measures of PA dose that are indicative of vastly different characteristics of movement activities by a child, and volume and intensity appear to be a fraction within the motor- cognitive system that integrate online use of executive function during PA. Movement quality outcomes may, therefore, be a stronger marker of learning and executive development than a snapshot of a child's activity in any one week. This adds to the growing body of knowledge that considers the intertwined relation between PA, motor competence, and cognition (Tomporowski & Pesce, 2019).

The significant association of exploratory movement capability and motor proficiency with executive function highlights the potential value of focusing on movement quality in school physical education. The design of rich environments can promote movement proficiency and exploration based on pedagogies informed by movement learning theories (Rudd et al., 2020). This is especially relevant when considering the descriptive results of PA, executive functions, and movement assessments relative to normative data of the participants in this study, living in an area of low socioeconomic status. This study indicated a low mean score compared to normative data in children aged 5-6 years in inhibitory control, working memory and executive flexibility (Slotkin et al., 2012). Of the children who completed PA measurements, 244 (67%) met the daily PA recommendation for a child aged 5-6 years represented by 60-minutes of MVPA. Further, children had relatively moderate level of motor proficiency, and a relatively low level of stability skill. When physical and cognitive development are already compromised by aged 5 years, it is critical to understand the specific experiences that promote an enhancement of under-developed skills.

Limitations and Conclusions

This study contributes to our understanding of the associations between movement behaviors and executive function in children, emphasizing the importance of exploratory movement capability in predicting executive function in primary school children aged 5-6 years. Such findings are particularly relevant for designing interventions to support the developmental needs of children living in socio-economically disadvantaged areas. However, the study has its limitations.

First, the cross-sectional design provides only a snapshot of the associations between children's movement and executive function abilities, offering limited insight into the directionality of these relationships and how they may develop throughout childhood. Future longitudinal research is needed to examine the trajectory of these associations and determine causal links between movement behaviours and executive function. The direction of causation could be the reverse whereby higher executive function levels lead to better coordination, more varied movement patterns and higher PA levels. Second, the executive function assessment was conducted using an iPad, providing only an approximation of cognitive abilities. Including measures of academic performance or intelligence would have provided a more comprehensive evaluation of children's executive function. To further understand the statistical associations between exploratory movement and executive function observed in this study, an intervention study aiming to promote movement qualities underpinned by motor learning theories may provide evidence of an interaction effect for enhancing children's executive functions. These functions are strongly associated with higher academic achievement and longitudinal health outcomes, independently of intelligence (Diamond & Ling, 2019; von Stumm, 2017). Third, the generalisability of the study's results is limited by the age and demographic characteristics of the sample. The study focused exclusively on children aged 5-6 years living in areas of socio-economic disadvantage, which may not fully represent the diverse range of children's experiences and developmental trajectories. It is important for future research to examine the associations between movement behaviours and executive function in children from different socio-economic backgrounds, age groups, and cultural contexts to determine whether these relationships hold across varied populations. This broader understanding will further inform the development of tailored interventions to support children's executive function development and motor development.

In conclusion, these findings show that among children aged 5-6 years living in areas of socio-economic disadvantage, DMA exhibited the strongest association with executive function. The study also showed, there is a combined association of quantity and quality assessments of children’s movement on executive function. A follow up to this study, would be an intervention study that combines both the interplay of movement quality and quantity and the importance of environments that invite children’s exploratory movement behaviour.

Author Contributions

Conceptualisation; JR, LF and LOC, Data curation: LOC, MC, JR, LO, LF, Formal analysis; MC, JR, LC, LOC, Investigation; LOC, JR, MC, KFD LF, LB, Methodology; LOC, JR, LF MC, LO Supervision; JR, LF, LB CP Writing - original draft; LOC, JR, LF and Writing - review & editing; All authors

REFERENCES

Adolph, K.E. & Hoch, J.E. (2018). Motor development: embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, 12-41. https://doi.org/10.1146/annurev-psych-010418-102836.

Adolph, K. (2019). An ecological approach to learning in (not and) development. *Human Development*, *63*, 180-201. DOI: 10.1159/000503823

Alvarez-Bueno, C., Hillman, C.H., Cavero-Redondo, I., Sanchez-Lopez, M., Pozuelo-Carrascosa, D.P. & Martinez-Vizcaino, V. (2020). Aerobic fitness and academic achievement: a systematic review and meta-analysis. *Journal of Sports Science, 38*(5), 582-589. DOI: 10.1080/02640414.2020.1720496.

Bardid, F., and Utesch, T. (2018). “Motor competence,” In S. R. Hackfort and B. Strauss (eds.). *Dictionary of Sport Psychology*, Elsevier, 336.

Barnett, L.M., Lai, S.K., Veldman, S.L.C., Hardy, L.L., Cliff, D.P., Morgan, P.J., Zask, A., Lubans, D.R., Shultz, S.P., Ridgers, N.D., et al. (2016) Correlates of Gross Motor Competence in Children and Adolescents: A Systematic Review and Meta-Analysis. *Sports Medicine*. *46*, 1663–1688. DOI: 10.1007/s40279-016-0495-z

Best J. R. (2010). Effects of Physical Activity on Children's Executive Function: Contributions of Experimental Research on Aerobic Exercise. *Developmental review*, *30*(4), 331–551. https://doi.org/10.1016/j.dr.2010.08.001

Blair, C. (2002). School readiness: Integrating cognition and emotion in a neurobiological conceptualization of child functioning at school entry. *American Psychologist*, *57*, 111–127. https://doi.org/10.1037/0003-066X.57.2.111

Blair, C. & Razza, R.P. (2007). Relating effortful control, executive function and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development*,*78*(2), 647-663. doi: 10.1111/j.1467-8624.2007.01019.x

Bolger, L.E., Bolger, L.A., O'Neill, C., Coughlan, E., O'Brien, W., Lacey, S., Burns, C. & Bardid, F. (2020). Global levels of fundamental motor skills in children: a systematic review. *Journal of Sports Science*, *39* (7), 717-753. https://doi.org/10.1080/02640414.2020.1841405

Bruineberg, J., Chemero, A. & Rietveld, E. (2019). General ecological information supports engagement with affordances for higher cognition. *Synthese*, *196* (12). DOI: 10.1007/s11229-018-1716-9.

