Cognition and Movement among 5-7-year old children

Laura O’Callaghan

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

May 2025

Table of contents

List of Tables

List of figures

List of abbreviations

Abbreviations	Definition
BMI	Body Mass Index
EF	Executive Function
MVPA	Moderate-to-Vigorous Physical Activity
PA	Physical Activity
PE	Physical Education
SEN	Special Educational needs
RCT	Randomised Control Trial
ENMO	Euclidean Norm Minus One
RCS	Response to Challenge Scale
SDQ	Strengths and Difficulties Questionnaire
SAMPLE-PE	Skill Acquisition Methods Fostering Physical Literacy in Early-Physical Education
DMA	Divergent Movement Ability Assessment
IG	Intensity Gradient
MVPA	Moderate-to-Vigorous Physical Activity
MPA	Moderate Physical Activity
VPA	Vigorous Physical Activity
BRIEF-P	Behaviour Rating Inventory of Executive Function, Preschool version
INT	Intervention
CONT	Control
LIN	Linear
NL	Nonlinear
EFA	Exploratory Factor Analysis
AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion

Glossary of terms

Term	Definition
Cognitive flexibility	Selecting information in a changing environment and the ability to switch flexibly between tasks (Dajani & Uddin, 2015)
Cognitive function	The process of acquiring knowledge and understanding through thoughts and experiences
Deprivation	Living in an area of deprivation means residing in a neighbourhood or community where children generally face disadvantages, as well as low income, it included multiple factors that affect quality of life and opportunities. This includes high unemployment rates and low-paying jobs, lower-performing schools, higher crime rates, poorer living environments, barriers to housing and healthcare services.
Divergent movement	The exploration of varied movement solutions to achieve a specific goal, deviating from habitual behaviours and routines (Hulteen et al., 2023)
Executive function	“Higher-order cognitive functions which enable goal-directed thoughts and actions” (Koskulu-Sancar et al., 2023)
Inhibitory control	It enables an individual to override an internal predisposition and selectively attend, suppressing attention to other stimuli (Diamond, 2013)
Linear pedagogy	It is based on the information processing learning theory about movement learning (Schmidt, 1975) and it is characterised by a teacher-centred approach to movement education, where the teacher is the main source of direct instruction and leads the performers through an incremental series of activity
Movement competence	An individual’s degree of proficient performance in a broad range of motor skills

	as well as the underlying mechanisms including quality of movement, motor coordination and motor control (Utesch & Bardid, 2019)
Motor creativity	The ability to adapt and combine motor skills, to creating functional and original solutions to emerging motor problems (Vasilopoulos et al., 2023)
Nonlinear pedagogy	It is based on ecological dynamics and follows a learner-centred approach where children are invited to explore different functional movement solutions. Teachers vary the constraints of the task and environment at an individual level
Pedagogy	The interactions between teachers, children and the learning environment and tasks, commonly defined as the art and science of teaching (Shah, 2021)
Physical activity	Defined as “any bodily movement produced by skeletal muscles resulting in energy expenditure” (Casperson et al., 1985)
Physical education	Defined as “A high-quality physical education curriculum inspires all pupils to succeed and excel in competitive sport and other physically demanding activities. It should provide opportunities for pupils to become physically confident in a way which supports their health and fitness. Opportunities to compete in sport and other activities build character and help to embed values such as fairness and respect.” (Department of Education, 2013)
Primary school	In England, primary schools cater for 4-11-year-olds (Gov.UK, 2024)
Self-regulation	Self-regulation reflects a child’s ability to adjust their behaviour, thoughts and emotions to meet the physical, cognitive, social and emotional demands of a situation.

Working memory	manipulate information and temporarily store information (Baddley, 1992)

Abstract

At the primary school stage, children experience rapid development in both movement and cognition. However, those living in an area of deprivation often exhibit lower-than-expected age-related skills, emphasizing the need for targeted interventions. A well-designed physical education curriculum can play a crucial role in fostering executive function and self-regulation, which are vital for children's everyday health, academic success, and overall well-being. To achieve this, firstly it is essential to clarify the nature of the relationship between movement and executive function, as current research debates whether the quantity or quality of movement is more strongly associated with these cognitive processes. Secondly, experimental research is needed to determine how physical education pedagogical interventions grounded in motor learning theory can effectively support the development of executive functions and self-regulation in children.

The overall aim of this thesis is to explore the influence of different aspects of movement on cognition among children aged 5-7 years living in an area of socio -economic disadvantage. **Study 1** within this PhD thesis investigated the associations of physical activity dose and movement quality with executive functions in children aged 5-6 years living in an area of deprivation. **Study 2** and **Study 3** assessed the efficacy of utilizing Linear and Nonlinear pedagogy within Physical Education to improve children's executive function and self-regulation aged 5-7 years. The data used in **Study 1, Study 2** and **Study 3** was collected from within the SAMPLE-PE project clustered randomised control trial where 360 children (age 5.9±0.3 years, 55% girls) from 12 primary schools were assessed at 3 timepoints (T0 = baseline, T1 = post-test, T2= follow-up) and randomly allocated to a 15-week Linear pedagogy (LP n=3) or Nonlinear pedagogy (NP n=3) PE intervention delivered by trained coaches, or to a control group (n=6) where schools followed usual practice. In **study 1** movement was assessed using accelerometery (physical activity dose),

test of gross motor development 3 (movement proficiency) and divergent movement assessment (movement exploration). In **study 1** and **study 2** the NIH toolbox, an iPad-based test was used to measure executive function. In **study 3,** the Strength and Difficulties Questionnaire (SDQ) (Goodman, 1997) and Response to Challenge Scale (RCS) (Lakes, 2012) was used to assess self-regulation.

Study one showed that after controlling for demographics, motor competence and physical activity variables better predict executive functions when considered together. When considered individually both motor competence variables were significant predictors of executive function whilst physical activity variables were not. Among the two movement competence facets, exploratory movement exhibited the strongest association with executive function. The findings of **study two** suggest that primary PE interventions focussing on motor skills underpinned by Linear pedagogy and Nonlinear pedagogy can support the development of some executive functions. Participation in Nonlinear pedagogy PE interventions led to an improvement in working memory when compared to participation in the control group at the post-intervention and follow-up timepoints. Participation in Linear pedagogy led to an improvement in cognitive flexibility when compared to the control group at follow-up. Participation in both Linear and Nonlinear pedagogy led to no improvement in inhibitory control. **Study Three** suggest that primary PE interventions focussing on motor skills underpinned by Linear pedagogy and Nonlinear pedagogy can support the development of some aspects of self-regulation. Participation in Nonlinear pedagogy led to an improvement in the SDQ total difficulties score of self-regulation at the post-intervention and follow-up timepoints and an improvement in the RCS physical score at follow-up. Participation in Linear pedagogy led to an improvement in RCS total score at post-test, an improvement in RCS cognitive score at follow-up and a deterioration in SDQ total difficulties score at post-test and follow-up.

Finally, participation in Linear pedagogy led to an improvement in the pro social behaviour score of self-regulation at the post-intervention and follow-up timepoints.

These studies demonstrate that movement competence and physical activity variables better predict executive function when they are combined. These studies also show that Linear and Nonlinear pedagogy have a beneficial effect on different aspects of executive function and self-regulation. Together, these findings highlight the importance of prioritizing movement quality in schools and highlight how PE pedagogies underpinned by motor learning theory can effectively enhance both executive function and self-regulation.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Communications resulting from this PhD work:

Conference presentations (oral)

O'Callaghan, L., Foweather, L., Crotti, M., Fitton-Davies, K. & Rudd, J. The association between movement and executive functions. 3rd Meeting of the UK and Ireland Children's Motor Competence Network conference 8/01/2020 Liverpool UK

O'Callaghan, L., Foweather, L., Roberts, S., Ultesch, T., Bardid, F., Watson, P.M., Button, C., Lubans, D., Pesce, C., Crotti, M., Fitton Davies, K. & Rudd, J.R. Exploring the effects of a pedagogical intervention upon psychological factors in 5-7-year-old children. Health and Active Kids, 14/09/2019, Verona, Italy

O'Callaghan, L., Foweather, L., Crotti, M., Fitton Davies, K. & Rudd, J.R**.** Physical Education Pedagogy and Cognitive Functions. Power of Sport Conference, 11/05/2019, Liverpool John Moores University

O'Callaghan, L., Foweather, L., Crotti, M., Fitton Davies, K. & Rudd, J.R**.** The association between cognitive function and motor competence. Power of Sport Conference, 10/05/2018, Liverpool John Moores University

Peer-reviewed publications

O'Callaghan, L., Foweather, L., Crotti, M., Opicci, L., Pesce, C., Boddy, L.M., Fitton Davies, K. & Rudd, J. (2023). Associations of physical activity dose and movement quality with executive functions in socioeconomically disadvantages children aged 5-6 years. Psychology of Sport and Exercise, 70(5).

Crotti, M., Rudd, J., Roberts, S.J., Fitton Davies, K., **O'Callaghan**, L., Utesch, T. & Foweather, L. (2022). Physical activity promoting teaching practices and children's physical activity within physical education lessons underpinned by motor learning theory (SAMPLE-PE). PLOS One, 17(8).

Fitton Davies, K., Foweather, L., Watson, P.M., Bardid, F., Roberts, S.J., Davids, K., **O'Callaghan,** L., Crotti, M., Rudd, J.R. (2021). Assessing the motivational climates in early physical education curricula underpinned by motor learning theory: SAMPLE-PE. Physical Education and Sport Pedagogy, 28(3), 1-28.

Crotti, M., Rudd, J.R., Weaver, G., Roberts, S., **O'Callaghan, L.,** Fitton Davies, K. and Foweather, L. (2021). Validation of modified SOFIT+: relating physical activity promoting practices in physical education to moderate-to-vigorous physical activity in 5-6-year-old children. Measurement in Physical Education and Exercise Science.

Crotti, M., Rudd, J., Roberts, S., Boddy, L.M., Fitton Davies, K., **O'Callaghan, L.,** Utesch, T. and Foweather, L. (2021). Effect of Linear and Nonlinear pedagogy physical

education interventions on children’s physical activity: a cluster randomised control trial (SAMPLE-PE). Children, 8,1.

Fitton Davies, K., Foweather, L, Watson, P.M., Bardid, F., Roberts, S.J., **O’Callaghan, L.,** Crotti, M. and Rudd, J.R. (2021). Influence of Linear and Nonlinear pedagogy on motivational climate, need satisfaction and enjoyment in physical education among 5–6-year-old children: SAMPLE-PE. Physical Education and Sport Pedagogy

Oppici, L., Rudd, J.R., Buszard, T., Spittle, S. & **O’Callaghan, L**. (2020) Comparing the efficacy (RCT) of learning a dance choreography and practicing creative dance on improving executive functions and motor competence in 6–7-year-old children. Psychology of Sport and Exercise

Rudd, J.R., **O’Callaghan, L**. and Williams, J. (2019). Physical Education pedagogies built upon theories of movement learning: How can environmental constraints be manipulated to improve children’s executive function and self-regulation skills? International Journal of Environmental Research and Public Health, 16, 1-8

Rudd, J.R., Crotti, M., Fitton-Davies, K., **O’Callaghan, L**., Bardid, F., Utesch, T., Roberts, S., Boddy, L.M., Walsh, B., Cronin, C., Knowles, Z., Watson, P.M., Button, C., Lubans, D.R., Pesce, C., Buzsard, T., Foulkes, J.D. and Foweather, L. (2020). Skill acquisition methods fostering physical literacy in early physical education (SAMPLE-PE) in 5-6-year-old children: rationale and study protocol for a cluster randomised control trial. Frontiers, 11, 1-18.

Book Chapters

Rudd, J., Fitton Davies, K., **O’Callaghan**, L., Crotti, M., Grace, R. & Foweather, L. Physical Education. In: Rudd, J., Renshaw, I., Savelsbergh, G., Chow, J.I., Roberts, W., Newcombe, D. & Davids, K. (2021) Nonlinear pedagogy and the athletic skills model. Routledge: New York.

Rudd. J.R., Fitton-Davies, K., **O’Callaghan, L**., Crotti, M., Grace, R. & Foweather, L. (2021). Physical Education: Combining movement education and nonlinear pedagogy to provide meaningful physical education experiences. *In:* Rudd, J.R., Renshaw, I., Savelsbergh, G.J.P., Yi Chow, J., Roberts, W., Newcombe, D. & Davids, K. (2021). Nonlinear pedagogy and the athletics skills model: the importance of play in supporting physical literacy. Routledge, NY

Acknowledgements

It would not have been possible to complete this thesis and my PhD without the support of some wonderful people I was fortunate enough to work with along the way. Firstly, to my supervisory team Dr James Rudd, Dr Lawrence Foweather and Dr Lynne Boddy and my advisory team Dr Caterina Pesce, Dr Luca Oppici and Professor Til Utesch. It has been quite a journey both personally and professionally, thank you for giving me all of the opportunities this project has brought and continuing to believe in me and support when I was lacking belief in myself! I have learnt so much from you all and the time you put into my research; I will be forever grateful. Dr Matteo Crotti, Dr Katie Fitton-Davies and Rachael Grace who were the best teammates to work alongside during data collection, they inspired me to push harder with the exceptional bar that they set as students in what they achieved. Also, thank you to my team at Oxford Brookes, the support of my manager Dr Sarah Howcutt has given me the window of opportunity to get to this final stage of the journey.

I dedicate this thesis to my family; I have tested their patience to get to the finish line! To my parents, Anthony and Myrtle O'Callaghan, I hope I make you proud to finally see this in the black and white! All those hours, you helped me especially during data collection, doing the school run for me and making dinners when I was so occupied. I can't wait for the day when my mum and dad don't have to ask me, "where is it up to!" To my younger brother Martin O'Callaghan, I would not have had such ambition without watching you excel in your career, I have always wanted to keep up with you somehow! To my Granny, Cecilia O'Callaghan and Uncle Jack Thompson this PhD would not have been possible without your financial support.

Finally, to my two beautiful children, Amelie and Finley, I also can't wait for you two to stop asking me, "is it finished yet!" You were the same age as the children in this study and from the moment I started to talk to James about the potential of movement for children's cognition, I spent many a late night, inspired by what I read and observed in your play. I hope I make you proud!

Chapter 1: Introduction

Context of the thesis

The Importance of Physical Education

The importance of high-quality physical education (PE) in a primary school setting can be understood by appreciating the breadth of its purpose: developing fundamental movement skills (FMS), participation in competitive sport, ensuring experiences that will determine lifelong involvement in physical activity (PA) and shaping individuals immediate and long-term health, development and wellbeing (Department for Education, 2013). This is an ambitious number of outcomes for a subject that is taught in primary schools for up to 2 hours per week. Schools are viewed as the ideal setting to promote PA; however, it has been reported for some time there are competing priorities that create confusion about what informs PE curriculum design (WHO, 2022; Mura et al., 2015, Burrows et al. 2020; Kirk 2019; Ofsted, 2023). One example of a competing priority is that for children living in an area of deprivation, by aged 5 years, they are twice as like to be obese when compared to their least deprived peers and three times likelier by age 11 years (NHS, 2024). This drives an agenda of prioritising the quantity of PA to reduce the prevalence of obesity at the potential expense of ensuring the development of other movement qualities such as FMS (Malcolm et al., 2023; Garcia-Hermoso et al., 2021). FMS include locomotor (e.g. running), object control (e.g. throwing) and stability skills (e.g. log roll) (Rudd et al., 2015).

For some children living in areas of deprivation, PE is their first experience of ‘organised’ PA (Ofsted, 2023; Brockman et al., 2009). To this point, they have often had limited access to greenspaces and the opportunity to play with equipment such as bats and balls in a garden that would help develop FMS (Turner et al., 2024). Young children starting primary school are eager to experience a range of activities that will support their learning and development, and PE teachers work hard to communicate the importance and enjoyment of PA (Sullivan, 2021; Kirk 2010). However, research has highlighted that PE is dominated by games, insufficient challenge, and a lack of enjoyment among children (Youth Sports Trust, 2024; Ofsted, 2023). To optimise the learning and development opportunities of PE, it is important to question the methodology behind teaching practices. Traditionally, PE has involved repetitive practice of techniques required of sports and decontextualised practices (Kirk, 2010). Typical teaching styles in PE often mean the teacher makes the decision about what is to be taught and learned, in what sequence, providing verbal commands or directives and visual demonstrations (Sullivan, 2021). Whereas newer pedagogical models promote innovative teaching styles using guided discovery and problem solving, where child-centered approaches are favoured. Specific teaching approaches may have the potential to create meaningful movement opportunities and benefit the children’s development in a multitude of ways (Roscoe et al., 2024). For example, quality-based PE interventions which promote exploration and problem-solving by the children have been found to benefit children's cognition (Youth Sport Trust, 2024; Garcia-Hermoso et al., 2021). Indeed, the potential of a teaching approach in PE to promote cognitive development and subsequent academic achievement has become a topic of great interest in education and research.

Executive Function and Movement

Neuroimaging research shows childhood is cited as a period of rapid growth of neural networks and the primary substrate in the brain’s pre-frontal cortex (Fuster, 2002; Diamond, 2002; Fiske & Holmboe, 2019). Executive functions (EF) are ‘orchestrated by activity within the prefrontal cortex’ and represent an umbrella term for three core cognitive functions: inhibitory control, working memory and cognitive flexibility (Best & Miller, 2010). Collectively, the three EF are understood to be responsible for goal-directed behaviours that involve playing with ideas whereby impulses are controlled, focus is maintained and new ideas ‘outside the box’ are considered (Diamond 2013; Best & Miller, 2010). EF have been found to be predictive of school readiness, academic success and are associated with a wide range of health and well-being outcomes (Blair 2002, Blair and Razza 2007, Rosen et al., 2020). An important association of EF is that an individual’s movements are coordinated by the same brain regions (Hillman et al., 2009). Children’s movements are an effective platform to understand EF in more detail as a flexible and adaptable process that is nurtured through interactions in a child’s environment (Richardson et al., 2008; Adolph & Robinson, 2015).