Bursac Z, Gauss CH, Williams DK, Hosmer DW. Purposeful selection of variables in logistic regression. *Source Code Biol Med*. 2008;3:17. Published 2008 Dec 16. doi:10.1186/1751-0473-3-17

Caspersen, C.J., Powell, K.E. & Christenson, G.M. (1985). Physical activity, exercise and physical fitness: definitions and distinctions for health-related research. *Public Health Reports*, *100* (2), 126-131. PMID: 3920711; PMCID: PMC1424733.

Chang, S. H., & Kim, K. (2017). A review of factors limiting physical activity among young children from low-income families. *Journal of exercise rehabilitation*, *13*(4), 375–377. https://doi.org/10.12965/jer.1735060.350

Chow, J.Y., Davids, K., Hristovski, R., Araújo, D. & Passos, P. (2011). Nonlinear pedagogy: Learning design for self-organizing neurobiological systems. *New Ideas Psychology*, *29*, 189–200. DOI: 10.1016/j.newideapsych.2010.10.001

Cicchetti, D.V. (1994). Guidelines, criteria and rules of thumb for evaluating normed and standardised assessment instruments in psychology. *Psychological Assessment*, *6*(4), 284-290. https://doi.org/10.1037/1040-3590.6.4.284

Ciria, L.F., Román-Caballero, R., Vadillo, M.A., Holgado, D., Luque-Casado, A., Perakakis, P., & Sanabria, D. (2023). An umbrella review of randomized control trials on the effects of physical exercise on cognition. BioRxiv. https://doi.org/10.1101/2022.02.15.480508

Cole, T.J., Bellizi, M.C., Flegal, K.M. & Dietz, W.H. (2000). Establishing a standard definition for child overweight and obesity worldwide: international survey. *British Medicine Journal, 320*(7244). doi: 10.1136/bmj.320.7244.1240

Cleland, F. (1990). The Relationship of Selected Factors to Young Children's Divergent Movement Ability. *ProQuest*.

Cohen, J. (1988). *Statistical power analysis of the behavioural sciences*. Academic press.

Cook, C.J., Howard, S.J., Scerif, G., Twine, R., Kahn, K., Norris, S.A. & Draper, C.E. (2021). Associations between South African preschoolers' routine physical activity, self-regulation and psychosocial well-being. *Mental Health and Physical Activity, 20*. https://doi.org/10.1016/j.mhpa.2021.100383

Cook, C.J., Howard, S.J., Scerif, G., Twine, R., Kahn, K., Norris, S.A. & Draper, C.E. (2019). Associations of physical activity and gross motor skills with executive function in preschool children from low-income South African settings. *Developmental Science*, *22*. DOI: 10.1111/desc.12820

Cortes Pascual, A., Moyano Munoz, N. Robres, A.Q. (2019). The relationship between executive functions and academic performance in primary education: review and meta-analysis. *Frontiers in Psychology*,*10* (1582). DOI: 10.3389/fpsyg.2019.01582

Craig, E., Bland, R., & Reilly, J. (2013). Objectively measured physical activity levels of children and adolescents in rural South Africa: high volume of physical activity at low intensity. *Applied Physiology, Nutrition, and Metabolism, 38*(999), 81–84. https://doi.org/10.1139/apnm-2012-0115

Crotti, M., Foweather, L., Rudd, J.R., Hurter, L., Schwarz, S. & Boddy, L. (2020). Development of raw acceleration cut-points for wrist and hip accelerometers to assess sedentary behaviour and physical activity in 5-7 year old children. *Journal of Sports Science, 38*(9), 1036-1045. doi: 10.1080/02640414.2020.1740469.

Davids, K. & Araujo, D. (2010). The concept of 'organismic asymmetry' in sports science. *Journal of Science and Medicine in Sport*, *13*(6), 633- 640. https://doi.org/10.1016/j.jsams.2010.05.002

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

Diamond, A. (2014). Want to optimise executive functions and academic outcomes? *Minnesota Symposium on Child Psychology, 37*, 205-232.

Diamond, A. & Ling, D.S. (2019). Aerobic-exercise and resistance-training interventions have been among the least effective ways to improve executive functions of any method tried thus far. *Developmental Cognitive Neuroscience*, *37*. https://doi.org/10.1016/j.dcn.2018.05.001

Donnelly, J.E.; Hillman, C.H.; Castelli, D.; Etnier, J.L.; Lee, S.; Tomporowski, P.; Lambourne, K. & Szabo-Reed, A.N. (2016) Physical activity, fitness, cognitive function, and academic achievement in children: A systematic review. *Medicine and Science in Sports and Exercise*, *48*, 1197–1222. doi: 10.1249/MSS.0000000000000901

Erickson KI, Hillman C, Stillman CM, Ballard RM, Bloodgood B, Conroy DE, Macko R, Marquez DX, Petruzzello SJ, Powell KE., (2019) Physical Activity, Cognition, and Brain Outcomes: A Review of the 2018 Physical Activity Guidelines. *Medicine Science Sports Exercise*. *51*(6):1242-1251. doi: 10.1249/MSS.0000000000001936.

Field, A. (2018). *Discovering statistics using IBM SPSS statistics*. Sage; London.

Field, A., Miles, J., & Field, Z. (2012). *Discovering statistics using R* (Vol. 3). London: Sage

Gibson, E. (1988). Exploratory behaviour in the development of perceiving, acting and the acquiring of knowledge. *Annual Review of Psychology*, *39*, 1-41.