It is hard to reconcile cognitive constructs such as EF as abstract components of a child’s learning in development (Adolph, 2019). For example, when a child is moving around an environment, picking up, discarding and using equipment in different ways, they appear to make decisions in the moment rather than by a central processor before every action. Therefore, EF needs to be understood as part of an active system where adaptation to constant changes in daily life is the central unit of analysis (Adolph, 2019; Raja, 2019). Adaptation infers a child has found an effective solution for a particular situation by coupling individual, environment and task constraints that will be in constant flux (Adolph & Hoch, 2018). A way of thinking about EF is that it is a continuous process working within a system beyond the biological boundary because the body, brain and environment co organise and adapt (Adolph & Hoch, 2018). Observing a child moving around an environment gives insight into a child’s decision-making processes, for example, the different ways they might choose to play with a ball or hoop. A child will search, explore and discover the use of different aspects of motor skills which, reflects self-organising learning mechanisms (Adolph, 2019).

There is great debate and a large amount of literature that has aimed to pinpoint which type of children's movement has the strongest association with EF. One suggestion is that walking for 20-minutes is enough to increase the blood flow and activate the shared brain region responsible for cognitive functions (Hillman et al., 2009). However, a number of systematic reviews and meta-analyses provide evidence that a child's movement experience needs to develop their FMS to challenge EF (Van der Fels et al., 2015; Gandotra at al., 2022; Singh et al., 2019, Tomporowski & Pesce, 2019). Specifically, the variability of a movement task and context in motor skill learning challenges EF by engaging the child in dynamic interactions with the task and environment (Moreau, 2013, Pesce et al., 2016).

Self-Regulation

Movement represents a goal-directed action, and recognizing cognition as an active, integral process in children achieving movement goals highlights the importance of understanding how an intervention focused on developing motor skills impacts self-regulation. Self-regulation involves controlling emotions, behaviours and thoughts in response to environmental demands. Self-regulation and EF are a key focus in the UK education system, especially to support children living in areas of deprivation (EEF,2024). Diamond (2013) illustrated the association between inhibitory control and self-regulation, specifically describing control processes that involve response inhibition and maintaining optimal levels of arousal. The way a child is taught a motor skill may promote these processes in different ways and it is important to assess self-regulation through methods that gives insight into self-regulation as a multi-dimensional construct.

Introduction to the thesis

The overall aim of this thesis is to explore the influence of different aspects of movement on cognition among children aged 5-7 years living in an area of socio -economic disadvantage. This age group was chosen because the children were in their first year of full-time primary school education which includes their first experience of mandatory physical education lessons. The thesis comprises three studies which are described within the thesis study map, located at the start of each chapter. Following this introductory chapter is **Chapter two** (literature review) which will provide a review and critique of the relevant research related to EF, self-regulation, PA, motor competence, PE and pedagogy. This review will outline the gaps in the literature base and ends with the rationale and aims for the subsequent study chapters. **Chapter three** introduces *Study 1*, which investigates the associations of physical activity dose and movement quality with EF of 5–6-year-old children living in areas of deprivation. **Chapter four** introduces *Study 2*, which aims to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve EF of children aged 5-7 years living in an area of deprivation. **Chapter five** introduces *Study 3*, which aims to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve self-regulation of 5–7-year-old children living in areas of deprivation. **Chapter six** provides a synthesis of the results from the study chapters, highlighting recommendations for future research and potential impact upon research, policy and practice

Table 1 Thesis studies map

Study	Study content
Study 1	Investigate the associations of physical activity dose and movement quality with executive functions of 5–6-year-old children living in areas of deprivation
Study 2	Assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve EF of 5–7-year-old children living in areas of deprivation
Study 3	Assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve self-regulation of 5–7-year-old children living in areas of deprivation

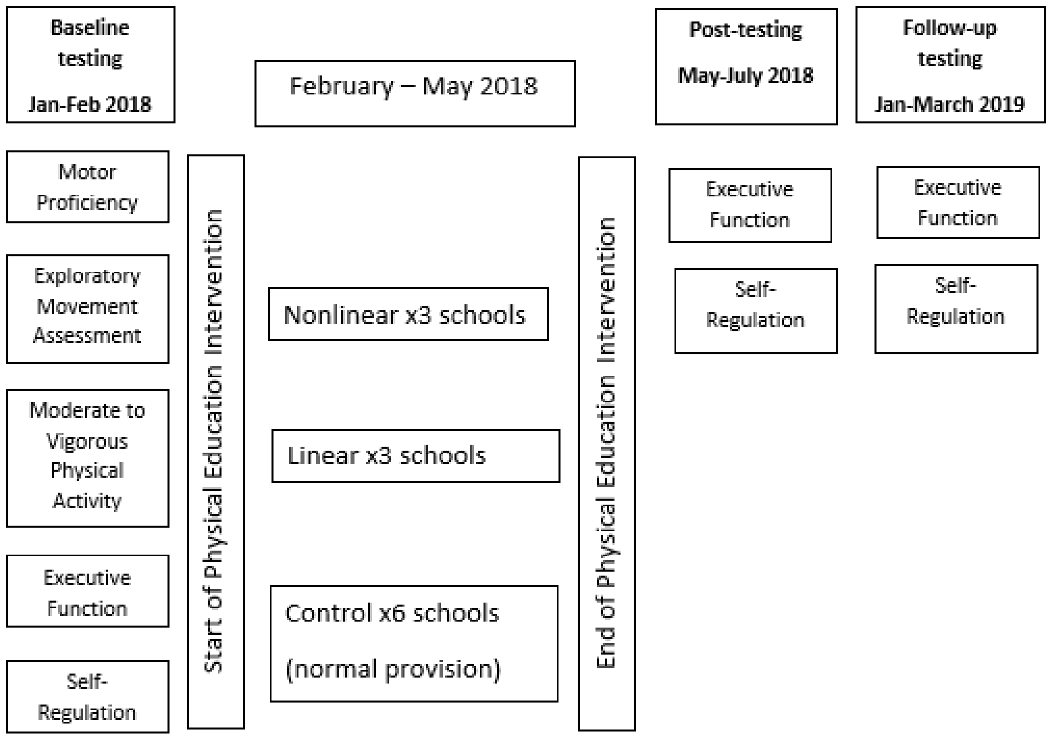

Figure 1. Schematic overview of PhD study data collection

Wider project: SAMPLE-PE

This PhD was part of a cluster randomised control trial (RCT) called the Skill Acquisition Methods Fostering Physical Literacy in Early Physical Education (SAMPLE-PE). The wider project included me and two other PhD students, who were evaluating different aspects of the RCT (motivation and PA, respectively), as well as our research supervisors. SAMPLE-PE sought to understand how Linear pedagogy and Nonlinear pedagogy can support the development of physical literacy amongst children aged 5-7 years (Rudd et al., 2020). Twelve schools were recruited from areas of high deprivation in a city in Northwest England. Three schools were randomly allocated in the Linear pedagogy group, three schools were allocated to the Nonlinear pedagogy group, and six schools were allocations to the control group. Over a 15-week period the two intervention groups received PE from coaches who were trained to deliver either Linear pedagogy or Nonlinear pedagogy. The

15 weeks were divided into 5 weeks of dance, 5 weeks of gymnastics and 5 weeks of ball skills. The control groups carried on with normal PE provisions. All schools had PE lessons twice a week for 60 minutes. Across the 12 schools, 360 children were recruited to take part in the assessments. Assessments took place before the intervention (baseline), immediately after the intervention had finished (post-test) and 6-months after the intervention had finished (follow-up). Data was collected on their moderate-to-vigorous-physical-activity (MVPA), movement proficiency, motor creativity skills, cognitive functions and self-regulation. Table 2 below will detail my role and the wider team's role in each of my studies.

Table 2 Individual and team contributions to PhD studies

Study	My Role	SAMPLE-PE team members role
Study 1	Study design. Recruitment. Data collection and coding of EF and motor competence. Data Analysis and write up.	Worked as a team to support recruitment. Supported each other with motor competence data collection and coding Fellow PhD student data collection and coding of PA variables
Study 2	Study design. Training of intervention coaches. Data collection and coding of EF. Data analysis and write up.	Worked as a team to support training of intervention coaches
Study 3	Study design. Design of RCS assessment. Training of intervention coaches. Data collection and coding of self-regulation assessments	Worked as a team to support training of intervention coaches Fellow PhD students supported the data collection of RCS

Chapter 2: Literature Review

Chapter 2 Literature Review

The purpose of this chapter is to review the literature that investigates the association between the development of cognition and movement, specifically within the child population aged 5-7 years. This literature review will seek to: (i) define and discuss the association between movement and cognition (ii) review and critique the associated research in this field conducted to date, providing a clear rationale for this thesis and (iii) consider the assessment and pedagogical approaches that support movement and cognition of 5-7-year-old children. Finally, this chapter will conclude with the aims and objectives of the thesis and a justification of the methodological approaches that have been used within it.

Introduction

In the history of cognition research, there has been a longstanding focus on 'higher-order functioning' to enable predictions about an individual's capabilities. The brain has been studied by calculating the consequences of the sum and omission of its parts for example, comparing typical behaviour with those who have a brain injury (Goldstein et al., 2014). The problem with these explanations is that blanket suggestions about brain activity will often not account for nonlinear developments in cognitive functioning and their associated areas of achievement (Faghiri et al., 2017; Casey et al., 2000). The prefrontal cortex of the brain has been shown to be an important structure for the performance of 'higher order' EF (Funahashi & Andreau, 2013). Examples of higher order EFs include planning, reasoning and problem solving (Diamond, 2012). Lower order skills include basic recall of facts such as knowing vocabulary. Higher-order functioning implies there are certain skills which can be distinguished from lower order thinking skills, that control and coordinate other cognitive abilities and behaviours (Lewis & Smith, 1993). One criticism of much of the literature, however, is that there is limited primary research to support these ideas. There is, however, a strong motivation in the research field to identify the core cognitive functions that are significantly associated with academic achievements and health outcomes (Cortes Pascual et al., 2019). In their analysis of the literature, Cortes Pascual et al. (2019) concluded that EF in primary school years were powerful predictors of future academic achievement. However, researchers such as Kauffman (1993) emphasised the challenge of predicting cognitive functioning and subsequent academic achievements when he expressed, ‘neural systems even in relatively simple organisms, enlist the joint parallel activities of billions of neurons to assess, categorise and respond to exterior and interior milieu’. This challenging position is termed the greatest scientific challenge of the 21st century by the authors of the Human Connectome Project who are using the latest neuroimaging technology to map the human brain to explain the connection between its structure and human functioning and behaviour (CCF, 2023).

One criticism of much of the literature on EF is that there is great variability in the way the construct is defined. For example, in a recent review by Koskulu-Sancar et al., (2023), EF was defined as “higher-order cognitive processes which enable goal-directed actions, emotions and thoughts”; whereas another by Furley et al., (2023) defined them as “a family of cognitive processes that enable humans to exercise self-control and discipline, take alternatives into consideration, reflect on past occurrences, consider an imagined future and update and adjust oneself flexibly to new information”. Under the umbrella term 'executive functions', in their mapping project, Jones et al., (2016) found that there were over 40 different cognitive functions that have been listed as EF across studies. Most commonly inhibitory control, working memory and cognitive flexibility are detailed as the three core cognitive functions termed EF (Diamond, 2016; Baggetta & Alexander, 2016). In their review, Baggetta & Alexander (2016) found that the most cited outline of EF was the one put forward by Miyake et al. (2000); in this study EF is proposed to be both a unitary construct and have three separate but related components. The process of using EF is described as the ability to acquire and retrieve the knowledge used to problem solve. All the evidence reviewed so far, however, define this process differently and vary the name of each EF. For example, the authors of one study names the skill as ‘shifting’, another lists it as ‘cognitive flexibility’. A consensus in the literature that clarifies each of the core EF would aid the interpretation of evidence and enable comparisons between studies.

A way of understanding children’s EF is to study the connection with other development areas and associated behaviours. It does not just require developments in technology to understand cognitive functions in this way, there is a clear loop of critique back to the history and theory of child development still used today by practitioners working with children. A longstanding viewpoint is that cognition is associated broadly with how children adapt in their environment (Piaget, 1973). This perspective created early links between development areas such as the coordination of movement, which was understood as the mechanism in which children acquire knowledge of the world around them because of sensorimotor schemes stored in the brain at different age-related stages (Piaget, 1973; Aviles et al., 2020). The key problem with this explanation is the idea that there is a reliance on stored information to produce a movement. The measurement of movement, however, can be a window into the thought processes at the different stages of carrying out a movement. There are contrasting views on whether EF has the most impact on movement in the planning stages and/or during the movement (Gray, 2023). A common criticism of the literature on motor skills and expert performance, which is often used to explain cognitive processes, is that much of the research involves adult participants. As a result, the findings may have limited applicability to children, who's cognitive and motor development differs significantly from that of adults

Research into children's movement and cognitive functions are entrenched in history, philosophy and multiple areas of science: there are intersects of indeterminacy that need to be embraced as well as a fusion of parameters which can inform practitioners of a sustainable approach to children's health and development (Chow et al 2011). To define the features of children's cognition and movement in a way that benefits practitioners working with children and cut through a dense and powerful storm of conflicting scientific, political and philosophical positions, the point of reference for any researcher in this field is the individual nature of children (Shi & Feng, 2022). There is a complexity to understanding children as living systems and the coevolving features of their ecosystem that they move within, but it is important to provide the anchor points of child development that can shape practice. Practitioners need to be able to make predictions that an environment and task design will support children's development; especially when a child is more reliant on their school experience when their home life has presented a great deal of challenge during their early years (Bonetti et al., 2020; Oppenheim & Archer, 2021).

A child facing adversity in their environment, notably from living in areas of deprivation has a potentially life limiting effect on EF skills (Lawson et al., 2018; Last et al., 2018, Mackes et al., 2020). However, such studies have methodological limitations, for example in the study by Last and colleagues (2018), the mean age of the participants was 17.25 years and so it must be used with caution when applying the results to children; in the meta-analysis by Lawson et al. (2018), the variability of measurement to assess EF may have influenced the outcomes. It is reported in the literature that living in an area of deprivation is associated with lower EF because the children are more likely to face adversity such as parental stress, violence and food insecurity, as well as different levels of cognitive stimulation (Cuartas et al., 2022; Hackman et al., 2015). When examining the longitudinal effect of deprivation on EF, complex methodology using neuroimaging shows detrimental changes to the brains size, volume, and thickness within areas responsible for EF (Farah, 2017). The brain's malleability to environmental influence is particularly of concern, as living in an area of deprivation will likely impact a child's experience-dependent learning, which will detrimentally affect their receptiveness to rich interactions within different environments (Lupien et al., 2009, Last et al., 2018, Rosen et al., 2020). Issues identified at an early stage tend to persist and increase over time (Cuartas et al., 2022). A longitudinal study of 1292 children in an area of deprivation found that EF mediated negative associations with academic readiness and early academic skills (Perry et al., 2018). The paper by Perry et al (2018) is limited, however, as it makes no attempt to distinguish between the separate constructs of EF. Therefore, research on the impact of deprivation that considers each construct of EF would be more useful to the design of effective interventions.

In areas of deprivation in the UK, there is investment in primary schools to enable early intervention and reduce the disparity that exists in children's development. Despite significant funding in the UK such as the pupil premium (which aims to improve educational outcomes for children living in an area socioeconomic disadvantage), interventions which seek to overcome deprivation as a moderator of EF often fail to make significant gains (Gov.UK, 2024; Mackes et al., 2020). Suggestions as to why interventions fail for this group of children include the challenge of the tasks being too demanding and the intervention needing to meet their cognitive needs as well as their physical, social and emotional needs at the same time (Diamond & Ling, 2016). However, in contrast, Blair and Raver (2015) reported improvements in EF, demonstrating effect sizes of 0.8 in response to their classroom-based Tools of the Mind intervention by children from an area of deprivation. This was supported by a meta-analysis by Scionti et al. (2020), which found that cognitive training that involved computerised and non-computerised methods to play games was significantly more effective for children living in an area of deprivation when compared to children in average socioeconomic status families. One major drawback of cognitive training is that it can take many forms. Often, interventions also target specific skill areas in isolation using computerised training, for example, rather than a joined-up view of how development areas impact one another. A principled and biologically plausible understanding of developmental mechanisms is needed to specify which aspects of a child’s experience supports development in EF and should determine intervention design in primary schools (Rosen et al., 2020).

Executive Functions

There are many different definitions of EF, some of which share similarities, all of which, are challenging to measure. A basic definition of EF is that it is the 'control and regulation of thought and action' (Baggetta & Alexander, 2016). The main weakness with this theory is forming a method of assessment to test such a function. The challenge for applying theory to practice is the myth of a control mechanism hidden inside the human brain because we can’t easily understand children’s development with such an unknown entity (Richardson et al., 2008; Koester, 2023). However, when we consider how multiple systems of the body work together, such as observations of movement at every age range for example, it can potentially help to measure and understand such a concept of ‘control and regulation’ in action (Adolph & Hoch, 2018).

A question that remains in the literature is at what level of conscious or automatic processing of EF exists. There are further definitions of EF that detail the process of control and regulation as the ability to override automatic responses, manipulate information and focus attention on selected aspects of the environment (Goldstein et al., 2014). Similarly, Diamond (2013) implies EF at a conscious level when she states, 'EF make possible mentally playing with ideas; taking the time to think before acting, meeting novel, unanticipated challenges; resisting temptations and staying focussed'. Again, the key problem with this explanation is that it is hard to measure some aspects of this conceptualisation of conscious or automatic processing.

To support an application of theory to practice, other authors refer to EF as higher order cognitive processes that are involved in goal-oriented behaviour (Ahmed & Miller, 2011). In a systematic review of 106 studies investigating the conceptualisation of EF it was found that 'higher order cognitive processes' and 'goal-directed action' were the most used terms to define EF (Baggetta & Alexander, 2016). A key feature of higher order cognition is being able to process information across multiple timescales (Owen & Manning, 2024). A further explanation of higher order functioning is that it involves a process of planning and orchestrating complex sequences of behaviour (Miller & Wallis, 2009). It is suggested that ‘daily functioning in the world requires a hierarchy of plans’ (Miller et al., 1968; Cowan 2013). Similarly, there are descriptions of EF having a supervisory role whereby EF control and regulate lower-level cognitive processes such as planning and monitoring (Alvarez & Emory, 2006; Goldstein et al., 2014). However, the review by Avery & Emory (2006) makes no attempt to distinguish between child and adult functioning which is an issue because EF in early childhood are not fully developed. The understanding of EF by practitioners working with children needs to be unambiguously clear for their practice to support its development.

The literature also provides a wealth of evidence that EF contribute to a variety of outcomes including school readiness and academic success (Pascual et al., 2019; Diamond & Lee, 2011; Baggetta & Alexander, 2016). The reason suggested for this is that EF are responsible for processing and organising the information an individual receives and regulates activity towards achieving a goal (Cortes-Pascual et al., 2019). However, the direction of causality is challenged in the literature because engagement in academic activities requires children to practice EF skills (Gunzenhauser & Nuckles, 2021). However, most of the literature suggests that a child's level of EF drives academic achievement (Best et al., 2011; Cortes Pascual et al., 2019). This view is supported by the limited progress made by intervention studies focussed on improving EF with the aim of subsequent progress in academic achievement. It could be that there is a mediating factor rather than a direct link between EF and academic achievement such as learning-related behaviours including self-regulation and the ability to pay attention and follow rules in the classroom (Brock et al., 2018; Nesbitt et al., 2015).

Some of the literature has identified specific EF skills as being more strongly associated with academic performance and stated that the association is dependent upon age and academic subject (Cortes-Pascual et al., 2019; Blair & Razza, 2007). For example, inhibitory control was the strongest predictor of maths performance in a study of 5-11-year-old children (Cortes-Pascual et al., 2019; Gerst et al., 2015). In a systematic review by Cortes-Pascual et al. (2019) that examined the relationship between EF and academic achievement in primary education, working memory had the most significant association with academic performance. However, most often in the literature all three constructs are measured and considered to contribute collectively to the process of EF that supports academic achievement, despite the suggestion that they each have a different level of influence. All three constructs are required to enable higher order abilities including reasoning, problem solving and planning, see figure 2. The next section will define the three separate constructs of EF.

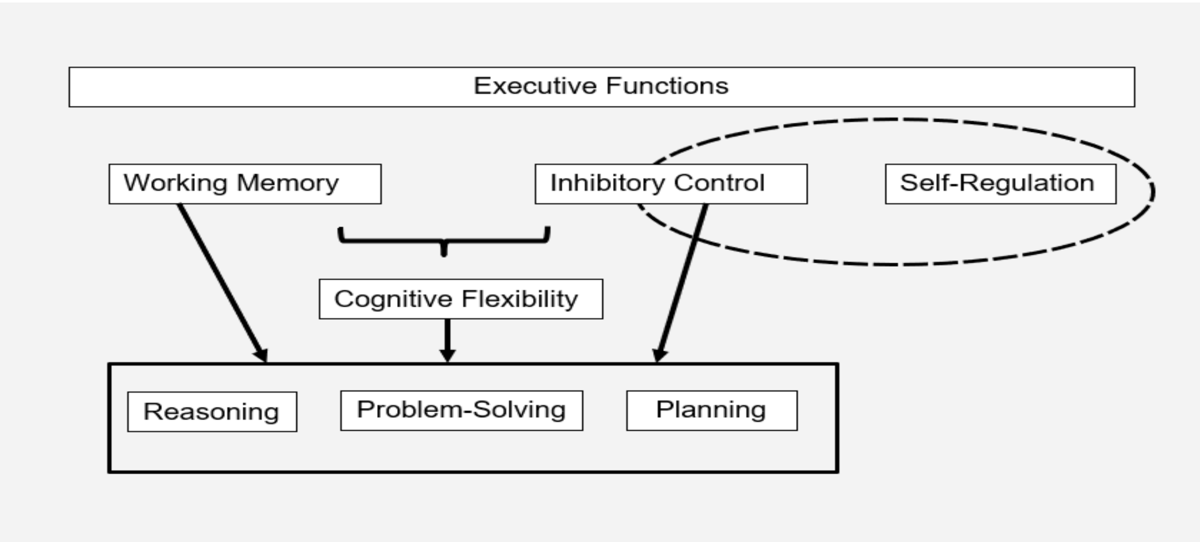

Figure 2. Adele Diamond's (2016) outline of executive functions and related terms

Defining inhibitory control, working memory and cognitive flexibility

Inhibitory control is one of the three EF that originated from the descriptions of an individual named Phineas, who was severely injured when pierced with an iron rod through the frontal lobe and displayed subsequent "disinhibited" behaviours

(Goldstein et al., 2014). Inhibitory control is often discussed by comparing ‘normative’ functioning with impaired functioning and the consequences when a child fails to inhibit (Munakata et al., 2012). However, this perspective requires careful consideration because viewing a child's inability to perform a specific task in one context as an impairment does not account for the possibility that they may demonstrate the skill in a very different situation. The child’s ability to perform an activity might be influenced by factors such as the context, motivation, or environment, which could affect their performance (Diamond, 2013). A child being impulsive and lacking self-control is seen as counterproductive for children’s academic achievement, and knowledge of inhibitory control by practitioners will lead to the development of activities that help children to resist temptation and consider their options before acting. When we compare younger children to older children, it is reasonable to consider that inhibitory control is a foundational skill that will likely develop prior to the other EF because when children are starting to interact within the routines of early years education settings, they will have to learn to control their impulses and wait before speaking or acting.

The prefrontal cortex has been labelled as the area in the brain that specialises in actively maintaining and representing abstract information, and inhibitory control is the first of a downstream of mechanisms that determines a behavioural outcome (Munakata et al., 2011). Beyond, the control of impulses, inhibitory control is also understood as the mechanism that can override old habits and predispositions through the control of thoughts and emotions to do what is needed for the goal that has been determined (Diamond, 2016). The control of thoughts and emotions implies an ability to focus and not to be overcome by potential distractions in the environment. Inhibitory control is a form of discipline to stay on task and not give up on completing the task despite there being potential temptation of other alternatives (Diamond, 2013; Sitaresmi & Kurniastuti, 2024). As a child continues on their education journey, the ability to persist at a task becomes critical to developing skills such as reading and writing. Inhibitory control indicates a child is capable of choosing how to react and behave by selectively attending and focussing on particular stimuli based upon their goals or intentions (Diamond, 2016). It also involves suppressing prepotent mental representations whereby a child repeats a task they have done before in a different way than how they have practiced (Diamond, 2016). Another perspective is that when detailing the skill of inhibitory control, it indirectly implies the simultaneous functioning of other systems such as the perceptual system and the physical body. This joined up thinking of how systems work together is often missing from the literature focussing on EF and each construct is often defined in isolation without indicating how other systems are involved. This prevents an understanding of how different systems of the body support and enhance EF.

Baddley (1992) detailed the second EF - working memory - as being part of a central executive that can manipulate information and temporarily store information. The part of the brain responsible for working memory is the dorsolateral prefrontal cortex (Diamond, 2013). Baddley (1992) emphasised that working memory was used when the task had elements of complexity such as learning something new or requiring reasoning. Working memory can be viewed as a gatekeeper to skills, for example, a child independently creating an efficient way of reaching a goal that is different from previous attempts (Alloway, 2011, Cowan & Alloway, 2008). The book by Alloway (2011) would have been more robust if it had included longitudinal data to support the claims that there are age-related expectations. Diamond (2013) described working memory as being critical to making connections between conceptual knowledge and perceptual input and considering how past events inform future plans and actions. Diamond (2013) also emphasised the connections between inhibitory control and working memory to control the ability to create new ways of doing things rather than repeating past thought patterns. The paper by Diamond (2013) does not ascertain whether inhibitory control and working memory are employed in some activities more than others, this is an important area of research to identify, especially with the view that activities must be of a certain complexity to use working memory.

Over time, memory has been categorised in different ways; the difference between short-term memory and working memory, for example, is that short term memory is holding information whereas working memory holds information and manipulates its meaning (Diamond, 2013). Another distinction between working memory and long-term memory is that working memory is the information held on a certain task whereas long term memory is the information saved from across the lifespan (Cowan, 2014). Working memory would therefore be responsible for the stage of holding a small amount of information most relevant to the task and combining it into a coherent, complete thought (Cowan, 2014). One challenge of this, is the view that working memory is the gatekeeper to executing a new task and when we look at the fluidity of how children move and act in their surroundings, it is hard to reconcile such a mechanistic way of thinking sitting behind their every act.

Cognitive flexibility is viewed as the third EF that builds upon inhibitory control and working memory and develops much later (Diamond, 2013). Posner & Snyder in (1975) detailed cognitive flexibility as an executive branch of attention responsible for selecting information in the environment and the ability to switch flexibly between tasks. This means a child solves a problem using one approach and switches to using a different approach to solve the same problem (Nunes de Santana et al., 2022). It is important to understand how children use multiple systems of the body to solve a problem for different skills and situations. The review by Nunes de Stantana et al., (2022) focussed only on the positive correlation between cognitive flexibility and mathematics performance, and it would have provided a more comprehensive insight if the review had compared problem solving in a range of activities and the association with each EF. A broader view of cognitive flexibility is that it requires a child to think differently about the same task, also described as 'thinking outside the box' (Diamond, 2013). However, this theory does not fully explain the process of how a child thinks differently and whether other systems of the body are involved in this process such as the perceptual system.

Children below the age of 6 years often continue to respond at speed at the cost of accuracy and will therefore deploy limited cognitive flexibility (Zelazo et al., 2013). It is believed that a child will not be able to switch flexibly on each trial they are presented until they are aged 7-9 years (Diamond, 2013). Cognitive flexibility is particularly helpful when a child finds themselves in a situation where their approach to solving a problem is not working, and they need to come up with an alternative solution. Cognitive flexibility implies that they can make an adjustment that is appropriate for the goal of the behaviour, not just continuing by randomly trying different approaches. Cognitive flexibility builds upon the other EF because switching to a different response first requires the inhibition of a previous response, taking in the relevant information using working memory to manipulate it, and then switch the response (Dajani & Uddin, 2015). Cognitive flexibility is a model of attention that implies both stimuli driven, bottom-up processing and goal-directed, top-down processing is required when needing to efficiently respond to a changing environment and searching through a problem space (Canas et al., 2003; Dajani & Uddin, 2015).

Similarly, to inhibitory control, cognitive flexibility is also understood by considering its opposite, cognitive inflexibility. An example of cognitive inflexibility would be a child continuing to proceed with an action that did work in previous situations but doesn't work in a new situation. The child needs to adapt their sequence of operations or restructure their knowledge to fit an effective interpretation of the requirements of the new situation (Canas et al., 2003). Again, such a definition of cognitive flexibility infers the involvement of the other EF. As a separate construct, one view of cognitive flexibility is that it is the function responsible for focussing attention on a changing environment, including the perception of factors in the environment that could disrupt the current task. However, a challenge for knowing how to promote cognitive flexibility in the early stages of its' development, is the finding that skilful individuals are less likely to change their strategy despite detecting significant changes in the environment (Canas et al., 2003). Additionally, it is not without understanding how multiple systems of the body work together, that it can be explained how there is subtle variability in each action of an expert (Gray, 2023). It is important to note however that the book by Gray (2023) makes no attempt to provide information on the difference between a child and an adult when discussing the findings of skilful performance. The next section of the thesis will present the most used tools for assessment of EF and its separate constructs.

Assessing executive functions

There is a view that each construct of EF does not need to be measured separately, especially when the participants of a study are young children because factor analysis has shown that at an early development stage, EF are a unitary model (Silva et al., 2022; Wiebe et al., 2008; Hughes et al., 2010). To measure EF as a whole construct, in the systematic review of 49 studies by Silva et al. (2022), Behaviour Rating Inventory of Executive Function, Preschool version (BRIEF-P) was found to be the most frequently used measure for the global assessment of EF. BRIEF-P involves the use of ratings scales by adults to measure a child's competence when carrying out everyday tasks and reference to behaviours such as "difficulties with concentrating on schoolwork" (McCoy, 2019). The focus is on behaviours that have been a problem across a 6-month period and are rated on a 3-point scale (never, sometimes and often). The most proposed deficiency of some EF assessments is that they are often derived from tests on adults and for clinical purposes. However, the BRIEF-P was specifically designed for children aged 2-6 years and had good convergent validity with another rating scale (Duku & Vaillancourt, 2014). Although it is suggested that there is weak construct validity between rating scales and performance-based tests in general (Souissi, Chamari & Bellaj, 2022).

Most commonly, each construct of EF is measured separately, and this enables researchers to align with theoretical models of EF that can inform intervention design. For example, a focus on inhibitory control and working memory rather than the improvement of cognitive flexibility in interventions with children under the age of 6 years. When assessing each construct separately however, it is important to note that, especially when assessing children, there is likely to be a degree of measurement impurity whereby the scores for each construct reflect a broader range of skills (McCoy, 2019). For example, a working memory assessment such as the backward digit span will also capture inhibitory control skills (McCoy, 2019).

When using performance-based tests to assess each construct separately, the tasks most commonly use a pattern of presenting objects as stimuli of different shapes and colours, and the measured indices are the number of errors and omissions (Silva et al., 2022). On the one hand, conducting these tests on the iPad has been argued to be assessing optimal performance under controlled conditions that are not representative of real-world problems (Souissi, Chamari & Bellaj, 2022). On the other, Berg et al. (2020) reported that children enjoy play-based assessment on iPads, and this increases the reliability of the test. Another advantage of iPad-based assessment is that it leads to objective scoring rather than potential bias by a researcher conducting in-person assessments such as 'Simon says'. The main weakness of the study by Berg et al. (2020) is that it only compared the use of two apps on an iPad, it did not contrast this with a non-iPad task to examine any reliability and enjoyment level differences.

When determining methods of assessment, differing models and views of each construct are proposed. For example, for inhibitory control, Petersen et al. (2016) and Garon et al. (2008) proposed that there are tasks which measure 'simple' response inhibition where a child has to delay or inhibit a response in "delay" and "don't" tasks; and 'complex' inhibitory control tasks which also require a response to a salient, conflicting response e.g. flanker text. For research on children up to age 5 years, a systematic review by Silva et al. (2022) reported that the most used test of inhibitory control was tasks using the Stroop paradigm. This involves a stimulus being presented that consists of two dimensions such as a colour and word that are the same (e.g. red written in red) in congruent trials and conflicting (e.g. red written in green) in incongruent trials; error rates and response times are recorded. Other measures include the Simon task, delay-of-gratification tasks, go/no-go tasks and the Flanker task (Diamond, 2013). The flanker task was first introduced by Eriksen and Eriksen (1974). The stimulus is presented in the centre and is 'flanked' by stimuli on either side, that are congruent (e.g. in the same direction) and incongruent (e.g. opposite direction). The shape of the stimuli is often arrows or letters in a line, whereas the NIH toolbox uses the shape of a fish, and the test takes approximately 4 minutes to complete. The NIH toolbox computes an accuracy score, suitable for children and reaction time, however this is a more relevant measure of adult performance (Weintrab et al., 2013). It was reported to have 'excellent developmental sensitivity, reliability and convergent validity' among 8-15-year-old children (Zelazo et al., 2013). Weintrab et al. (2013) reported strong test-retest reliability of the NIH toolbox flanker test and convergent validity (r= 0.70) with the Wechsler Preschool and Primary Scale of Intelligence Third UK Edition (WPPSI-III) in 3-6-year-old children.

When assessing working memory, there is a similar approach to breaking down the construct into subsections. For example, digit-span tasks are said to use short-term memory as well as working memory (Pickering, 2006; Diamond, 2013). They are also referred to a simple working memory task because the task only requires retention of information (Kurgansky, 2022). In a digit span task, the child must recall a list of digits or words they have just been presented. Silva et al. (2022) reported that the backward digit span task was most used when assessing children up to aged 5 years. Pickering (2006) reported that children between the ages of 4 and 5 years could retain 4-5 items and children aged 14 to 15 years could retain 5-7 items. The book by Pickering (2006) however, does not compare findings from different assessment tools and reports age related expectations based on the use of one test, the Working Memory Test Battery for Children (WTMB-C). There needs to be caution when applying these values as the norm when other assessment tools are being used because it could be that when a child is assessed using a different measure, the number of items they retain will increase or decrease.

Complex working memory tasks involve the retention of information but also the transformation of the information such as a repeating a list in reverse order or listing in size order (Kurgansky, 2022). Diamond (2013) and Zelazo et al. (2013) stated that asking participants to reorder items they have just seen or heard is an 'excellent' measure of working memory. The NIH toolbox uses animals and food in the presentations of shapes that need to be reordered in size from smallest to largest. A picture of each stimulus is presented one after another, each one being displayed on the screen for 2 seconds whilst the name of the stimulus is heard via computerised voice. The child has to remember each one and recite the name of each stimulus in size order. If the child is unable to provide the correct response, they get a second trial of the same number of items and incorrect responses on two trials with the same number of items brings the task to a close. If the child is successful at remembering and reciting 1-list versions of the task they will move on to the 2-list section which requires them to remember and recite food and animals in size order. The task takes approximately 10 minutes to administer. There is some debate in the literature as to the age appropriateness of the NIH list sorting working memory test, with Tulskey et al. (2014) reporting its use with children over 7 years and NIH Toolbox (2024) stated children aged 5 years and over can use it. With children over aged 7 years, Tulskey et al. (2014) reported a high degree of consistency in the test-re-test reliability (ICC = 0.77) of the NIH toolbox list sorting working memory test. It also demonstrated convergent validity through correlations with other tests (r = 0.57) and discriminant validity (r=0.24). The main weakness of the study by Tulskey et al. (2014) was the sample size did not enable analysis within each age subgroup. Weintrab et al. (2013) reported strong test re-test reliability (ICC= 0.77), convergent validity (r = 0.64) among children aged 3-6 years. The study by Weintrab et al. (2013) would have been more useful if it had compared 3-4 years with 4-5 years and 5-6 years rather than grouping age range together. It could be that the assessment is more effective for children of certain ages within this age range.