Gordon, E.M., Chauvin, R.J., Van, A.N., Rajesh, A., Nielsen, A., Newbold, D.J., Lynch, C.J., Seider, N.A., Krimmel, S.R., Scheidter, K.M., Monk, J., Miller, R.L., Metoki, A., Montez, D.F., Zheng, A., Elbau, I, Madison, T., Nishino, T., Myers, M.J., Kaplan, S., Badke D'Andrea, C., Demeter, D.V., Feigelis, M., Ramirez, J.S., Xu, T.,Barch, D.M., Smyser, C.D., Rogers, C.E., Zimmermann, J., Botteron, K.N., Pruett, J.R., Wilie, J.T., Brunner, P., Shimony, J.S., Kay, B.P., Marek, S., Norris, S.A., Gratton, C., Sylvester, C.M., Power, J.D., Liston, C., Greene, D.J., Roland, J.L., Petersen, S.E., Raichle, M.E., Laumann, T.O., Fair, D.A. & Dosenbach, N.U.F. (2023). A somato-cognitive action network alternates with effector regions in motor cortex. *Nature*, https://doi.org/10.1038/s41586-023-05964-2

Gov.UK (2018). English indices of deprivation. DOI: English indices of deprivation - GOV.UK (www.gov.uk)

Hacques, G., Komar, J., Dicks, M. & Seifert, L. (2021). Exploring to learn and learning to explore. *Psychological Research, 85*, 1367-1379. https://doi.org/10.1007/s00426-020-01352-x

Haft, S. L., & Hoeft, F. (2017). Poverty's Impact on Children's Executive Functions: Global Considerations. *New directions for child and adolescent development*, *158*, 69–79. https://doi.org/10.1002/cad.20220

Hair, N.L., Hanson, J.L., Wolfe, B.L. & Pollak, S.D. (2015). Association of child poverty, brain development and academic achievement. *JAMA paediatrics*, 1-25. doi:10.1001/jamapediatrics.2015.1475.

Hambrick, Z., Burgoyne, A. & Araujo, D. (2020). Working memory and expertise: an ecological perspective. *Working Memory*. DOI:10.1093/oso/9780198842286.003.0008

Hillman, C.H., Pontifeux, M.B., Raine, L.B., Castelli, D.M., Hall, E.E. & Kramer, A.F. (2009). The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. *Neuroscience, 159*(3), 1044-1054. doi:10.1016/j.neuroscience.2009.01.057.

Hillman, C.H., McAuley, E., Erickson, K.I., Liu-Ambrose, T. & Kramer, A.F. (2019). On mindful and mindless physical activity and executive function: a response to Diamond & Ling (2016). *Developmental Cognitive Neuroscience, 37.* http://dx.doi.org/10.1016/j.dcn.2015.11.005

Hulteen, R. M., Barnett, L. M., True, L., Lander, N. J., del Pozo Cruz, B., & Lonsdale, C. (2020). Validity and reliability evidence for motor competence assessments in children and adolescents: A systematic review. *Journal of Sports Sciences, 38*(15), 1717-1798. https://doi.org/10.1080/02640414.2020.1756674

Hulteen, R.M., Terlizzi, B., Abrams, C., Sacko, R.S., De Meester, A., Pesce, C. & Stodden, D.F. (2022). Reinvest to assess: advancing approaches to motor competence measurement across the lifespan. *Sports Medicine, 53* (1), 1-18. DOI: 10.1007/s40279-022-01750-8

Hulteen, R.M., True, L. & Kroc, E. (2023). Trust the “process”? When fundamental motor skill scores are reliably unreliable. *Measurement in Physical Education and Exercise Science.* DOI: https://doi.org/10.1080/1091367X.2023.2199126

Jylanki, P., Mbay, M, T., Hakkarainen, A., Saakslahti, A. & Aunio, P. (2022). The effect of motor skill and physical activity interventions on preschoolers’ cognitive and academic skills: a systematic review. *Preventative Medicine, 155.* https://doi.org/10.1016/j.ypmed.2021.106948

Kaiser, H. 1974. An index of factor simplicity. *Psychometrika 39,* 31–36

Last, B.S., Lawson, G.M., Breiner, K., Steinberg, L. & Farah, M.J. (2018). Childhood socioeconomic status and executive function in childhood and beyond. *PloS One,* 13(8). DOI 10.1371/journal,pone.0202964.

Lobo, L., Heras-Escribano, M., & Travieso, D. (2018). The history and philosophy of ecological psychology. *Frontiers in Psychology, 9,* 2228. DOI: https://doi.org/10.3389/fpsyg.2018.02228

Lubans, D.R., Richards, J.A., Hillman, C., Faulkner, G.,Beauchamp, M., Nilsson, M., Kelly, P., Smith, J., Raine, L. & Biddle, S.J.H. (2016). Physical activity for cognitive and mental health in youth: a systematic review of mechanisms. *Pediatrics, 138*(3). DOI: 10.1542/peds.2016-1642.

Lubans DR, Leahy AA, Mavilidi MF, Valkenborghs SR. (2021)Physical Activity, Fitness, and Executive Functions in Youth: Effects, Moderators, and Mechanisms. *Current Top Behavoir Neuroscience*. doi: 10.1007/7854_2021_271.

Luby JL. (2015) Poverty’s most insidious damage: the developing brain. *JAMA Paediatrics.* 169(9):810-811. doi: 10.1001/jamapediatrics.2015.1682

Ludyga, S., Gerber, M., Puhse, U., Looser, V.N. & Kamijo, K. (2020). Systematic review and meta-analysis investigating moderators of long-term effects of exercise on cognition in health individuals. *Nature Human Behaviour, 4*, 603-612. https://www.nature.com/articles/s41562-020-0851-8

Maeng, H., Webster, E., and Ulrich, D. (2016). Reliability for the test of gross motor development-third edition (TGMD-3). *Research Quarterly for Exercise and Sport*, *87*(38). DOI: https://doi.org/10.1123/apaq.2016-0026

Noonan, R.J., Boddy, L., Fairclough, S. & Knowles, Z.R. (2017). Parental perceptions on childrens out-of-school physical activity and family-based physical activity. *Early Child Development and Care*, *187*(12), 1909-1924. DOI: 10.1080/03004430.2016.1194409

Northwestern University (2018). NIH toolbox and PROMIS ipad apps. https://nihtoolbox.my.site.com/s/article/what-is-the-nih-toolbox-app.