The third EF, cognitive flexibility, is often assessed by asking children to sort by different factors such as colour and shape. The most used assessment for children's cognitive flexibility is the Dimensional Change Card Sort test (Silva et al., 2022; Doebel & Zelazo, 2015) designed by Zelazo et al. (1996). A child is shown cards with shapes of different colour and asked to match by colour and shape. On the NIH toolbox, the score for the dimensional change card sort test combines accuracy and reaction time for children with an accuracy score greater than 80%. Zelazo et al., (2013) reported excellent test re-test reliability, developmental sensitivity across childhood and strong convergent validity among children aged 3-6 years. However, the main weakness of the study by Zelazo et al. (2013) was the sample size meant grouping the participants into a wider age range, rather than analysis at each age year. It could be that children at certain ages within this age range respond better to the assessment. A meta-analysis by Doebel and Zelazo (2015) differentiated within this age range when they reported that children under 5 years were found to sort by pre-switch rules whereas children over 5 years could follow the rule change and switch flexibly when asked to change from sorting by colour to shape for example. The next section of the thesis will discuss the development timeline of EF and its association with other areas of development

The developmental trajectory of executive functions and its association with other development areas

EF develop over a long period of time and there is debate in the literature as to the age range during which EF act as a unitary function or as discrete functions. Research investigating a development trajectory of EF often cite childhood as a period of rapid growth because of maturational changes in specific brain regions. However, it equally emphasises the protracted nature of EF development into adulthood (Best et al., 2009). Previous studies using confirmatory factor analysis emphasise that middle and late childhood reflects the active use of multiple EF, with an increasingly discrete nature of skill mechanisms (Miyake et al., 2000). It is proposed that at aged 7-12 years, a unitary factor model provides the best fit, with some research reporting that from aged 5 years when children start school, inhibitory control is more pronounced in its rapid and robust development (Best & Miller, 2010, Baker et al., 2019, Garon et al., 2008, Hughes et al., 2010). All the studies reviewed so far, however, suffer from the fact that there is limited analysis of studies consistently using the same form of measurement across age ranges which results in a lack of comparability. A lack of agreement as to whether EF should be considered as a unitary function or as separate constructs poses a challenge in measurement; most often, EF is measured as separate constructs.

The diversity and unity of the EF constructs and other associated areas of development at primary school age is indicative of a child's increasing ability to function and adapt within an enriched environment (Karr et al., 2018; Best, 2010; Miyake, 2000). However, when observing a child interacting in their environment, there is still an air of mystery as to how the brain has 'cognitive control', coming from certain parts of the brain termed a 'central executive' (Posner & Snyder, 1975; Baddeley, 1986). Before any advances in technology that helped to evidence the workings of the brain, scientists were unable to provide context of how multiple systems of the body work together. Technological advances in neuroimaging have increased an important discussion about activity between pairs of brain regions termed functional connectivity (Elam et al., 2021). In their ground-breaking investigation, Elam and colleagues (2021) aimed to use up to date technologies to elicit neuroimaging from 1200 participants. The large-scale project that investigates individual differences from birth onwards across the lifespan has opened up wide-ranging discussions of pattern and relationships between physical, cognitive and affective functions (Elam et al., 2021). A construct that has a physical, cognitive and affective function is self-regulation (Lakes & Hoyt, 2004) and the relationship between EF and self-regulation is postulated as bi-directional (Muir et al., 2023). In their analysis of interventions, Muir et al. (2023) identified that interventions can target EF and self-regulation together when working with preschool children, however one of the main difficulties with this line of reasoning is whether this can be the approach adopted for school age children. The next section of the thesis will discuss self-regulation and its assessment.

Self-regulation

Self-regulation is understood to be an underlying mechanism in the association between deprivation and mental health (Palacios-Barrios & Hanson, 2019). One criticism however, of much of the literature on mental health and deprivation is that the causal chain is unknown. It is suggested that children living in an area of deprivation are two to three times more likely to develop mental health issues (Marmot et al., 2010; Wickham et al., 2017; Wade et al., 2022). Higher self-regulation aged 3-5 years has been shown to predict better mental health as an adolescent (Palacios-Barrios & Hanson, 2019; Dajun Zhang et al., 2014). However, such explanations tend to overlook the fact that there may be controllable and uncontrollable influences on self-regulation at this age. When a child is living in an area of low SES, there are stressors that can compromise typical development of processes such as self-regulation. These stressors include limited levels of stimulation and resources at home, increased household noise and anti-social behaviour in the community (Evans & Kim, 2013; McEwen & McEwen, 2017); research has shown that this can lead to structural differences in brain activity (Palacios-Barrios & Hanson, 2019). An early view of self-regulation is that children learn to regulate their internal state in response to external stressors: detrimentally in the example of external stressors caused by deprivation (Robson et al., 2020; Palacios-Barrios & Hanson, 2019). From a positive perspective, such self- regulation of their internal state can mean children can take on the challenges that they are given the opportunity to trial and pursue the learning of different skills (McEwen & McEwen, 2017).

There are normative challenges for all children including transitions such as starting school which require coping mechanisms and an ability to modulate responses. Self-regulation in a school environment would broadly mean a child demonstrates 'control' of their emotion, interpersonal interactions, thinking and behaviour (Muir et al., 2023; Robson et al., 2020). The key problem with this explanation, however, is that ‘control’ is potentially a very subjective construct that is hard to observe objectively, considering the multiple factors involved. It is sometimes useful to refer to the opposite view of the construct and a child with limited self-regulation would avoid the pursuit of goals (Robson et al, 2020). Again, one of the main difficulties with this line of reasoning is making this measurable. A goal is a desired end state and can include carrying out a specific behaviour, demonstrating a particular thought or attitude, or maintaining a particular emotional state (Inzlicht et al., 2021). When a child is in pursuit of a goal, there are many stages they go through including the decision about which goal to pursue, how to go about getting there, and implementing different ways of achieving the goal whilst monitoring progress and concerns or competing demands (Inzlicht et al., 2021). Some children will be more able than others to persist at the different stages of goal setting. Self-regulation is required throughout this process to modulate thoughts, emotions and behaviours (Inzlicht et al., 2021). For example, there are physical goals such as jumping over a box which, could elicit fear and a child must regulate their response in order to even attempt the goal that has deemed by an adult as age appropriate. For another child, their emotional response could be one of excitement at the prospect of the challenge and they will have to modulate their thoughts about how to carry it out successfully. In their important review, Inzlicht and colleagues (2021) suggest that EF and self-regulation should be simultaneously measured because although they are distinct, they predict the same outcomes.

School is an important environment for children to develop self-regulation skills because it offers the opportunity for children to pursue goals in many different forms. The development of self-regulation can occur in daily activities ordinarily planned into the school day as well as through targeted intervention. Lakes and Hoyt (2004) found that a martial arts intervention implemented in schools promoted self-regulation. The martial arts intervention was proposed to have a beneficial effect on self-regulation because of the questioning techniques used during the intervention that encouraged the children to monitor their own behaviours during each task. One of the main difficulties with this line of reasoning however is that it may only be an appropriate intervention feature for older children. Lakes and Hoyt (2004) also reported that in their intervention, there was an incremental level of challenge, and the children enjoyed the goals that the activity involved. This view is supported in the review by Muir et al. (2023) which focussed on a younger age group, who found interventions that were cognitively challenging were most beneficial to self-regulation. This included rule changes (e.g. increasing the number of defenders in an attack vs. defenders' game), constraints added (e.g. extra hoops added to a leap jump activity) and adjustments (e.g. increasing the size of a space according to the increasing ability of the children). To develop self-regulation, children must have the opportunity to make decisions independently and likely, at an individual level regardless of the actions of others. This can be challenging to achieve in group settings and findings indicate that even once an activity has started, to promote self-regulation, there needs to be different angles and stages of decision-making by the child.

A common measure of self-regulation is observation rating scales filled out by parents and teachers, for example the Strengths and Difficulties Questionnaire (Goodman 1997). It has 25 items, broken down into 5 categories that are questioned using both positive and negative prompts. Mieloo et al. (2021) in a study of 4750 children reported that the validity and reliability of the total difficulties score of the parent and teacher SDQ was satisfactory in children aged 5-6 years. Other assessments that have been used to assess self-regulation previously are Delay of Gratification tasks (Robson et al., 2020) and a novel approach developed by Lakes (2012) called the 'Response to Challenge' Scale. This involved a progressively challenging physical obstacle course that children complete whilst being assessed on their approach to each challenge. The scale of assessment has a physical, cognitive and emotional regulation score. The author proposed that the intent of the physical regulation score was to 'answer the question: does this child exhibit motor control?' (Lakes, 2012) because theoretically it has been proposed that self-regulation manifested itself in motor control (Kopps, 1991). The author proposed that the intent of the cognitive regulation score was to answer the question 'does the child exhibit control over mental processes including attention and concentration' (Lakes, 2012).

Theoretically it had been proposed that self-regulation involves control over mental processes including the ability to persist at tasks and concentrate (Baumeister, 1991). The author proposed that the intent of the affective regulation score was to answer the question ‘does this child exhibit control over their affective state and mood’ (Lakes, 2012). In a test re-test reliability analysis, the affective and physical scores have a sufficient coefficient (0.84 and 0.80 respectively), however the cognitive scale was lower (0.64) showing it may be a more difficult construct to score (Lakes, 2012). Lakes (2012) provided strong evidence for the convergent and discriminant validity of the RCS. An examination of construct validity demonstrated that self-regulation is a construct that can be measured across different domains (Lakes, 2012). The limitation of this approach to measurement, however, is that it has not been used with younger children or at-risk groups where the expectation is that they will have lower abilities. The effect of deprivation will be discussed in the next section.

The influence of living in an area of deprivation

Living in an area of deprivation is associated with negative developmental outcomes, one of which is a deficit of EF and self-regulation (Miguel et al., 2023; Haft & Hoeft, 2017). This can lead to inequalities in academic achievement, employment outcomes and health (Haft & Hoeft, 2017). In their thorough analysis of the literature, Haft & Hoeft (2017) said that cross-cultural differences were an important consideration when detailing how environmental enrichments was a mediating variable. One explanation is that children living in deprivation are exposed to stressors that causes neuroendocrine changes that may lead to structural changes in the prefrontal cortex (Haft & Hoeft, 2017). Other factors contributing to the development of EF and self-regulation include the qualities of caregiving practices such as the parental support given to regulate a child's stress response and guide their goal-directed activities.

Indeed, parents' responsivity and sensitivity were found to mediate the association between deprivation and EF (Miguel et al., 2023; Blair et al., 2011; Haft & Hoeft, 2017). Financial limitations can mean children living in deprivation have a lack of stimulating materials in the home such as books and computers, which has also been shown to mediate the association between deprivation and EF (Haft & Hoeft, 2017).

Other adverse childhood experiences including abuse and household dysfunction are associated with deprivation and can happen at certain timepoints including during pregnancy, the postnatal period and into childhood (Miguel et al., 2023). Adverse childhood experiences are associated with deficits in EF in children (Miguel et al., 2023). A weakness with this argument, however, is that both genetic and environmental factors likely contribute to EF. One view is that during childhood, the brain changes in response to environmental experience, termed heightened brain plasticity (Miguel et al, 2023). The brain structure's inherent dynamic to adapt and change according to the environment leads to vulnerability during deleterious events; the cumulative effect of deprivation widens disparities and trajectories become more firmly established (Zatorre et al., 2012; Grissom & Reyes, 2019; Mackes et al., 2020).

The neurodevelopmental consequences of differences in Body Mass Index (BMI) of children living in an area of deprivation have also been explored (Dennis et al., 2022). The study by Dennis et al (2022) was a large-scale longitudinal study of 11000 children that were followed for 10 years found that household income and parental education was associated with BMI and EF and that BMI had a mediating role in the association between deprivation and EF. However, one problem with their method was that the children were first assessed at age 9 years and so doesn't account for early childhood development of EF. It is also proposed that children are at increased risk of obesity and low levels of FMS dependent upon their socioeconomic status (Roscoe et al., 2019; Jebeile et al., 2022). Parental education level can determine a child's PA and nutrition, as well as a location can have crime rates and fast-food outlets that hamper healthy choices. In studies of younger children (aged 2-5 years), it has been found that obese children performed significantly lower on EF tasks (Likhitweerawong et al., 2022). However, a criticism of the experimental design by Likhitweerawong et al., (2022) was that they only used cross-sectional data, therefore causality could not be inferred.

Protective influences are often the inverse of a risk factor such as a lack of stimulation; this involves, a child being able to physically navigate an enriched environment that has variety and opportunity for expression of individual level challenges and goals (Walker et al., 2011). A review found that a child's access to nature can enhance cognition (Veclla-Brodrick & Gilowska, 2022). However, a limitation in this review was the level of contact with nature was variable across the studies included, this varied from plants in a classroom to actual time exploring green space outdoors. For children living in highly urbanised areas, the school environment provides the opportunity for children to connect with nature, although some schools have different levels of access to greenspace. The suggestion that greenspace could influence cognitive function has the potential to add to the discussion on defining EF in a way that supports a practitioner to understand the influence of environment enrichment. In the next section, an alternative approach to defining EF will be discussed.

Executive functions as embodied, embedded and encultured cognitive functions

It is hard to reconcile cognitive constructs such as 'executive functions' as isolated processed computed by a central executor, therefore referring to 'cognitive functions' broadens the discussion of the processes involved. Cognitive function needs to be understood as part of an active system where adaptation to constant change to daily life is the central unit of analysis (Adolph, 2020; Raja, 2019). The key problem with this explanation is that it is a very broad statement, and an understanding of cognitive function needs to be specific and measurable. Contemporary research explores the role of cognitive function supporting an 'embodied organism' where developmental mechanisms lie in the emerging relations between a child and their environment (Gottiwald et al., 2016). The findings in Gottiwald et al (2016) study would have been much more representative if they had included participants from a wider age range as the mean age of participant was 18 months old. It is further suggested that the constant change in an environment engages a child continually in situated problem solving of which stimuli to visit, ignore or explore. This implies the brain, body and environment will co-organise or co-adapt during varied and creative patterns of behaviour when a child is working towards a goal (Chow et al., 2011, Smart, Cowes & Heersmink, 2017). One of the main difficulties with this line of reasoning is measuring such processes of co-adaptation across the systems of the brain, body and environment.

Ecological approaches to cognition (embodied, embedded and enactive) are fast becoming a dominant theory, at the heart is the reciprocity of a child's action and exploration (Gibson 1988; Adolph 2019). These are non-representational approaches to understanding how a child's exploratory information gathering behaviours resonate with ecological information. This is the mutual relationship between an organism's capacities and the dynamics of their environment (Smith & Thelen, 1996; Adolph 2019; Gottiwald et al., 2016; Gibson, 1979). Through the continued interactions, a child's subsystems are constrained and evolve leading to new ecological information and a continued functional process of learning in development. In ecological theories of cognition, 'embodied' implies continual interaction with the environment;

‘embedded’ details the variations across the organism-environment system in continual flux and ‘enactivism’ infers that socio-cultural practices become part of this process.

Cognitive functions need to be flexible and embedded to advance a child’s logical, creative and reflective thinking (Adolph & Hoch, 2018). A task that leads to constant shifting of meaning and information generation across the subsystems of the body and environment, challenges a child to adapt their temporally coherent cognitive functioning (Richardson et al., 2008). In this view, the three core cognitive functions inhibitory control, working memory and cognitive flexibility would be defined as follows: inhibitory control supports the regulation of sub-systems in the human brain including emotions and underlying neurochemical changes which prevent a pre-potent response that might not be advantageous in a current context (Nigg, 2000; Best et al., 2009). Working memory enables a child to sustain and manipulate information to identify nuance and fluency of a goal-directed action (Alloway & Alloway, 2010). Cognitive flexibility involves the ability to think laterally and beyond a child’s current action, which is also aligned to the shifting of attention within a context (Diamond 2013, Oppici et al 2020). In the next section motor development theory will be discussed.

Motor development theory

FMS serve as the foundation for motor development (Roscoe et al., 2024). Whithall et al., (2020) reviewed motor development and determined four theoretical phases of discussion that still influence practitioners’ approach to understanding the processes involved in each movement. The precursor period (1787-1928) used longitudinal observations to indicate how infant motor development was a measure of brain development (Whithall et al., 2020). In the maturational period (1928-1946), observations were made of sequences of movement amongst multiple children and descriptions of FMS were created (Whithall et al., 2020). In the Normative/Descriptive period (1946-1970), greater detail was identified at each stage of motor development, in particular school-aged children and the impact of the environment and learning on motor outcomes such as throwing and catching (Whithall et al., 2020). A child's individual characteristics in terms of physiological changes as they grew and developed were related to fitness and athletic performance and there was also a great understanding of intervention effects (Whithall et al., 2020). Since 1970, there has been a focus on process-oriented explanations of motor development from two contrasting viewpoints: dynamical systems (Kelso, 1997) and information processing (Schmidt, 1975). Information processing is a theoretical perspective that works upon the framework that the movement in an environment is an input of information into a computer process of perceiving, selecting and programming to determine the movement behaviour output (Whithall et al., 2020). According to Schmidt (1975), motor programmes were hierarchically determined by "recall and recognition schemas" and practice focussed on ways of controlling and refining such motor programmes. A dynamical systems perspective was outlined in a landmark paper by Kugler, Kelso and Turvey (1982) entitled "On the control and coordination of naturally developing systems", the authors aimed to unify multiple disciplines. In the next section of the thesis, an ecological view of the association between movement and cognitive function will be discussed.

An ecological view of the association between movement and cognitive function

An ecological view of movement emphasises how purposeful behaviours occur because of the mutual relations, or 'inseparable pairing' between a child and the dynamics of their environment (Gibson 1979, 1986; Richardson et al., 2018). It is proposed there is a continuous process of identifying task and organism-relevant properties in the environment rather than a sole reliance on an internal coordinator of action (Richardson et al., 2018). A child's movements generate the information during explorations that instigate subsequent explorations of a situation to achieve an outcome. The environment has features that persist, newly arise and dissolve as does the child's changing body and biophysical subsystems; together they are a combined whole system (Turvey et al., 1978; Richardson et al., 2018; Adolph & Hoch, 2018). There is fit between the body and the environment that requires a dynamic beyond the biological boundary to coordinate adjustments, adaptation, and reaction (Adolph & Hoch, 2018). The nervous system will continually adjust in different ways to the unique environment features that complement the requirements of a task; this indicates a cognitive architecture that is situated not central (Wilson, 2002). It is the collective role of cognition, perception and action that embeds what is perceived, known to be pertinent, relevant and acted upon (Richardson et al., 2018). Even the perception of catching a ball as a relatively simplistic task, requires a situation specific coordination of a child's cognitive, perceptual and action systems to react to the complex dynamics of speed, distance and time. A transdisciplinary perspective of learning involving motor and cognitive skills encourages a child to digress beyond engrained norms within each system, in a mutual knowledge space. Skilful action is therefore not repetitive movements but 'dynamic, body-environment interactions through which individuals self-regulate to achieve their intended task goals' (Wood et al., 2022).