Pesce C. Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. (2012) *Journal of Sport and Exercise Psychology*. *34*(6):766-86. doi: 10.1123/jsep.34.6.766.

Pesce, C., Croce, R., Ben-Soussan, T.D., Vazou, S., Mccullick, B., Tomporowksi, P. & Horvat, M. (2019). Variability of practice as an interface between motor and cognitive development. *International Journal of Sport and Exercise Psychology*, *17*, 133–152. http://dx.doi.org/10.1080/1612197X.2016.1223421

Pesce, C., Stodden, D.F. & Lakes, K. (2021). Editorial: Physical activity "enrichment": a joint focus on motor competence, hot and cool executive functions. *Frontiers in Psychology*. DOI: https://doi.org/10.3389/fpsyg.2021.658667

Pesce, C., Vazou, S., Benzing, V., Álvarez-Bueno, C., Anzeneder, S., Mavilidi, M.F., Leone, L., & Schmidt, M. (2021) Effects of chronic physical activity on cognition across the lifespan: a systematic meta-review of randomized controlled trials and realist synthesis of contextualized mechanisms, *International Review of Sport and Exercise Psychology*, DOI: 10.1080/1750984X.2021.1929404.

Raja, V. (2018). A theory of resonance: towards an ecological cognitive architecture. *Minds and Machines*, *28*, 29-51. DOI: https://doi.org/10.1007/s11023-017-9431-8

Raja, V. (2019). From metaphor to theory: the role of resonance in perceptual learning. *Adaptive Behaviour*, *27*(6), 405-421. DOI: https://doi.org/10.1177/1059712319854350.

Rakesh, D., Seguin, C., Zalesky, A., Cropley, V. & Whittle, S. (2021). Associations between neighbourhood disadvantage, resting state functional connectivity and behaviour in the adolescent brain cognitive development study: the moderating role of positive family and school environments. *Cognitive Science and Neuroimaging*, *6*(9), 877-886. DOI: 10.1016/j.bpsc.2021.03.008

Reed, E.D. (1988) James.J.Gibson and the psychology of perception. University Press, Yale.

Rosen, M.L., Hagen, M.P., Lurie, L., Miles, Z.E., Sheridan, M.A., Metzoff, A.N., McLaughlin, K.A. (2020). Cognitive stimulation as a mechanism linking socioeconomic status with executive function: a longitudinal investigation. *Child Development*, *91*(4), 762-779. DOI: 10.1111/cdev.13315

Rowlands, A.V., Dawkins, N.P., Maylor, B., Edwardson, C.L., Fairclough, S.J., Davies, M.J., Harrington, D.M., Khunti, K. & Yates, T. (2019). Enhancing the value of accelerometer-assessed physical activity: meaningful visual comparisons of data-driven translational accelerometer metrics. *Sports Medicine*, *5*(47). https://doi.org/10.1186/s40798-019-0225-9

Rudd, J. R., Barnett, L. M., Butson, M. L., Farrow, D., Berry, J., and Polman, R. C. J. (2015). Fundamental movement skills are more than run, throw and catch: the role of stability skills. *PLoS One*, *10*. doi: 10.1371/journal.pone. 0140224

Rudd, J., Crotti, M., Fitton-Davies, K., O'Callaghan, L., Bardid, F., Utesch, T., Roberts, S., Boddy, L., Cronin, C., Knowles, Z., Foulkes, J., Watson, P.M., Pesce, C., Button, C., Lubans, D.R., Buszard, T., Walsh, B. & Foweather, L. (2020). Skill acquisition methods fostering physical literacy in early-physical education (SAMPLE-PE): rationale and study protocol for a cluster randomised controlled trial in 5-6 year old children from deprived areas of north west England. *Frontiers in Psychology*, *11*(1228), 1-18. doi: 10.3389/fpsyg.2020.01228

Rudd, J.R., Pesce, C., Strafford, B.W. & Davids, K. (2020). Physical literacy – a journey of individual enrichment: an ecological dynamics rationale for enhancing performance and physical activity in all. *Frontiers In Psychology*, *11*(1904), 1-13. https://doi.org/10.3389/fpsyg.2020.01904

Save the Children (2016). Ending educational and child poverty in Europe. Brussels.

Singh, A.S., Saliasi, E., van den Berg, V., Uijtdewilligen, L., de Groot, H.M., Jolles, J., Andersen, L.B., Bailey, R., Chang, Y.K., Diamond, A., Ericsson, I., Etnier, J.L., Fedewa. A.L., Hillman, C.H., McMorris, T., Pesce, C., Puhse, U., Tomporowski, P. & Chinapaw, M.J.M. (2019). Effect of physical activity interventions on cognitive and academic performance in children and adolescents: a novel combination of a systematic review and recommendations from an expert panel. *British Journal of Sports Medicine*, *53*, 640-647. doi:10.1136/bjsports-2017-098136

Slotkin J, Kallen M, Griffith J, Magasi S, Salsman J, Nowinski C, & Gershon R (2012a). NIH Toolbox technical manual: NIH Toolbox Dimensional Change Card Sort Test Unpublished manuscript, Department of Psychology, Northwestern University, Chicago, Illinois.

Slotkin J, Kallen M, Griffith J, Magasi S, Salsman J, Nowinski C, & Gershon R (2012b). NIH Toolbox technical nanual: NIH Toolbox Flanker Inhibitory Control and Attention Test Unpublished manuscript, Department of Psychology, Northwestern University, Chicago, Illinois.

Slotkin J Nowinski C, Hays R, Beaumont J, Griffith J, Magasi S, Gershon R. (2012c). NIH Toolbox scoring and interpretation guide Unpublished manuscript, Department of Psychology, Northwestern University, Chicago, Illinois.

Stodden, D.F., Lakes, K., Cote, J., Aadland, E., Brian, A., Draper, C.E., Ekkekakis, P., Fumagalli, G., Laukkanen, A., Mavilldi, M., Mazzoli, E., Neville, R., Niemisto, D., Rudd, J., Saakslahti, A., Schmidt, M., Tomporowski, P., Tortella, P., Vazou, S., Pesce, C., Benzing, V. (2021). Exploration: an overarching focus for holistic development. *Brazillian Journal of Motor Behaviour, 15* (5), 301-320

Stodden, D.F., Pesce, C., Zarrett, N., Tomporowski, P., Ben-Soussan, T.D., Brian, A., Abrams, T.C. & Weist, M.D. (2023). Hollistic functioning from a developmental perspective: a new synthesis with a focus on multi-tiered system structure support. *Clinical Child and Family Psychology Review, 26,* 343-361. https://doi.org/10.1007/s10567-023-00428-5

Strife, S. & Downey, L. (2009). Childhood development and access to nature. *Organisation & Environment*, *22* (1), 99-122. doi: 10.1177/1086026609333340

Tocci, N., Scribinetti, P., Mazzoli, E., Mavilidi, M.F., Masci, I., Schmidt, M. & Pesce, C. (2022). Giving ideas some legs or legs some ideas? Children's motor creativity is enhanced by physical activity enrichment: direct and mediated paths. *Frontiers in Psychology*, *13*. DOI: https://doi.org/10.3389/fpsyg.2022.806065.

Tomporowksi, P. & Pesce, C. (2019). Exercise, sports and performance arts benefit cognition via a common process. *Psychological Bulletin, 145*(9), DOI: 10.1037/bul0000200

Ulrich, D.A. (2013). The test of gross motor development3 (TGMD-3): administration, scoring & international norms. *Journal of Sports Science*, *24*(2), 27-33.

Van der Fels I.M.J., te Wierike S.C.M., 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*, 697–703. doi: 10.1016/j.jsams.2014.09.007

Van Hees, V.T., Gorzelniak, L., Dean Leon, E.C., Eder, M., Pias, M., Taherian, S., Ekelund, U., Renstrom, F., Franks, P.W., Horsch, A., et al. (2013). Separating movement and gravity components in an acceleration signal and implications for the assessment of human daily physical activity. *PLoS ONE, 8*. https://doi.org/10.1371/journal.pone.0061691

Van Hees, V.T., Fang, Z., Langford, J., Assah, F., Mohammad, A., da Silva, I.C., Trenell, M.I., White, T., Wareham, N.J. & Brage, S. (2014) Autocalibration of accelerometer data for free-living physical activity assessment using local gravity and temperature: An evaluation on four continents. *Journal of Applied Physiology*, *117*, 738–744

Von Stumm, S. (2017). Socioeconomic status amplifies the achievement gap throughout compulsory education independent of intelligence. *Intelligence*, *60*, 57-62. https://doi.org/10.1016/j.intell.2016.11.006

Wade, M., Wright, L. & Finegold, K.E. (2022). The effects of early life adversity on children's mental health and cognitive functioning. *Translational Psychiatry,* 12, 244. DOI: https://doi.org/10.1038/s41398-022-02001-0.

Wassenaar, T.M., Williamson, W., Johansen-Berg, H., Dawes, H., Roberts, N., Foster, C. & Sexton, C.E. (2020). A critical evaluation of systematic reviews assessing the effect of chronic physical activity on academic achievement, cognition and the brain in children and adolescents: a systematic review. *International Journal of Behavioural Nutrition and Physical Activity, 17*(79), https://doi.org/10.1186/s12966-020-00959-y

Weintraub, S., Dikmen, S. S., Heaton, R. K., Tulsky, D. S., Zelazo, P. D., Bauer, P. J., et al. (2013). Cognition assessment using the NIH toolbox. *Neurology 80*(11), S54–S64. doi: 10.1212/WNL.0b013e3182872ded

Zeng, N., Ayyub, M., Sun, H., Wen, X., Xiang, P & Gao, Z. (2017). Effects of physical activity on motor skills and cognitive development in early childhood: a systematic review. *BioMed Research International*. DOI: https://doi.org/10.1155/2017/2760716

Table 1 Inter- and intra-rater mean Intraclass Coefficient Correlations for movement outcome measures

Measure	Outcome measure	Inter-rater reliability Mean ICC (range)	Intra-rater reliability Mean ICC (range)
TGMD-3	Locomotor	.98 (.97 -.99)	.98 (.98 - .99)
	Object control	.97 (.95 - .97)	.97 (.95 - .98)
TSS	Stability	.98 (.98)	.98 (.97 - .98)
DMA	Fluency	.96 (.93 - .98)	.97 (.96 - .99)
	Flexibility	.96 (.93 - .98)	.97 (.96 - .99)

Note. ICC = Intraclass Correlation Coefficient, TGMD-3 = Test of Gross Motor Development 3rd Edition, TSS = Test of Stability Skills, DMA = Divergent Movement Assessment