A movement task that engages the core cognitive functions can be mapped as a series of non-linear transactions in a landscape of affordances detected during movement (Chow et al., 2011). Affordances are the properties of the environment relative to the individual and reflect a “bottom up” workspace used by children rather than a “top down” use of a mental sketchpad (Pezzulo & Cisek, 2016). From an ecological perspective complexity lies in the information nested in the specifics of a situation which embeds cognitive functions (Araujo & Davids, 2009; Wood et al., 2022). Through the passage of learning children become more efficient at being able to deal with more complex problems that might present themselves in the environment (Adolph, 2019; Gibson & Pick, 2000). Adaptation infers a child has found an effective solution for a particular complex situation by coupling individual, environment and task constraints that will be in constant flux (Adolph & Hoch, 2018).

In everyday life children learn through purposeful and self-regulated engagement with the world around them. These purposeful goal-directed interactions happen across varied and diverse environments ranging from play at home to asserting themselves in tasks at school (Adolph & Hoch, 2018; Grissom & Reyes, 2019). Motor skills create new opportunities for learning during childhood, however this does not mean a child needs to rely on instructional methods to formalise a motor programme (Chow et al., 2011). To prevent an overreliance on repetitive movements using an imposed sequence; there needs to be the opportunity for multiple levels of self-reorganisation to consolidate neural activity and memory traces effectively. Through the use of affordances - the opportunities for action that emerge during movement explorations - information is generated in real time influencing goal direction (Chow et al., 2011). When child can self-regulate and move, it creates a dynamic formation of neural synergies that are integrated with situation-specific perceptions and actions

(Wilson; 2002; Raja & Anderson, 2019). In the next section of the thesis, an information processing view of the association between movement and EF will be discussed.

An information processing view of the association between movement and executive function

Information processing theory has a standpoint that the brain is a metaphoric computer and EF are processing a sensory input and providing an output that determines a motor response (Gottiwald et al., 2023). A limitation with this argument, however, is the speed in which decisions and actions are made, often do not lend themselves to such lengthy processes. However, information processing theory proposes that thought and action occurs in a systematic way and this theory aims to make it clear how complex functions of the brain occur.

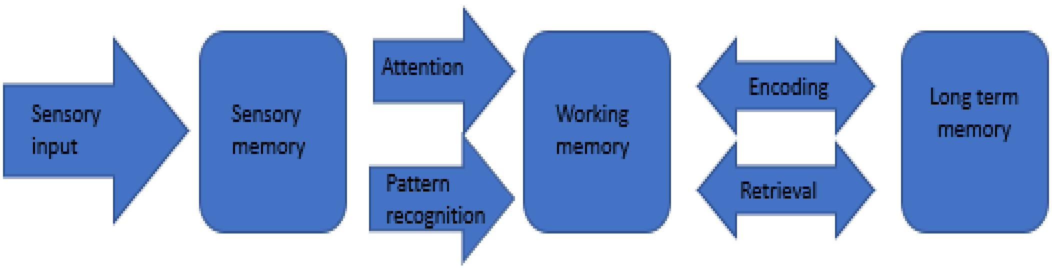

Figure 3 The information processing model (Gurbin, 2015).

The initiator of information processing is sensory input, this is viewed as being a system separate from EF and either present as unfiltered input or shaped for us in everyday activities and instruction (Zavitz & Price, 2019). Such stimulus activates the nervous system and at an unconscious level, the sensory memory will distinguish between information that can be discarded, and relevant stimuli that needs bringing into the working memory for processing (Cowan & Morey, 2009). However, this theory does not fully explain why some actions would happen at an unconscious level and others would be at a conscious level.

Information processing theory proposes that it is the attention span that will determine whether there is a concentration of information from one source or multiple sources (Oberauer, 2019). A key component of information processing theory is pattern recognition in which there is a connection between the incoming stimuli and existing knowledge stored in memory (Mattson, 2014). Information processing theory, however, potentially relies too heavily on actions happening because of the information stored in memory. It is suggested that the working memory space that brings new and existing information together, where information will be encoded into memory and stronger connections mean it will transfer to long term memory (Loaiza & Souza, 2024). Retrieval is the process of accessing information that has been previously stored and is now needed by working memory for the current task. One of the biggest challenges to this theory is that the metaphor of a computer implies a universality of EF, however it remains a dominant theory in cognitive science that has had influence and overlap with multiple fields including motor learning.

In motor learning, information processing theory is presented in several ways; one of which is the view that EF during movement is the processing of schemas stored in memory that mean movement actions are pre-programmed. Schemas are representations stored in memory of the general characteristics of actions that can be drawn upon to execute a movement (Gottiwald et al., 2023). However, this theory does not fully explain how a child can complete an action, that they have never tried before on the first attempt. According to schema theory (Schmidt, 1975), movement is produced by a generalised motor program which is a set of motor commands including the order of sequences, timing and forces to be generated (Wulf, 2013). The general motor program stored in memory will function for movements that have a pattern that is completely fixed. The theory has been challenged on this point because it appears the suggestion is too simplistic to account for movement in more complex situations (Shea & Wulf, 2005). However, the theory was welcomed because it provided a more efficient account of the cognitive functioning that determined movement when compared to the work of earlier theorists such as Adams (1971) closed loop theory. Information processing theory proposed that the 'recall schema' scales the generalised motor programme and governs the relationship between parameters and outcomes so that patterns of actions can be changed and adjusted to suit the situation. This is understood to require a systematic approach to planning stages of constant practice, for example hitting a forehand in tennis multiple times in the same way, carefully balanced with sequential steps of variable practice which would introduce different speeds of ball for the same forehand shot for example.

Anson et al. (2005) propose that as well as Schmidts (1975) schema theory, Fitts' three-stage model of motor learning also reflects the information-processing approach. The three stages describe gradual changes to the nature of information processing (Button et al., 2008). The first stage is called the 'cognitive stage' where the child tries out different movement configurations, making lots of errors and variable movements. In the second stage, called the 'associative stage' movements are more consistent and the movement patterns have been refined. The final stage is where information processing abilities have been acquired, it is called the 'autonomous stage' because the learner can perform a movement with minimal mental effort. Perceptual-motor information is represented in the central nervous system and used effectively. However, a challenge to this view is that autonomous movement would be inflexible and devoid of influences that are so changeable on a situation-by-situation basis. Skilled performers have been reported to have significant variability in their movement performance which, does not imply the reduced mental effort that the autonomous stage infers (Gray, 2023). Weaver (2015) reported that different parts of the brain are activated during the three-stage model of motor learning, rather than it be a consolidation of a specific neural network. However, a criticism of the experimental design used by Weaver (2015) is that a visual-motor task on a computer was used rather than a gross motor task that had greater movement expectations. The next section of the thesis will discuss motor skills association with EF.

The association between motor skills and executive function

Importantly, numerous systematic reviews and meta-analyses provide evidence for the increased benefits of motor skill learning on EF (Van Der Fels et al., 2015; Zeng et al., 2017; Gandotra et al., 2021; Tomporowski & Pesce, 2019). A review of 21 studies by Van Der Fels et al. (2015) showed evidence of positive associations between motor skill and EF that ranged from weak to strong. The strongest associations observed were between EF and fine motor skills, bilateral body coordination and timed performance (Van der Fels et al., 2015). The weakest association with EF was strength, agility and balance. It is suggested that is because there is a difference in the cognitive demand between different types of motor skills (Van der Fels et al., 2015). However, there is debate in the literature as to which motor skills create the most cognitive demand because other research reports that gross motor skills have the strongest association with EF (Shi & Feng, 2022; Fathirezaie et al., 2022). A criticism of Fathirezaie et al. (2022) experimental design was that they used a rating scale to assess EF, it is reported that rating scale measure of EF assess different underlying cognitive functioning (Toplak et al., 2013) and so may be less valid in comparison to performance-based assessments. The review by Shi and Feng (2022) would have been more robust if they had differentiated by age groups because it could be that when comparing younger children to older children, there is a different effect of each motor skill. In a study of 394 children aged 4 years, a comparison between locomotor and object control skills (assessed using the Test of Gross Motor Development (TGMD-2)) and EF (assessed using the NIH toolbox) found that locomotor skills were significant predictors of inhibitory control and working memory, whereas object control was only a significant predictor of inhibitory control (Han et al., 2022). The study by Han et al. (2022) would be more rigorous if it included longitudinal data because the impact of object control and locomotor skills could change as children get older. In addition, a meta-analysis of 32 studies by Gandotra et al. (2021) also found a contrasting finding to Van der Fels et al. (2015) because they reported that balance had the strongest association with EF. The suggestion that different types of motor skills have varying influence on EF could be due in part to differences in the assessment of motor skills. For example, a review by Griffiths et al. (2018) reported that a commonly used assessment tool, the TGMD may be measuring a slightly different construct than the other seven assessment tools that they compared in their review. They suggest it could be because other assessments include balance and fine motor tasks, or it could be because the TGMD criterion assesses the quality of the movement instead of satisfactory completion of the task (Griffiths et al., 2018).

A further finding in Van der Fel et al. (2015) review is that the relationships between EF and motor skills were stronger among younger children (under the age of 13 years). This is supported by other studies that report there is a shared, accelerated development of motor skills and EF in infancy and childhood (Kim et al., 2018;

Adolph, 2008; Davis et al., 2011). However, a criticism of the experimental design by Kim et al. (2018) was that only one subtest was used to test attention rather than all constructs of EF which prevent comparability with other studies that have measured each construct of EF. A limitation of the Davis et al. (2011) study was that it used a total composite score of motor skill which may not make the study directly comparable with studies that have assessed each type of motor skill. An alternative explanation is that certain motor skills will activate shared parts of the brain responsible for both motor and EF and this is most prominent in early childhood when development is accelerated (Shi & Feng 2022; Diamond, 2000). The studies reviewed so far however, have not reported this based on primary research.

Among young children aged 2-6 years, another review reported a negative correlation whereby stronger motor skills related to lower EF (van der Veer et al., 2022). However, the strength of correlation was reported to be weak to moderate (-.285 to .761). The authors may have discovered this finding because of the varying experience of movement children will have in their preschool years and in the first few years of school (Cook et al., 2019). It is essential to understand whether a focus on FMS has the largest effect on EF when compared to other types of movement. Despite experiences of deprivation and subsequent poor levels of motor skill and lower levels of PA, a cross-sectional study in South Africa with preschool children found a significant relationship between motor skills and EF, but not between EF and PA dose (Cook et al., 2019). A criticism of the experimental design in the Cook et al. (2019) study was that they only had 127 participants, limiting the generalisability of the study findings.

In previous research, the measurement of motor skill proficiency reflects a standardisation of outcomes needed to monitor the expected achievement levels in

FMS competence by children aged 7 years (Bolger et al., 2020). In a review that compared seven different assessment tools, it was found that there was some consistency of the items included in each test (Griffiths et al., 2018). For example, for locomotor, tasks such as running were consistently included and throwing and catching for object control; some included balance tasks such as standing on one leg and some included strength assessments (Griffiths et al., 2018). Similarly, a review by Hulteen et al. (2020) identified 57 different skill assessment tools, with the most used tasks being the throw, catch, jump and hop. The TGMD-3 is commonly used to assess motor skill, it assesses 13 fundamental locomotor and ball skills (Ulrich, 2013). When using a motor proficiency assessment, a child is measured against how well they conform to an optimal movement template of each skill in isolation, in a closed environment, based upon the verbal and visual example given by a trained instructor (Ulrich, 2013). As a child grows, the measurement of motor skill proficiency is an important outcome that needs to be carefully assessed; ensuring there is an understanding of process-oriented functional outcomes of movement (Adolph, 2019). There are assessments which have quantitative, product outcome scores that are easier to score and less time consuming, such as measuring the distance hopped (Hulteen et al., 2020). Process oriented assessments that determine whether technique criteria are present or absent requires more training of administrators (Hulteen et al., 2020). There have been some hybrid assessments developed that combine both process and product scoring, however, there remains to be a "gold standard" measure (Hulteen et al., 2020).

A difference between motor skill assessments is the administration time, the TGMD and MAND (McCarron Assessment of Neuromuscular Development) are reported to take 15-20 minutes to complete per participant whereas other assessments require 20-60 minutes (Griffiths et al., 2018). When compared to other assessments, the TGMD-2 and 3 are reported to have the most support for validity and reliability in children aged 2-12 years (Hulteen et al., 2020; Griffiths et al., 2018). Griffiths et al., (2018) reported that the Bayley-III (Bayley scale of infant and toddler development), BOT-2 (Bruininks Oseretsky test of motor proficiency) and PDMS-2 (Peabody developmental motor scales) have excellent test-retest reliability and the MABC-2 (movement assessment battery for children) and TGMD-2 have good to excellent test-retest reliability. Hulteen et al. (2020) concurred that the TGMD second and third edition have the best reliability when compared to 57 assessments in 107 studies, confirming that they are the best available instrument however, training of the administrators is critical. Newer assessments such as the Canadian Agility Movement Skill Assessment that does combine a process and product score may be more appropriate with an adolescent sample (Hulteen et al., 2020). The next section of the thesis will discuss motor skill interventions that support EF.

Motor skill interventions that support executive function

In an insightful review by Moreau and Conway (2013), it is proposed that integrating complexity, diversity, and novelty into the design of motor skill learning programmes will challenge EF and increase the likelihood of transfer to everyday tasks. Research shows that young children in particular respond well to interventions focussed upon improving motor skills (Malambo et al., 2022; McClelland & Cameron, 2019). However, there needs to be further investment to set up evidence-based motor skill interventions in education settings to promote FMS, especially in areas of deprivation (McClelland & Cameron, 2019; Foulkes et al., 2015).

Previous interventions successfully employed a wide variety of strategies to improve motor skills to enhance EF (see Table 3). One way of differentiating between the different types of intervention is to compare interventions focussed solely on fundamental skills or those that combine the practice of motor skill with an academic activity such as storytelling (Jylanki et al., 2022). Combined movement and storytelling interventions are emerging as a way of improving multiple skills across both the motor and cognitive domain (Vargas-Vitoria et al., 2023). The concept involves using story-book theme to introduce a movement pattern that relates to a character, for example jumping and leaping to the theme of a mouse or and owl as in The Gruffalo storybook (Duncan et al., 2019). In comparison, those interventions that focus on FMS only, will often cover the full range of fundamental skills by following a scheme that runs through locomotor and object control skills.

The interventions for 3-7-year-old children can be implemented across one week to one academic year and can also vary in duration from five minutes to three hours (Jylanki et al., 2022). The intervention studies range from up to 30 children to 240 children most often working with primary school aged children (4-11 years). The interventions most often tend to be atheoretical, although there are some that detail the theory upon which they are planned, for example the SKIP motor skill intervention by Mulvey et al. (2018) was underpinned by Newell's constraint theory. There is, however, limited intervention research which compares the effect of different theoretical approaches.

Another way of differentiating between intervention type is a focus on gross motor skills as opposed to fine motor skills. It has been suggested that specifically gross motor skill interventions support the development of working memory (Gandotra et al., 2021; Diamond & Ling, 2019). Gross motor skills can also be linked to outdoor play and the reported benefit to cognitive functions (Koepp et al., 2022). Another approach to detailing motor skills is open and closed skills. A review by Gu et al. (2019) and Heilmann et al. (2022) found that open skill exercise had a greater effect on EF. This is proposed to be because open skill exercise include sports such as tennis, basketball or boxing where the environments are unpredictable, and the task requires active decision making (Gu et al., 2019). There is an argument that exists in the literature between researchers as to whether all PA interventions inherently challenge motor skills to some degree, on a gradient of complexity (Hillman et al., 2019; Best, 2010). Research continues to try to pinpoint a specific mechanism rather than accept the association between movement and cognitive function is only because of a shared period of rapid development at school age (Wassenberg et al., 2005). The next section of the thesis will discuss exploratory movement.