Table 2. Descriptive Statistics of study variables

	M ± SD or %	Range	Normative data	
Demographics *(n = 360)*				
Age (years)	6.0 ± 0.3	5.1 - 6.9		
Sex (female)	55 %			
Ethnicity (White British)	56 %		74.4%	Gov.UK (2022)
Special Education Needs (SEN)	12 %		12.6%	Gov.UK (2022)
Height cm *(N= 321)*	115.7 ± 5.5	100 - 133	115-116	RCPCH, (2012)
Weight *(N = 321)*	22.0 ± 3.9	14 - 36	21	RCPCH (2012)
BMI (N = 321)	16.4 ± 2.0	12 - 25	15.3-15.4	WHO (2007)
Cognitive Function (n = 335)				
Executive Function Total	10.3 ± 5.7	0.8 - 28		
Inhibitory Control	4.9 ± 2.0	0 - 8	8.1-8.5	Casaletto et al., (2015)
Working Memory	2.1 ± 3.6	0 - 16	16	Casaletto et al., (2015)
Cognitive Flexibility	3.3 ± 2.2	0 - 10	7.4-7.8	Casaletto et al., (2015)
Physical Activity *(min/day)* (n = 262)				
Light physical activity (LPA)	230.8 ± 35.5	138 - 373		
Moderate physical activity (MPA)	49.7 ± 13.2	22 - 89		
Vigorous physical activity (VPA)	19.0 ± 7.4	4 - 49		
Moderate-vigorous physical activity (MVPA)	68.7 ± 19.3	26 - 135		
Intensity Gradient	-2.1 ± 0.1	-2 - -2		
Average Acceleration (ENMO)	60.9 ± 14.0	32 - 114		
Motor Proficiency (n = 250)				
Motor Proficiency Total Score	57.7 ± 12.2	23 - 92	76.0	
Object control	24.4 ± 8.1	6-49	35.3	Webster & Ulrich (2013)
Locomotor	26.0 ± 5.9	8-40	40.7	Webster & Ulrich (2013)
Stability	7.0 ± 3.6	0 - 18	12.9 ± 4.4	Rudd et al (2015)
Exploratory Movement (n = 294)				
DMA Total	29.3 ± 12.1	2 - 78		
Flexibility	18.1 ± 6.3	2-39	37.44±14.45	Zachopoulou & Makri (2004)
Fluency	11.1 ± 7.0	0-39	24.76±10.28	Zachopoulou & Makri (2004)

Table 3. Multiple regression analysis with demographic factors on executive function (EF).

	Coefficient		
Predictor	**Estimate**	**Std.error**	**p value**
Intercept	-6.28	6.19	0.311
Age (yrs)	2.68	1.04	0.010
Sex (0-1)	1.33	0.61	0.031
Special Educational Need (0-1)	-4.02	0.96	<0.001
Deprivation decile (1-10)	3.45	0.90	<0.001
R^2 of the model = 0.120			

Table 4 Multiple regression analyses with motor competence and PA variables added individually to the model. Executive function (EF) is the dependent variable of interest, and each row represents an individual model. All analyses were controlled for age, sex, deprivation decile, and SEN.

	Coefficient			Model
Predictor	**Estimate**	**Std.error**	**p value**	R^2
DMA	0.13	0.03	<0.001	0.193
Motor proficiency	0.10	0.03	0.007	0.159
MVPA	-0.01	0.02	0.41	0.128
IG	1.60	3.07	0.60	0.121
ENMO	-0.02	0.02	0.32	0.123
MPA	-0.03	0.02	0.22	0.125
VPA	-0.02	0.04	0.59	0.123

MVPA: moderate-to-vigorous PA (minutes); MPA: moderate PA (minutes); VPA: vigorous PA (minutes); IG: intensity gradient (arbitrary units); ENMO: spread of acceleration across the day (milligravity): DMA(arbitrary units): MP (arbitrary units).

Table 5 Multiple regression analyses with a combination of the motor competence variables, and motor competence with PA variables. Executive function (EF) is the dependent variable of interest. All analyses were adjusted for age, sex, deprivation decile, and SEN.

Model	**R^2**	**Term**	**Estimate**	**Std.error**	**p value**
DMA + motor proficiency + VPA	0.229				
		DMA	0.11	0.03	<0.001
		Motor proficiency	0.11	0.04	0.010
		VPA	-0.12	0.05	0.015
DMA + motor proficiency + ENMO + IG	0.235				
		DMA	0.12	0.03	<0.001
		Motor proficiency	0.10	0.03	0.008
		ENMO	-0.05	0.02	0.031
		IG	-0.63	3.10	0.840

MVPA: moderate-to-vigorous PA (minutes); MPA: moderate PA (minutes); VPA: vigorous PA (minutes); IG: intensity gradient (arbitrary units); ENMO: spread of acceleration across the day (milligravity): DMA(arbitrary units): MP (arbitrary units)

APPENDIX

Table 2

	EF	DMA	Motor proficiency	MVPA	IG	MPA	VPA	ENMO
EF	1	0.25 (<0.01)	0.24 (<0.01)	-0.11 (0.07)	-0.068 (0.28)	-0.097 (0.13)	-0.12 (0.07)	-0.1 (0.10)
DMA	0.25 (<0.01)	1	0.17 (<0.01)	0.074 (0.28)	0.18 (<0.01)	0.03 (0.66)	0.17 (0.01)	0.11 (0.10)
Motor proficiency	0.24 (<0.01)	0.17 (<0.01)	1	0.31 (<0.01)	0.26 (<0.01)	0.26 (<0.01)	0.35 (<0.01)	0.33 (<0.01)
MVPA	-0.11 (0.07)	0.074 (0.28)	0.31 (<0.01)	1	0.26 (<0.01)	0.97 (<0.01)	0.86 (<0.01)	0.95 (<0.01)
IG	-0.068 (0.28)	0.18 (<0.01)	0.26 (<0.01)	0.26 (<0.01)	1	0.094 (0.13)	0.58 (<0.01)	0.45 (<0.01)
MPA	-0.097 (0.13)	0.03 (0.66)	0.26 (<0.01)	0.97 (<0.01)	0.094 (0.13)	1	0.72 (<0.01)	0.86 (<0.01)
VPA	-0.12 (0.07)	0.17 (0.01)	0.35 (<0.01)	0.86 (<0.01)	0.58 (<0.01)	0.72 (<0.01)	1	0.93 (<0.01)
ENMO	-0.1 (0.10)	0.11 (0.10)	0.33 (<0.01)	0.95 (<0.01)	0.45 (<0.01)	0.86 (<0.01)	0.93 (<0.01)	1

MVPA: moderate-to-vigorous PA (minutes); MPA: moderate PA (minutes); VPA: vigorous PA (minutes); IG: intensity gradient (arbitrary units); ENMO: spread of acceleration across the day (milligravity): DMA(arbitrary units): MP (arbitrary units).