Table 3 Primary school physical education intervention studies that focussed on motor skills to enhance executive function

Study & Country	Sample & Baseline age	Intervention description	PE Intervention Duration	EF Assessment Method	EF and motor Skills Outcomes
Mulvey et al (2018), USA	107 children, Mean age = 5.14 years	SKIP motor skill intervention (theory based, Newell's 1984, 1986 constraint theory & Brian et al. 2017). The tasks were divided into locomotor and object control skills. There were in-task variations to meet the needs of individual children. Each child had their own equipment to maximise the amount of practice trials.	Twice a week for 6 weeks, 30 minutes per session	Whole construct measure of EF: Heads, Shoulders, Knees and Toes task.	INT>CONT Motor skills improved pre and post-test in the intervention group η^2_p= 0.38 EF improved pre and post-test for the intervention group η^2_p=0.058
Hudson et al 2020, USA	53 children, mean age 4.3 years	The curriculum included object control, locomotor, stability, balance and bilateral coordination in a small-group setting and individual needs were met using	Twice a week for 8 weeks, 30 minutes per session	EF Touch computer battery test, 3 inhibitory control tasks, two working memory tasks and one attention shifting	INT>CONT

		games-based activities (atheoretical)		task to construct overall EF score	Small to moderate increases in motor skills (Cohen *d* = 0.29) and EF (Cohen *d* = 0.41)
Lee et al 2020, USA	31 children age 6.65±0.98	Intervention focussed upon the mastery of 12 motor skills, participants divided into groups dependent on competence and the sessions involved cooperative and self-competition games, independent and goal-driven activities (atheoretical)	Three times per week for 8 weeks, 60-minute sessions	Whole construct measure of cognitive functioning using the Paediatric quality of life inventory Cognitive Functioning Scale for children aged 5-7 years	INT = CONT Significant changes in motor skill (η^2= 0.6) but not in cognitive function (η^2= 0.005) between the intervention and control group over time
Sanchez-Lopez et al. (2018), Spain	240 children aged 5-7 years	MOVI-KIDS Intervention included three blocks of sports games, dance and motor skills (theoretical, socioecological model, Bronfenbrenner, 1992)	Three sessions a week for one academic year, 60-minute sessions	Whole construct score of cognitive performance using the Battery of General and Differential Aptitudes for schoolchildren aged 6-8 years	INT>CONT All cognitive variables were significantly higher in children in the intervention when compared with control (ES 0.33-0.87)

Stein et al (2017), Germany	102 children, aged 5-7 years	4 coordinative exercises including jumping and running in different combinations, balancing on a rope, bouncing a ball, throwing balls and kicking balls at targets. There were 5 levels of difficulty that the children progressed (atheoretical)	25-minute sessions	Motor inhibition assessed using Simon Says task; Cognitive inhibition and shifting assessed using the hearts and flowers task	INT = CONT
Xiong et al (2017), China	40 children, mean age 4.67 years	The intervention replaced break time and involved practicing FMS and applying them in games and activities (atheoretical)	30 minutes daily for 3 months	Whole construct assessment of EF: Sorting Task	INT>CONT A significant group effect for EF ($\eta^2 = 0.46$)

Exploratory Movement

Previously in the literature, exploratory movement has been discussed under the umbrella term motor creativity. A challenge of the term motor creativity is agreeing an intelligible definition that is not negatively affected by the cross disciplinary use and purpose. Creativity is associated with the notion of ‘original ideas’ (Guildford, 1956; Orth et al., 2017) and this could be limiting for a discussion of exploratory movement because so often movements are ‘repetitive’, which could by definition lack originality, but this does not necessarily mean, the movement has not got important qualities that need to be measured. The definition of exploratory movement capability will require a criterion upon which it can be observed and measured, again this is viewed as a challenge that could explain why associated terms such as motor creativity is often underreported in the literature (Orth et al., 2017). Rather than the term ‘original’, another way of viewing a concept such as exploratory movement capability is the ‘variation in ideas’ (Orth et al., 2017). This can be captured by assessments such as the Divergent Movement assessment designed by Clelland (1990), which measures variation using two criteria: (1) fluency - the number of different movement responses and (2) flexibility - the number of changes in body position for the same movement response. Children are asked to move and play in as many different ways as they can in 3 task spaces: one of which has a bench to encourage making different shapes with their body; the second task is a locomotor station that has different equipment set up for the children to explore; and in the third task, children are given a ball to play with a semi-circle coned area against a wall (Clelland, 1990). Rather than the traditional view that movement is an expression of an idea generated in the mind, such an exploratory movement assessment focuses on contextual characteristics. This assessment aims to show how exploratory movement is underpinned by the interaction between individual, task and environment to constrain possible solutions. A related definition to this view of exploratory movement is the ability to adapt, attune and combine motor skills, creating functional and original solutions to emerging motor problems (Vasilopoulos et al., 2023; Oppici, Frith & Rudd, 2020; Rudd et al., 2020).

Children often thrive in environments where they can explore and regulate their own actions. A child's thoughts about the task, their body position and gaze towards a stimulus array during movements are unique to an individual child; exploratory movements put the child "in charge of the task they are performing" (Oppici, Frith & Rudd, 2020; Vasilopoulos et al., 2023). Accordingly, such moments of independence and connection to a context, empowers a child to challenge and develop further the 'sense of fit' between their internal dynamics and the task and environment dynamics. For example, a child's independence and connection to music can be encouraged during dance shown to improve working memory (Vasilopoulos et al., 2023; Oppici et al., 2020).

Exploratory movement is likely to be mediated by the concurrent development of motor skills (Tocci et al., 2022; Pagona & Costas, 2008). Although there are some studies that report no association between motor creativity and motor skill proficiency (Marinsek & Lukman, 2022). Sample sizes are small in these studies and future research is required. Another important association is that a child's motor creativity has been shown to be associated with cognitive function (Vasilopoulos et al., 2023; Tocci et al., 2022; Scibinetti, Tocci & Pesce, 2011). There is, however, a limited amount of cross-sectional research examining the association between exploratory movement and EF; substantially more has looked at the intervention effect of motor creativity. Vasilopoulos et al., (2023) reviewed 92 studies focussed on children aged 5-12 years old and used a criterion to identify whether an intervention was 'fostering creative PA’: 1) if the activities were varied; 2) relied less on instruction or demonstration; 3) involved open spaces, resources or open-ended instruction; 4) involved interaction with others. They found that the levels of ‘creative PA’ varied greatly and did not have an association with EF (Vasilopoulos et al., 2023). However, other studies reported an association between motor creativity and specific EF. Tocci et al. (2022) compared traditional PE with a 6-month enriched PE intervention and found improvements to motor creativity that were mediated by improved inhibitory control. A challenge of this field of literature is that there are so many varied assessments and intervention types. Another study reported a similar finding that following a 3-month ‘creative programme’ underpinned by Nonlinear pedagogy, finding an increase in motor creativity and cognitive functions when compared with traditional PE (Richard et al., 2018). Although the measure of EF was divergent thinking using the Runco Creative Assessment Battery rather than a validated assessment of EF. A study using a creative dance intervention also reported specific improvements to inhibitory control and working memory (Oppici et al., 2020). The next section of the thesis will discuss the association between PA and cognitive function.

Physical activity and executive function

PA is defined as ‘any bodily movement, produced by skeletal muscles that results in energy expenditure (Caspersen et al., 1985). A body of the movement and EF literature pinpoints the biochemical mechanisms of PA volume and intensity to improve cognitive function. It is proposed that short bursts of PA are thought to prime the central nervous system due to immediate neurochemical changes to dopamine, adrenaline and noradrenaline; it has been reported that a behavioural effect occurs whereby children's allocation of attention improves (Best, 2010; Ferris, Williams & Shen, 2007; Verburgh et al. 2014; Ishihara et al., 2021). Another suggestion of a physiological response to PA was presented in an influential study using neuroimaging, that showed an increase of blood flow to the shared brain area (pre-frontal cortex) responsible for movement and EF following a low-level intensity activity of walking for 20-minutes; participants (children aged 9.5 years) demonstrated improved flanker test scores after the activity (Hillman, 2009). However, this result was based on 20 participants, despite this, the results are used widely in promotional material in the UK about the benefits of PA on EF. Other studies show contrasting results to the finding that low-level intensity is beneficial to EF. Using accelerometery, McNeill et al. (2018) report a positive association when replacing light intensity with vigorous intensity to improve EF. That said, it is reported moderate intensity is as beneficial as vigorous intensity on cognitive outcomes (Moreau & Chou, 2019). However, reviews consistently report a small effect size of moderate and vigorous intensity PA on cognitive functions across a wide age-range of participants (Wang et al., 2023; Erikson et al., 2019; Meijer et al., 2020; Ludyga et al., 2016, Moreau & Chou, 2019). The effects of vigorous PA on cognitive functions have been tested using activities such as high-intensity interval training (HIIT) which, involves brief intervals of activity that will increase the participants heart rate above 85% of maximum and short periods of low intensity PA of rest (Reyes-Amigo et al., 2022). A meta-analysis reported that there was some beneficial effect of vigorous PA only to working memory (Reyes-Amigo et al., 2022). Most studies of vigorous PA, however, are often carried out with older children above the age of 9 years. A more common measure of PA that would be expected in research with younger children would be an assessment of moderate-to-vigorous physical activity (MVPA) because the daily guidelines set that children aged 5-17 years should complete an average of 60-minutes MVPA per day for healthy growth and development (WHO, 2020). A study of 283 children aged 4-5 years compared motor skill and MVPA with EF and found that motor skill had the stronger correlation with EF than MVPA (Willoughby et al., 2021). There is limited literature on the association between MVPA and EF in typically developing children.

Exercise is ‘a subset of PA that is planned, structured, and repetitive and has as a final or an intermediate objective the improvement or maintenance of physical fitness (Caspersen, 1985). Another comparison that is made in the literature is comparing acute exercise consisting of a single bout of exercising lasting 10-60 minutes with chronic exercise interventions which last more than 4 weeks in duration, involving multiple sessions per week (Liu et al., 2020). In a meta-analysis, Liu et al. (2020) reported that among children and adolescents both acute and chronic exercise are beneficial to the development of EF. This finding is supported by Li et al. (2020) and de Greef at al. (2018), who suggest that frequency and duration are the features of chronic PA interventions that benefit EF, rather than the characteristics of the intervention. However, Liu et al. (2020) reported a larger effect size for chronic exercise interventions that focussed on one activity or sport in children aged 5-18 years (e.g., football, tennis, yoga). This is supported in a meta-analysis by Contreras-Osorio et al. (2021) who reported large effect sizes of sport-based interventions on each of the EF. Another study compared aerobic exercise with yoga and found that the group that did yoga performed significantly better on the EF tasks than the aerobic exercise group (Gothe et al., 2013).

A cumulative effect of aerobic exercise is also understood to lead to changes in fitness and this is reported to have a larger effect on EF because of the increase in blood flow and development of new blood vessels in the brain area responsible for EF and motor functions (Hillman, 2009; Van Waelvelde et al., 2019; Donnelly et al., 2016; Moreau & Chou 2019; Nieto-Lopez, 2020; Diamond, 2000; Xue et al., 2019). The review by Donnelly et al. (2016) reported that fitness is associated with EF, independent of most confounding variables. In a cross-sectional study of 130 children aged 9-13 years, it was found that physical fitness mediated the association between PA and EF (Muntaner-Mas et al., 2022). In younger children (261 participants aged 5-6 years), physical fitness was positively associated with inhibitory control and working memory, but not cognitive flexibility (Veraksa et al., 2021).

To evaluate the effects of PA interventions and understand the association with EF, accurate measurement of PA is needed. To measure the association with EF, PA is commonly broken down by intensity, timing and total duration; as well as measures of children's fitness and exercise (Alvarez-Bueno et al., 2020, Donnelly et al., 2016). Future work needs to establish whether the quantity of PA is associated specifically with EF by including a broad range of PA intensity, duration and total profile measures (Fairclough et al., 2019). Previously, a common measure to assess different dimensions of PA in children is accelerometry and there is a sizable amount of literature reporting its validity and reliability (Phillips et al., 2021; Lynch et al., 2019). Accelerometers were predominantly worn on the right hip, however evidence demonstrated better compliance to wear protocols when children and adults wear the devices on their wrist (Fairclough et al., 2023; Fairclough et al., 2016). Activity logs are needed alongside the wearing of an accelerometer to inform decisions about non-wear time. To identify non-wear time, 10-60 minutes periods of consecutive zeros have been used to make decisions about what data to include or exclude from the final analysis (Ridgers & Fairclough, 2011). However, there is no set criterion to identify partial non-compliance, it has been suggested that as little as three hours wear time a day enables reliable estimates of activity in young children (Ridgers & Fairclough, 2011). However better compliance improves the representativeness of actual daily PA (Fairclough et al., 2016).

The data from the accelerometer is processed and threshold are applied, often referred to as cut-points to classify acceleration signals into absolute intensities (e.g. inactive, light intensity, moderate intensity and vigorous intensity). There are, however, inherent issues when deploying cut-points within each age group and using data derived from different accelerometer brands to identify the different PA intensities (Rowlands et al., 2019). There has been a move to change from 'proprietary accelerometer metrics’, to potential device-agnostic raw acceleration ‘data-driven metrics' (Fairclough et al., 2023). Most of the studies reporting PA outcomes using raw accelerations have used the Euclidean norm minus one (ENMO) metric (Fairclough et al., 2019). There are challenges when analysing raw signals because there needs to be a procedure to separate the movement and gravitational components of the signal (Bakrania et al., 2016). ENMO does not require the data to be filtered to correct for gravity because it systematically takes this into account within their algorithm (Bakrania et al., 2016). A statistical package called GGIR has been developed to calculate the ENMO metric (Bakrania et al., 2016; Hildebrand et al., 2014). ENMO data can be classified into time spent in moderate-vigorous PA using age-appropriate validated cut-points (Crotti et al., 2020). However, again the use of cut-points with raw data causes issues when interpreting the data and requires further calibration studies (Crotti et al., 2020). It is crucial that future research can interpret activity levels, including those meeting PA guidelines using continuous raw acceleration data (Fairclough et al., 2023). Data on children meeting PA guidelines would broaden the view of PA mechanisms and the association with EF, by relating to longer-term morphological and functional changes in the brain rather than immediate neurochemical and physiological changes (Best, 2010). This level of theoretical neuroscience model testing requires a measure which, enables large-scale future comparison across datasets (Moreau & Chou, 2019; Fairclough et al., 2023).

Rather than just reporting moderate-to-vigorous intensity PA which, is the small proportion of cut-point derived PA, another measure using raw acceleration data is intensity gradient, it reflects the entire intensity profile and can be used in combination with average acceleration which is a measure of activity volume (Fairclough et al., 2019). Intensity gradient and average acceleration will indicate whether volume and intensity have an independent or an interactive effect on a variable under investigation, as previously used in health literature (Rowlands et al., 2019). The next section of the thesis will discuss qualities of PA in schools that enhance EF.

Qualities of physical activity in schools that enhance executive function

Often within the life of a school, the pursuit of developing EF and subsequent academic achievement, is at the expense of children's time doing PE (Garcia-Hermoso et al., 2021). However, research has indicated that there is no evidence that time spent doing PE has an adverse effect on academic attainment and there is literature which supports the view that PE and/or daily PA can have a positive effect on the development of EF (Garcia-Hermoso et al., 2021). A goal of PE curricula is to foster a health-enhancing level of PA (Kolovelonis & Goudas, 2022). This objective has evolved to include overall physical, social, emotional and cognitive development (Gov.UK, 2024) and there are many PE interventions designed to enhance EF that have been implemented in schools (Garcia-Hermoso et al., 2021). PE takes many forms, sometimes the focus is on the amount of PA, other times the focus shifts to developing motor skills, for example. PA interventions can sometimes be delivered outside of scheduled PE sessions. In the PA intervention literature, there has been a shift from focusing solely on the "quantity" of PA to also understanding the "qualities" of PA, that can lead to improvements in multiple domains, including EF (Garcia-Hermoso et al., 2021; Kolovelonis & Goudas, 2022). Research on initiatives such as the Daily Mile and other aerobic activity interventions implemented in schools have shown that the quantity of PA on its own, may not enhance EF (Schmidt et al., 2015; Morris et al., 2019). It could be that a combination of PA intervention ‘qualities’ may be required to promote EF.

The features of ‘quality’ PA interventions in schools include diverse activities such as those that are 'coordinatively demanding' and require 'non-automated sport related activities' (Schmidt et al., 2015; Best, 2010; Diamond & Lee 2011). In a study, the qualities of the intervention included the development of FMS, bodily expression and deliberate play; tennis was used as the focus of skill development (Crova et al., 2014). This was delivered as a two-hour skills-based and tennis-specific training programme in addition to the one-hour PE curricular. They found the intervention had a greater effect on EF than the control group who continued with the one-hour PE curriculum (Crova et al., 2014). In a review of 35 studies by Jylanki et al. (2022), it was reported that both motor skill and PA dose improved EF and that the effects were larger in combined (i.e. dose + skills) interventions for typically developing 3–7-year-old children. However out of the 35 studies, 24 studies were judged as being methodologically weak. An overlap between PA dose and motor competence cannot be assumed as an inherent characteristic of children’s PA interventions in school that improves EF without further empirical evidence identifying shared variance (Hillman et al., 2019).

Whilst the literature suggests that not all types of PA may be beneficial to EF, there is a focus on the qualities of PA that can ensure a level of 'cognitive demand', 'cognitive challenge' or be, 'cognitively engaging' (Song et al., 2022). One description of cognitively engaging interventions is that they last longer than 35 minutes and use sports such as basketball to improve EF performance (Song et al., 2022). Sport interventions are thought to bring together a set of characteristics that will promote the development of EF (Contreras-Osorio et al., 2021; Contreras-Osorio et al., 2022; Bidzan-Bluma & Lipowska, 2018). This is because they include unpredictable and changing environmental situations, requiring decision-making and goal focused behaviours that are viewed as cognitively demanding features of PA (Contreras-Osorio et al., 2022).

There are many descriptions of cognitively challenging PA that promote EF, another of which is that the interventions should promote children's discovery within a context that is constantly changing and requiring unpredictable sequences of action (Schmidt et al., 2015). A recent study compared two groups of children, one group who followed a PA program that focussed solely upon energy expenditure and fitness, with a second group who were expending energy in challenging conditions that presented novel and unpredictable tasks which required problem solving (Kolovelonis & Goudas, 2022). The children had to come up with multiple solutions because the task environment including the rules of the game kept changing (Kolovelonis & Goudas, 2022). Both groups showed an improvement to EF when compared to the control group who did no PE, and the second cognitively challenging group improved to a greater degree than the fitness focussed group (Kolovelonis & Goudas, 2022). The next section of the thesis will discuss Linear pedagogy underpinned by motor learning theory.

PE Pedagogy underpinned by motor learning theory

Linear Pedagogy

The focus of a traditional approach to PE termed ‘Linear pedagogy’ is based upon information processing theory and the view that children’s motor learning is a process of acquiring internal motor representations of universal, ideal movement patterns that are stored in the brain ready for movement execution (Fitts & Posner, 1967; Schmidt, 1975). Linear pedagogy works on the premise that increasing the number of times a motor skill is repetitively practiced in a sequential approach, enhances success in becoming an expert. Linear pedagogy has a traditional view that a child is reliant on a practitioner to learn the skill through their instruction and modelling of an optimal movement pattern (Valeh et al., 2020). To reduce cognitive load, Linear pedagogy involves a teacher-centred approach of encouraging an external focus of attention, for example an instruction about the supporting foot’s position on the floor leading into a kick (Crotti et al., 2022). Instructions and feedback aim to reduce random variability and instead, focus on achieving ideal movement patterns (Orangi et al., 2021). The focus is on the repetitive practice of drills which, follow a set sequence that aims to aid a child to gradually increase their mastery of each part of the skill. By sequentially increasing the difficulty of the skill, there is a linear learning progression through cognitive stages (cognitive, associative, autonomous) that indicate a reduction in cognitive processing as movement proficiency increases (Fitts & Posner, 1967).