Table 3 Regression analysis of divergent movement ability (DMA) with demographic covariates using completed cases and imputed data.

Predictor		Estimate	Std.error	p value
	Imputed	-8.13	5.90	0.169
DMA	Complete cases	0.12	0.03	<0.001
	Imputed	0.13	0.03	<0.001
Age	Complete cases	1.89	1.12	0.094
	Imputed	2.27	1.01	0.026
Sex	Complete cases	1.71	0.66	0.010
	Imputed	1.94	0.58	<0.001
Special Educational Need	Complete cases	-3.54	1.01	0.001
	Imputed	-3.00	0.93	<0.001
Deprivation decile	Complete cases	4.11	0.94	<0.001
	Imputed	3.73	1.00	<0.001
R^2 of the model	Complete cases (n=273)	0.192		
	Imputed	0.193		

Table 4 Regression analysis of motor proficiency with demographic covariates using completed cases and imputed data.

Predictor		Estimate	Std.error	p value
Intercept	Complete cases	-8.66	6.26	0.168
	Imputed	-7.03	5.98	0.241
Motor proficiency	Complete cases	0.08	0.03	0.002
	Imputed	0.10	0.03	0.007
Age	Complete cases	2.27	1.09	0.039
	Imputed	1.81	1.02	0.077
Sex	Complete cases	1.56	0.64	0.016
	Imputed	1.57	0.58	0.007
Special Educational Need	Complete cases	-4.00	1.03	<0.001
	Imputed	-3.32	0.91	<0.001
Deprivation decile	Complete cases	2.92	0.98	0.003
	Imputed	3.15	0.98	0.002
R^2 of the model	Complete cases (n=239)	0.190		
	Imputed	0.160		

Table 5 Regression analysis of Moderate-to-Vigorous Physical Activity (MVPA) with demographic covariates using completed cases and imputed data.

Predictor		Estimate	Std.error	p value
	Imputed	-7.65	6.02	0.205
MVPA	Complete cases	-0.02	0.02	0.289
	Imputed	-0.01	0.02	0.414
Age	Complete cases	3.09	1.25	0.014
	Imputed	3.06	1.01	0.003
Sex	Complete cases	2.06	0.77	0.008
	Imputed	1.26	0.61	0.041
Special Educational Need	Complete cases	-2.75	1.22	0.024
	Imputed	-3.86	0.96	<0.001
Deprivation decile	Complete cases	3.22	1.07	0.003
	Imputed	3.56	0.93	<0.001
R^2 of the model	Complete cases (n=246)	0.123		
	Imputed	0.128		

Table 6 Regression analysis of Moderate Physical Activity (MPA) with demographic covariates using completed cases and imputed data.

Predictor		Estimate	Std.error	p value
Intercept	Complete cases	-7.33	7.44	0.326
	Imputed	-6.00	6.69	0.373
MPA	Complete cases	-0.03	0.03	0.296
	Imputed	-0.03	0.02	0.216
Age	Complete cases	3.08	1.25	0.014
	Imputed	2.88	1.11	0.011
Sex	Complete cases	2.14	0.76	0.005
	Imputed	1.23	0.60	0.039
Special Educational Need	Complete cases	-2.75	1.22	0.025
	Imputed	-3.75	0.94	<0.001
Deprivation decile	Complete cases	3.22	1.07	0.003
	Imputed	3.46	0.95	<0.001
R^2 of the model	Complete cases (n=246)	0.123		
	Imputed	0.125		

Table 7 Regression analysis of Vigorous Physical Activity (VPA) with demographic covariates using completed cases and imputed data.

Predictor		**Estimate**	**Std.error**	**p value**
Intercept	Complete cases	-7.62	7.43	0.306
	Imputed	-8.56	6.14	0.165
VPA	Complete cases	-0.05	0.05	0.372
	Imputed	-0.02	0.04	0.589
Age	Complete cases	3.05	1.24	0.015
	Imputed	3.12	1.03	0.003
Sex	Complete cases	2.02	0.80	0.012
	Imputed	1.21	0.70	0.073
Special Educational Need	Complete cases	-2.76	1.22	0.024
	Imputed	-3.70	0.92	<0.001
Deprivation decile	Complete cases	3.22	1.07	0.003
	Imputed	3.51	1.03	0.002
R^2 of the model	Complete cases (n=246)	0.122		
	Imputed	0.123		

Table 8 Regression analysis of Intensity Gradient (IG) with demographic covariates using completed cases and imputed data.

Predictor		**Estimate**	**Std.error**	**p value**
Intercept	Complete cases	-8.76	10.38	0.400
	Imputed	-4.31	9.08	0.635
IG	Complete cases	-0.40	3.34	0.905
	Imputed	1.60	3.07	0.605
Age	Complete cases	2.92	1.24	0.019
	Imputed	2.87	1.04	0.006
Sex	Complete cases	2.23	0.83	0.008
	Imputed	1.63	0.69	0.019
Special Educational Need	Complete cases	-2.78	1.22	0.024
	Imputed	-3.59	0.93	<0.001
Deprivation decile	Complete cases	3.24	1.07	0.003
	Imputed	3.48	1.02	0.001
R^2 of the model	Complete cases (n=246)	0.119		
	Imputed	0.121		

Table 9 Regression analysis of Euclidean Norm Minus One gravity acceleration data (ENMO) with demographic covariates using completed cases and imputed data.

Predictor		**Estimate**	**Std.error**	**p value**
Intercept	Complete cases	-6.90	7.46	0.356
	Imputed	-7.34	6.34	0.249
ENMO	Complete cases	-0.03	0.03	0.246
	Imputed	-0.02	0.02	0.321
Age	Complete cases	3.10	1.24	0.013
	Imputed	3.10	1.05	0.004
Sex	Complete cases	2.01	0.78	0.011
	Imputed	1.23	0.64	0.055
Special Educational Need	Complete cases	-2.79	1.22	0.022
	Imputed	-3.67	0.93	<0.001
Deprivation decile	Complete cases	3.21	1.07	0.003
	Imputed	3.43	1.02	0.003
R^2 of the model	Complete cases	0.124		
	Imputed	0.123		

Table 10 Regression analysis of Divergent Movement Ability (DMA) and motor proficiency with demographic covariates using completed cases and imputed data.