Information processing theories, also called cognitivist theory aim to explain cognitive processes once information has been received and these processes serve as the basis for understanding human behaviour (Salkind, 2005). Cognitivist models are often presented as a step-by-step of processing information, one of the earliest models was encoding, retaining and retrieving by Miller in 1956 (Salkind, 2005). Miller (1956) was one of the first researchers to compare the human mind and its processing to a computer whereby the human brain takes in 'information, performs operations on it, changes its form and content, stores and locates the information and generates output' (Salkind, 2005). Parts of the information processing theory was used to explain motor skill performance, for example the decisions made by a performer were represented as a model of coding, storing and using information (Schmidt & Wrisberg, 2008). This view was built upon a substantial amount of literature that detailed movement skill classifications and categorised skills dependent upon the amount of motor and cognitive skills required (Schmidt & Wrisberg, 2008). Learning was categorised through a comparison of early-stage skill development and when performance becomes more accurate and consistent. The challenge point framework and gentile's taxonomy are examples of methodologies to design learning progressions of increasing difficulty within a Linear pedagogy approach (Valeh et al., 2020). The next section of the thesis will discuss Nonlinear pedagogy underpinned by motor learning theory.

Nonlinear pedagogy

The focus of Nonlinear pedagogy is the development of the relationship a child has with their environment through a child-centered approach to delivery (Vasilopoulos et al., 2023). The development of motor skills is viewed as being individual to each child and fostered through exploratory behaviour (Chow, Komar & Seifert, 2021). The role of the practitioner is to design activities that promote exploration of different movements in contexts that are representative of different sports performance situations. (Chow, Komar & Seifert, 2021). Once the task is set up, a key element of Nonlinear pedagogy is to employ a Constraints-Led Approach whereby task constraints that include the goals, rules and equipment, can be manipulated by the adult to encourage the children to explore different movements (Renshaw & Chow, 2018; Button et al., 2020; Chow, Komar & Seifert, 2021). The environment (e.g. equipment and space) is another constraint that can be manipulated to guide children to explore movements they can exploit as individuals (Chow, Komar & Seifert, 2021). The learning of new movements is not directed by an adult, but rather through the reciprocal interaction between the individual, environment and task constraints (Button et al., 2020). The opportunity for a child to be physically active when navigating an enriched environment engenders new ways to learn and adapt on a number of synergistic levels (Adolph & Hoch, 2018).

Nonlinear pedagogy is based upon ecological dynamics which, is a scientific framework that brings together ecological psychology and Nonlinear dynamics (Chow et al., 2021). Ecological dynamics views a child as a complex neurobiological system that has a mutual and reciprocal synergy with their environment (Chow et al., 2011). To account for the nonlinearity of human movement systems in the pedagogical approach of practitioners, skill acquisition needs to be understood as the 'development of a functional performer-environment relationship' (Chow et al., 2021). As opposed to Linear pedagogy which, views the adult as the guide, Nonlinear pedagogy promoted the idea that the information an individual child needs comes from their environment (Chow et al., 2021). The coordination of a movement skill varies dependent upon the context in which it is emerging, that can be different every time the skill is performed (Chow et al., 2021). A skilled behaviour is the functional movement solution that achieves the task goal, rather than the repetition of a set movement pattern (Chow et al., 2021). A key goal of Nonlinear pedagogy is the children become able to regulate their own learning experiences whereby they are able to thrive in dynamic environments which, are full of uncertainty, meaning and complexity (Chow et al., 2015).

A key principle of Nonlinear pedagogy that differs from traditional practices of highly repetitive training sessions is the role of variability. Variability in a complex adaptive system can be functional because it allows movement goals to be achieved in multiple different ways (Chow et al., 2015). Therefore, the term variability describes an individual's ability to adapt movement patterns and flexibly achieve movement solutions to solve problems in unpredictable environments and acquire the control that is essential to meeting the same goal multiple times (Chow et al., 2015). There has been a number of studies of expert performers that show they repeat a movement with greater variability than a novice (Gray, 2023; Bernstein, 1967). From a Nonlinear perspective, when learning a new skill, there can be an impact on the performance of other skills because of the intrinsic dynamic of competition between new and existing coordination states that can go through plateaus, progressions and regressions (Chow et al, 2015). A critical aspect of Nonlinear pedagogy is the need to help learners with their field of affordances, whereby a child is channelled to multiple different patterns of movement (Chow et al., 2015). Through a process of parametric control and scaling task constraints for example, directs the child to explore the functionality of different movement patterns.

Literature review summary

This literature review has highlighted that children living in an area of deprivation have low EF and self-regulation which are associated with academic performance and health outcomes. Interventions during Physical Education in primary schools may play a key role to developing EF and self-regulation. There are a number of different aspects to a child's movement that could form the focus of a school intervention including the dose of PA, motor proficiency and other movement qualities including exploratory movement. It was outlined that PE pedagogical approaches could have an impact, and it is important to explore the effect on EF and self-regulation.

Aim of this thesis

The overarching aim of this PhD thesis was to explore the influence of different aspects of movement on cognition among children aged 5-7 years living in an area of socio -economic disadvantage. This aim will be achieved through the objectives of each study included in this PhD.

Study 1 (chapter 3): Associations of physical activity dose and movement quality with executive functions in children aged 5-6 years living in an area of deprivation

- Examine how demographic factors are associated with executive function.
- Investigate the association of each measure of movement (physical activity dose, movement proficiency, exploration and production of divergent movement solutions) with executive function.
- Examine how the combination of physical activity and motor competence variables predict executive function.

Study 2 (chapter 4): The effect of physical education lessons underpinned by motor learning theory (SAMPLE-PE) on executive function: a cluster randomised controlled trial in 5-6-year-old children living in an area of deprivation.

- Examine the effect of Nonlinear or Linear pedagogy within PE compared to current PE delivery within schools on executive function of 5–6-year-old children living in an area of deprivation

Study 3 (Chapter 5): The effect of physical education lessons underpinned by motor learning theory (SAMPLE-PE) on self-regulation: a cluster randomised controlled trial in 5-6-year-old children living in an area of deprivation

- Examine the effect of Nonlinear or Linear pedagogy within PE compared to current PE delivery within schools on self-regulation of 5–6-year-old children living in an area of deprivation

Ethics

The World Medical Association developed the Declaration of Helsinki which, is a set of ethical principles that are to be used in research involving humans. Extra care and attention are to be taken when the research involves children. The statements include the following detail:

- It is the duty of the researchers to promote and safeguard the health, well-being and rights of participants (Statement 4 Helsinki Declaration). When working in the schools, the research team ensured the children were happy and free to ask questions throughout each task. The children were reminded of their right to opt out of the research activities. If a child disclosed any sensitive information, the class teacher was immediately informed and the school safeguarding policy followed.

- Research should protect the privacy and confidentiality of personal information (Statement 9 and 24 Helsinki Declaration). The personal information of the participants was stored on excel spreadsheets locked by passwords on the computer. To protect the anonymity of participants, each participant was given a code ID that was used in the analysis stages of the research.

- Research should only be conducted by researchers who have had appropriate training (Statement 12 Helsinki Declaration). The researchers were all trained by the supervisors prior to carrying out the assessments. For the intervention, the coaches took part in a 3-week training course that taught them how to conduct the intervention appropriately.

- All vulnerable groups should receive specifically considered protection (Statement 19 Helsinki Declaration). All research assistants entering the school to conduct the research had to present their Disclosure & Barring Service certification

- There should be a statement of ethical considerations. The trial is registered at ClinicalTrials.gov (identifier: NCT03551366) and received institutional research ethics committee approval (Reference 17/SPS/031).

- Informed consent must be sought and participation must be voluntary (Statement 25, Helsinki Declaration. Children, parents and the school provided informed consent once they had attended an information session and provided with an information booklet outlining the study.

Chapter 3 - Study 1: Associations of physical activity dose and movement quality with executive functions in children aged 5-6 years living in an area of deprivation.

Based on a paper published at Psychology of Sport and Exercise:

O'Callaghan, L., Foweather, L., Crotti, M., Opicci, L., Pesce, C., Boddy.L.M., Fitton Davies, K. & Rudd, J. (2023). Associations of physical activity dose and movement quality with executive functions in socioeconomically disadvantages children aged 5-6 years. Psychology of Sport and Exercise, 70(5).

Chapter Three (study one):	Objectives:
Investigate the associations of physical activity dose and movement quality with executive functions in children aged 5-6 years living in an area of deprivation.	• Examine how demographic factors are associated with executive function. • Investigate the association of each measure of movement (physical activity dose, movement proficiency, exploration and production of divergent movement solutions) with executive function. • Examine how the combination of physical activity and motor competence variables predict executive function.

Thesis Study Map

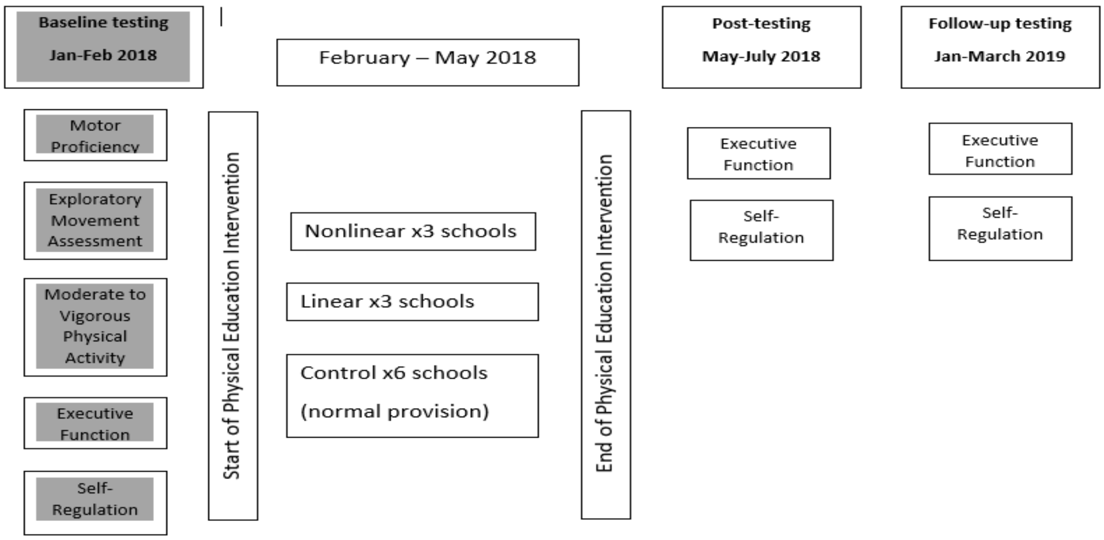

Figure 4 The design of study 1 within the RCT (greyed)

Introduction

Deprivation is multidimensional and encompasses more than just material and economic deprivation; it also leads to educational disadvantage 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 EF, 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 EF, 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 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 deprivation 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 EF 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 EF (Cook et al., 2019) and related self-regulation skills (Cook et al., 2019). Therefore, the PA-EF relationship in children appears to be more complex due to the moderation by deprivation, 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 1 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 EF (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 FMS (Bardid & Utesch, 2018). Its measurement mainly consists of predefined FMS patterns that children must reproduce (Hulteen et al., 2020, Bolger et al., (2020). In 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 FMS, 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 EF' 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 the associations of PA dose and movement quality with EF in children aged 5-6 years living in an area of deprivation: using three assessments of movement quantity and quality: PA dose, reproduction of FMS (movement proficiency), exploration and production of divergent movement solutions in an exploratory movement task and EF (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 an area of deprivation, which mostly considers the negative consequences of these disadvantages for PA levels (Chang & Kim, 2017), motor competence (Barnett et al., 2016), and EF (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 PE 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 Northwest England. This sample size was calculated for the broader project SAMPLE-PE (for details, see Rudd et al., 2020), and it provides 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 PA and motor proficiency with EF, with *shifting* showing the smallest association ($r2 = 0.181$; $\Delta r2 = 0.031$) (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 ($f2 = 0.038$), also in line with a recent umbrella review of RCTs showing small effects of PA on EF (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. This information was used to identify age, gender, special educational needs (SEN), ethnicity and deprivation decile., as measured by the Index of Multiple Deprivation (IMD). If information gathered from parents indicated that children had 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 PE (e.g., due to medical conditions) were excluded from data analysis.

Assessments Executive Functions

The NIH Toolbox is a comprehensive set of neuro-behavioural measurements that assess EF 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 EF, 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 center. 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 included 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 milli gravitational 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 (see Table 4).

Exploratory Movement

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 movements 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-hour 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 4 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 EF. 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 EF, 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 EF 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 EF 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 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, Moderate PA (MPA), Vigorous PA (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 PA 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 were used to pool the outputs of the regressions from the imputed data. Effect sizes were calculated using r2 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 (EF, n=335; exploratory movement, n=294; PA dose, n=262; motor proficiency, n=250). Table 5 includes the descriptive statistics for the demographic, EF, 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 (r2 = 0.12) and all variables but ethnicity were significant predictors (Table 6). Subsequent multiple regression analyses, whereby DMA, motor proficiency, MVPA, MPA, VPA, Intensity Gradient (IG), and ENMO were added individually to the previous model, showed that only DMA and motor proficiency were significant predictors of EF (Table 7). Further, r2 and the fit of the model improved only in the models with DMA (r2 = 0.19) and motor proficiency (r2 = 0.16), and not with PA variables. The coefficient and r2 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 EF (r2 = 0.23 and r2 = 0.235). While DMA and motor proficiency did not meaningfully change their coefficient, VPA and ENMO became significant predictors of EF (Table 7). In these models, all PA variables were negatively associated with EF, but only VPA and ENMO were significant predictors.

Table 4 Inter- and intra-rater mean intraclass correlation coefficients 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 5. Descriptive statistics of study variables

	M ± SD or %	Range	Normative data	Source of 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 6. Multiple regression analysis with demographic factors on executive function

	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 7 Multiple regression analyses with motor competence and physical activity variables added individually to the model. Executive function is the dependent variable of interest, and each row represents an individual model. All analyses were controlled for age, sex, deprivation decile, and special educational needs

	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 8 Multiple regression analyses with a combination of the motor competence variables, and motor competence with physical activity variables. Executive function is the dependent variable of interest. All analyses were adjusted for age, sex, deprivation decile, and special educational needs.

.

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)

Discussion

This study investigated the relationship between three assessments of movement (PA dose, motor proficiency, and DMA) and EF in children aged 5-6 years from an area of deprivation. 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 EF. However, the individual prediction by VPA and ENMO was nonsignificant, while both motor proficiency and DMA facets of motor competence were significant predictors of EF after controlling for demographic factors. Interestingly, among the two movement competence facets, DMA exhibited the strongest association with EF. 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 EF, aligns with previous research on the association between motor competence and EF in this age group of children (Van der Fels et al., 2015). The highest prediction of EF 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 deprivation 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 EF 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 EF 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, EF can be understood as integral to the reciprocity of a child's actions and explorations through specifying affordances in the environment (Gibson, 1988; Adolph, 2019; Raja, 2018; Lobo et al., 2018). In this framework, EF will be active in different ways for the same task as a child attunes to their environment, self-regulating functional movement behaviour (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 behaviour (Reed, 1988). It is at this intersection where higher-order EF 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 EF must also be discussed, as it does not support the body of previous studies reporting a benefit of a child's PA dose on EF (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 EF, which restricts comparisons with our study findings. Our results are in line with recent research showing no association or negative association between PA and EF 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 EF 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 EF highlights the potential value of focusing on movement quality in school PE. 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, EF, and movement assessments relative to normative data of the participants in this study, living in an area of deprivation. This study indicated a low mean score compared to normative data in children aged 5-6 years in inhibitory control, working memory and cognitive 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 5 years old, 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 EF in children, emphasizing the importance of exploratory movement capability in predicting EF 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 areas of deprivation. However, the study has its limitations.

First, the cross-sectional design provides only a snapshot of the associations between children's movement and EF 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 EF. The direction of causation could be the reverse whereby higher EF levels lead to better coordination, more varied movement patterns and higher PA levels. Second, the EF 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 EF. To further understand the statistical associations between exploratory movement and EF 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 EF. 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 deprivation, 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 EF in children from different areas of deprivation, 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 EF development and motor development.

In conclusion, these findings show that among children aged 5-6 years living in areas of deprivation, DMA exhibited the strongest association with EF. The study also showed that there is a combined association of quantity and quality assessments of children’s movement on EF. A follow up to this study is detailed in the next two chapters of 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.

Chapter 4 - Study 2: The effect of physical education lessons underpinned by motor learning theory on executive function (SAMPLE-PE): a cluster randomised controlled trial in 5-7-year-old children from deprived areas of Northwest England

Chapter 4 (study 2)	Objectives:
To assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve executive functions among 5–7-year-old children from deprived areas of Northwest England.	• Examine the effect of Nonlinear or Linear pedagogy compared to current PE delivery in schools on executive function of 5–7-year-old children from a deprived area of Northwest England.