Predictor		**Estimate**	**Std.error**	**p value**
Intercept	Complete cases	-4.31	6.72	0.522
	Imputed	-7.30	5.71	0.202
DMA	Complete cases	0.07	0.03	0.012
	Imputed	0.12	0.03	<0.001
Motor proficiency	Complete cases	0.08	0.03	0.005
	Imputed	0.08	0.03	0.026
Age	Complete cases	1.18	1.17	0.315
	Imputed	1.42	1.00	0.156
Sex	Complete cases	1.64	0.68	0.018
	Imputed	1.99	0.56	<0.001
Special Educational Need	Complete cases	-3.57	1.09	0.001
	Imputed	-2.82	0.91	0.002
Deprivation decile	Complete cases	2.72	1.00	0.007
	Imputed	3.44	0.96	<0.001
R^2 of the model	Complete cases (n=216)	0.205		
	Imputed	0.219		

Table 11 Regression analysis of Divergent Movement Ability (DMA), motor proficiency, and MVPA with demographic covariates using completed cases and imputed data.

Predictor		Estimate	Std.error	p value
	Imputed	-6.30	5.70	0.270
DMA	Complete cases	0.05	0.03	0.113
	Imputed	0.11	0.02	<0.001
Motor proficiency score	Complete cases	0.09	0.03	0.008
	Imputed	0.11	0.03	0.001
MVPA	Complete cases	-0.03	0.03	0.179
	Imputed	-0.03	0.02	0.096
Age	Complete cases	1.76	1.39	0.206
	Imputed	1.49	0.99	0.134
Sex	Complete cases	2.16	0.85	0.012
	Imputed	1.50	0.60	0.013
Special Educational Need	Complete cases	-2.88	1.33	0.032
	Imputed	-3.11	0.91	<0.001
Deprivation decile	Complete cases	2.11	1.17	0.074
	Imputed	3.35	0.90	<0.001
R^2 of the model	Complete cases (n=162)	0.205		
	Imputed	0.237		

Table 12 Regression analysis of Divergent Movement Ability (DMA), motor proficiency, and MPA with demographic covariates using completed cases and imputed data.

Predictor		Estimate	Std.error	p value
Intercept	Complete cases	-5.61	8.01	0.485
	Imputed	-4.61	6.11	0.453
DMA	Complete cases	0.05	0.03	0.127
	Imputed	0.11	0.03	0.004
Motor proficiency score	Complete cases	0.09	0.03	0.010
	Imputed	0.11	0.03	<0.001
MPA	Complete cases	-0.03	0.03	0.267
	Imputed	-0.04	0.02	0.060
Age	Complete cases	1.71	1.39	0.220
	Imputed	1.18	1.09	0.283
Sex	Complete cases	2.26	0.84	0.008
	Imputed	1.68	0.59	0.005
Special Educational Need	Complete cases	-2.92	1.33	0.030
	Imputed	-3.03	0.97	0.003
Deprivation decile	Complete cases	2.10	1.17	0.076
	Imputed	3.28	0.92	<0.001
R^2 of the model	Complete cases (n=162)	0.202		
	Imputed	0.241		

Table 13 Regression analysis of Divergent Movement Ability (DMA), motor proficiency, and VPA with demographic covariates using completed cases and imputed data.

Predictor		**Estimate**	**Std.error**	**p value**
	Imputed	-7.98	6.14	0.198
DMA	Complete cases	0.06	0.03	0.084
	Imputed	0.11	0.03	<0.001
Motor proficiency score	Complete cases	0.10	0.03	0.006
	Imputed	0.11	0.04	0.010
VPA	Complete cases	-0.10	0.06	0.120
	Imputed	-0.12	0.05	0.015
Age	Complete cases	1.75	1.38	0.206
	Imputed	1.72	1.05	0.103
Sex	Complete cases	2.02	0.87	0.021
	Imputed	1.18	0.66	0.079
Special Educational Need	Complete cases	-2.83	1.33	0.035
	Imputed	-2.93	0.95	0.003
Deprivation decile	Complete cases	2.17	1.17	0.065
	Imputed	3.29	1.11	0.009
R^2 of the model	Complete cases (n=162)	0.208		
	Imputed	0.229		

Table 14 Regression analysis of Divergent Movement Ability (DMA), motor proficiency, ENMO, and IG with demographic covariates using completed cases and imputed data.

Predictor		**Estimate**	**Std.error**	**p value**
	Imputed	-6.90	9.07	0.448
DMA	Complete cases	0.05	0.03	0.116
	Imputed	0.12	0.03	<0.001
Motor proficiency score	Complete cases	0.09	0.03	0.010
	Imputed	0.10	0.03	0.008
ENMO	Complete cases	-0.06	0.03	0.080
	Imputed	-0.05	0.02	0.031
IG	Complete cases	3.84	4.34	0.378
	Imputed	-0.63	3.10	0.840
Age	Complete cases	1.89	1.39	0.176
	Imputed	1.54	0.99	0.120
Sex	Complete cases	2.29	0.88	0.010
	Imputed	1.46	0.67	0.030
Special Educational Need	Complete cases	-2.99	1.33	0.026
	Imputed	-2.88	0.89	0.001
Deprivation decile	Complete cases	2.10	1.17	0.074
	Imputed	3.27	0.97	0.002
R^2 of the model	Complete cases (n=162)	0.212		
	Imputed	0.235		

Highlights

- Motor competence and physical activity variables better predict executive functions when they are combined
- This study extends the assessment of movement quality showing an association between divergent movement ability and executive function.
- When considered individually both motor competence variables were significant predictors of executive function whilst physical activity variables