Thesis studies map

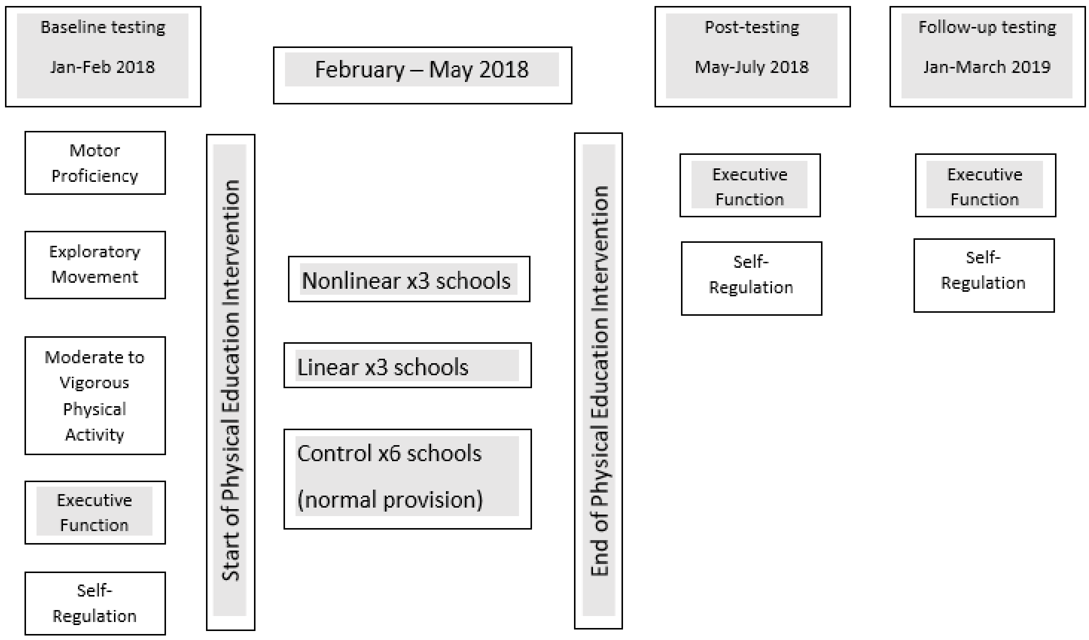

Figure 5 The design of study 2 within the RCT (greyed area)

Introduction

EF are conventionally defined as higher order skills responsible for the complex processing of inhibiting responses, manipulating information, and shifting attention (Diamond, 2016). They are crucial to children's physical and mental health and to developmental outcomes (Esmali et al., 2023; Schirmbeck, Rao & Maehler, 2020; Diamond, 2013). EF enable a child to learn how to organise their actions towards a goal, think flexibly and regulate their behaviour (Chen et al., 2023). The maturation process of EF is faster during childhood and this critical period coincides with the educational milestone of starting school (Keenan et al., 2019; Jacobsen et al., 2011; Blair 2002; Bierman et al., 2008). However, living in an area of high deprivation, detrimentally impacts cognitive functioning and its underlying neurobiology, meaning children aged 5-7 years will fall behind their advantaged peers (Bierman et al, 2008; Urasche & Noble, 2016). The development of children's EF is a clear priority in the education sector as they represent the core cognitive functions that are fundamental for school functioning, children's learning and academic achievement (Sankalaite et al., 2021; Cortes Pascual et al., 2019). The school environment influences the acquisition of EF with teachers playing a key role in implementing evidence-based interventions (Keenan et al., 2019; Diamond, 2016). Research suggests a number of different practices, some of which involve direct and indirect approaches to improving EF (Sankalaite et al., 2021; Diamond & Lee, 2011; Zelazo et al., 2016). PE is important for a child's holistic development including cognitive, affective and physical outcomes (UK Department for Education, 2024; UNESCO, 2024). The development of children's movement competence is a central objective of PE and has been reported to be associated with EF of children aged 5-6 years living in an area of deprivation (O'Callaghan et al., 2024).

Although, the development of cognition is documented clearly in the rationale for PE funding in UK primary schools (Gov.UK, 2024); curriculum design and pedagogical approaches to teaching and learning are not consistently underpinned by a contemporary evidence base of the movement-cognition relationship. To promote EF when designing primary school education, the linkage between the motor and cognitive development domains requires a carefully balanced consideration of PA dose, motor proficiency and children's exploratory movement capability (O'Callaghan et al., 2024; Cook et al., 2019). Teacher's perceptions and beliefs of the importance of such concepts can determine their choice of planned learning opportunities and instructional strategies (Kennan et al., 2019). However, primary school teachers report being poorly prepared to create meaningful PE experiences, and there is a need for improved clarity regarding how rich learning environments in PE promote EF (Rudd et al., 2020; Fletcher & Mandigo, 2012). The detrimental effect of deprivation on children's neural development, intensifies the need to understand the potential of a PE pedagogy model in primary schools to promote EF (Rudd et al., 2020).

A pedagogical model can be defined as the planning of a teaching-learning process, that must have sufficient evidence to detail the effect on learning and have a structure that is clear and concise for a teacher to follow (Arufe-Giraldez et al., 2023). A PE pedagogical model develops confidence and competency in delivery because it provides a clear structure of intended, evidence informed outcomes and creates meaningful PE experiences (Ni Chroinin et al., 2017). However, the successful implementation of a pedagogical model requires the teacher to have a clear theoretical understanding (Arufe-Giraldez et al., 2023). Few studies have outlined the effect of different PE pedagogical approaches on EF among children living in an area of deprivation. Two pedagogical approaches underpinned by motor learning theory, designed to foster movement skills, are Linear and Nonlinear pedagogy. Linear Pedagogy is based upon Schmidt (1975) notion of a schema whereby a movement pattern is stored and recalled by memory to produce a movement. Linear pedagogy aligns to cognitive science from a traditional view that the causal system underlying the regularity of a competent movement is an information processing system (Richardson et al., 2008). It is suggested that there is a systematic loop of sensory input and movement output attributed to centralised computation processes that involve EF (Richardson et al., 2008).

When implementing a Linear pedagogy approach, movement skills are taught by breaking down the skill into chunks of information that can be stored as representations in the brain. Direct instruction structures the children's systematic experience of firstly repeating small parts of the movement in a closed environment (e.g., a drill) and then progressing to applying the same movement in an open environment (e.g., a game). Variability during the learning process is viewed as detrimental and the goal is automaticity where the amount of information processed reduces when achieving mastery of the movement. Interventions that have features of Linear pedagogy include the teacher as the main source of instruction. Previous interventions using Linear pedagogy have been shown to improve children's motor competence and cognitive function (Vazou et al., 2016; Gallotta et al., 2015; Bedard et al., 2019). However, none of these studies have compared the effect of Linear pedagogy with an alternate pedagogy and neither have they investigated the effect on EF of children living in an area of deprivation.

Nonlinear pedagogy is based upon an ecological perspective whereby, the focus of pedagogy is the design of an informationally rich task and environment wherein children explore functional outcomes (Rudd et al., 2020; Adolph, 2019). In Nonlinear pedagogy, children are encouraged to be independent and create individual level movement solutions which, emerge in the task and environments that are carefully designed to represent a performance/game situation. The role of the teacher is to channel the learner's explorations with careful modifications of the task and environment, which will encourage variability and omit prescription of a singular solution (Chow et al., 2021). In Nonlinear pedagogy, when the task, instruction and learning environment are deployed with interconnected purpose, a child's motor skills and EF are part of an active system, adapting and seeking solutions (Rudd et al., 2020).

An ecological approach details EF embedded across a whole system because of the mutual relations between a child and the dynamics of their environment (Adolph & Hoch, 2019). Understanding the sub-systems of the body involved in the movement-cognition relationship is no longer isolated to views that the brain is a centralised controller of the entire system. EF are considered as part of a cyclical process of learning in development whereby; multiple, intra-systems of the body and environment are constrained during the emergence of movement (Adolph, 2019; Bruineberg, Chemero & Rietveld, 2019). Previous interventions that had Nonlinear pedagogy principles evidenced improvements to motor competence and cognitive functions (Pesce et al., 2021). A clear gap is understanding the effect of Nonlinear pedagogy on the EF of children living in an area of deprivation and comparing the effect to Linear pedagogy.

In summary, examining the implementation of different PE pedagogies is essential to ensuring the goals set out in UK National Guidelines for enhancing children's cognitive function through movement are achieved. It is important to identify how both PE pedagogies influence the development of cognitive function, which is particularly important for schools situated within areas of deprivation given that high deprivation is associated with lower cognitive development among children. To date, no study has examined the effect of Linear and Nonlinear pedagogy on cognitive function among children living in areas of deprivation. Our aim was to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve EF among 5–7-year-old children from deprived areas of Northwest England. It is hypothesised that Linear and Nonlinear pedagogy will have a greater effect on EF when compared to the control group.

Method

Study Design and Participants

This research was approved by Liverpool John Moores University Research Ethics Committee (Reference 17/SPS/031) and is part of the Skill Acquisition Methods fostering Physical Literacy (SAMPLE-PE) cluster randomised control trial (ClinicalTrials.gov identifier: NCT03551366). Briefly, SAMPLE-PE aimed to investigate the efficacy of PE curricula based upon different pedagogical principles and motor learning theories in promoting physical literacy amongst 5–6-year-old children. The main trial methods of the study have been described elsewhere (Rudd et al., 2020). Eligible schools were required to be located in a city in Northwest England situated within the most deprived tertile for the English population, based on the school's postcode as ranked by the 2015 English Indices of Deprivation index (Gov.UK, 2018). One hundred and nineteen eligible primary schools were invited to participate in the study via email and telephone. Gatekeeper consent was obtained from 12 eligible government-funded primary schools following an information meeting with the research team, where headteachers were given an in-depth overview of the project. The children from year 1 classes (aged 5-6 years) were then invited to participate in the study via a parent/carer and child invitation pack, including information sheets, parental consent forms, parent and child characteristics questionnaire, child medical information form, and child assent form. If information collated from parents identified children with special education needs (SEN), this was verified by the class teacher. Children who did not return consent and assent forms, signed by both the child and parent, were excluded from all assessments. Children who were not able to participate in PE (e.g., due to medical conditions) were excluded from data analysis.

Using a computer-generated procedure, schools were randomly allocated to one of three groups: 1) Nonlinear pedagogy intervention (n= 3 schools); 2) Linear pedagogy intervention (n = 3 schools) or 3) control group (n= 6 schools). All data was collected in each of the school halls. Baseline data (T0) collection occurred in January-February 2018. Following baseline assessment, intervention schools received a 15-week PE curriculum intervention delivered by trained coaches, while control schools continued usual delivery. All schools were asked to ensure the same amount of PE was delivered each week (2 x 60 minutes) for 15 weeks. Post-intervention assessments (T1) were completed within 2 weeks after the intervention period between June and July 2018, while follow-up assessments (T2) took place 6 months after post-intervention assessments between January and early March 2019. The design, conduct and reporting of this study was designed in accordance with the Consolidated Standards of Reporting Trials (CONSORT) (Shulz et al., 2010). Specifically, this study was designed to analyse the effect of PE pedagogies underpinned by motor learning theory on EF.

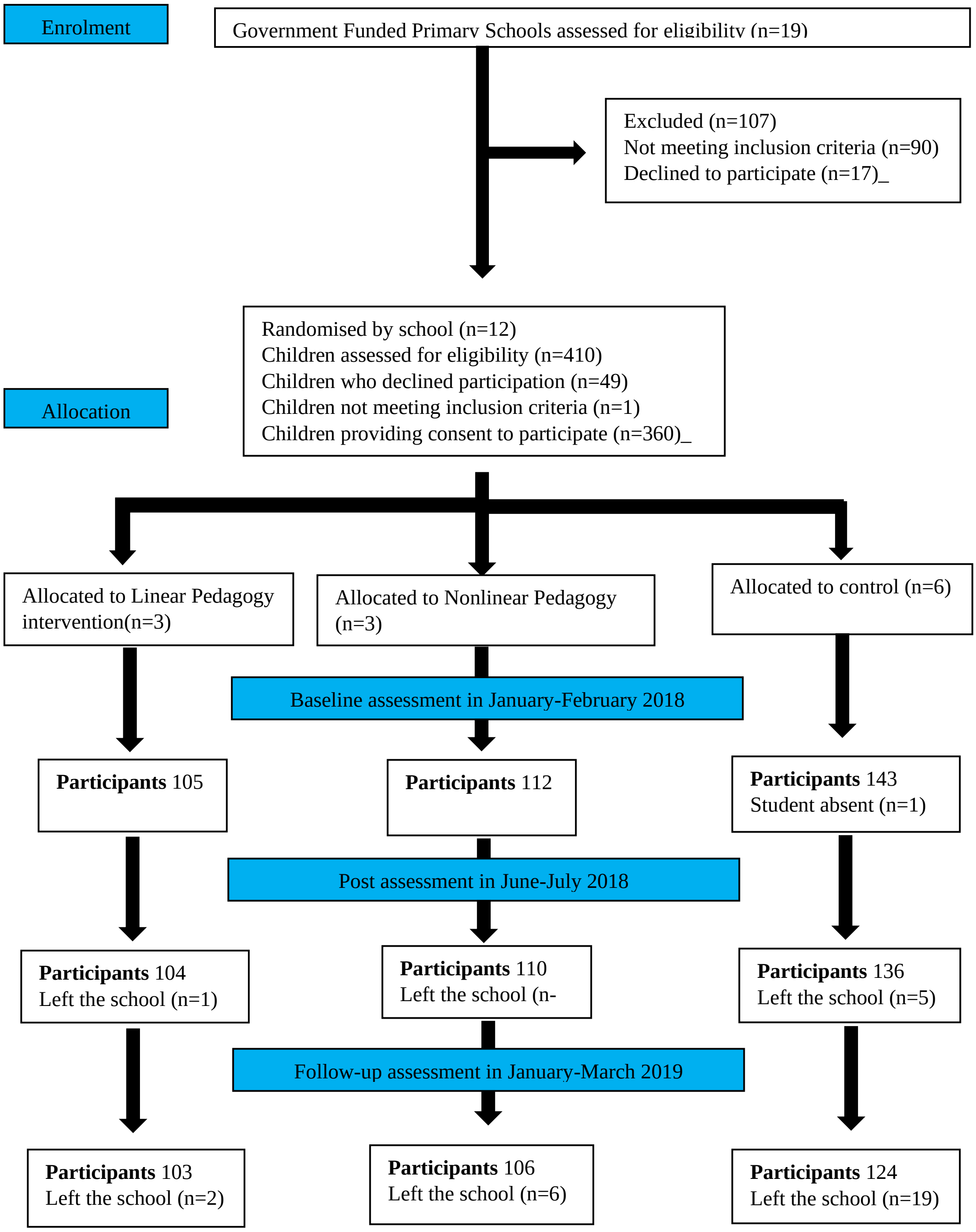

Figure 6 Flow Diagram of the participants included in the executive function assessments

Intervention – Deliverer Training

Both the Linear and Nonlinear pedagogy lessons were delivered twice a week for 15 weeks, which totalled 30 lessons. Lessons were delivered in 3 blocks of 10 lessons (i.e., 5 weeks x 2 lessons), with block one focussed on dance, block two on gymnastics, and block three was ball skills. These activities aligned with the outcomes of the key stage 1 PE National Curriculum (Department for Education, 2013). The intervention delivery team was made up of five sports coaches who possessed a level two coaching qualification as a minimum and had been observed by a member of the research team delivering PE lessons in a primary school not involved with SAMPLE-PE. Two intervention deliverers were from the research team while three sports coaches were recruited from a University in the Northwest of England with a longstanding reputation for delivering high quality BA (Hons) Physical Education and BSc (Hons) Sports Coaching programmes. All of the intervention deliverers took part in a series of training that involved both theoretical and practical knowledge development of the SAMPLE-PE interventions. The coaches were assigned to either a Linear (n =2) or Nonlinear (n=3) curriculum training programme based on their observed pedagogical approaches. The training was delivered by a member of the research team with expertise in both approaches and each training session was 180 minutes for five weeks. During the training programme, the coaches were observed leading a Year 2 (6–7-year-old children) PE lesson within a school not participating in the SAMPLE-PE project. Each coach received augmented feedback from members of the research team following the observations. The coaches kept a reflective log during the training to develop implementation strategies based upon the pedagogic practice. Each coach received a resource pack with training recordings, the pedagogical framework and lesson material that was planned with consideration for the equipment available in each of the participating schools. Following the training, coaches were supported by the research team through weekly phone calls to discuss the plan and delivery of lessons.

Linear Pedagogy Intervention Delivery

The Linear pedagogy intervention followed the theoretical principles of direct instruction and the information processing theory notion of a schema (Schmidt, 1975). A traditional structure of task order was followed: 1) A teacher-led warm-up activity; 2) Drill practice of movement skills; 3) a performance activity to apply the movement skill learnt earlier in the lesson and; 4) a cool down. The tasks at each stage of the lesson, invited to children to perform and repeat movement skills until they showed signs of automaticity. The intervention deliverers were trained to use Fitts and Posner (1967) cognitive stages (cognitive, associative, autonomous) to evaluate children's progression in movement proficiency in order to know when to increase the task difficulty (Fitts & Posner, 1967). At the start of each task and at intervals throughout each task, the intervention deliverers provided visual demonstrations and clear verbal instructions stating the order and purpose of each task, making it clear what proficient movements look like. Coaches used the principles from Gentile's taxonomy and challenge point framework to identify progressions of the tasks of increasing difficulty from simple and controlled movements to complex and dynamic actions (Adams, 1999; Guadagnoll & Lee, 2004).

Nonlinear Pedagogy Intervention Delivery

The Nonlinear pedagogy intervention followed the theoretical principles of the ecological dynamic's framework (Chow et al., 2011). The research team and coaches collectively identified the task (e.g. activity, type, duration, number of participants, rules within a task), environmental (e.g. space, boundaries, equipment type, amount, position) and individual (e.g. age, sex, ability) constraints that could be used to design the PE lessons. The coaches used the Space, Task, Equipment, People (STEP) framework to identify and modify the constraints during the lessons (Youth Sport Trust, 2002). At the beginning of each lesson, the children were invited to explore the space and the different objects set out; the lessons continued with activities representative of game or performance situations where the intervention deliverer introduced variability by changing the constraints appropriately. Coaches were trained to use Newell's stages of motor learning (coordination, control and skill) to monitor children's motor learning stage and appropriate individual and class level modifications of constraints (Newell, 1986). Visual demonstrations by the coach or corrective feedback were not used; children were invited to observe their peers individual level movement solutions. Coaches encouraged an external focus of attention by the children to encourage variability and learning of different, individual level movement solutions.

Outcomes and data collection timeline

Demographic outcomes were collected during baseline data collection (January-February 2018) whilst anthropometric and EF outcomes were collected during each data collection point comprising baseline, post-intervention (June-July 2018) and follow-up (January-early March 2019)

Demographics

Information about children's demographics (i.e., date of birth, gender, ethnicity, home postcode and special educational needs) were provided by parents or guardians using a questionnaire that was returned with the consent form. Children's neighbourhood deprivation decile and rank was calculated from the household postcode using the English indices of deprivation (Gov.UK, 2018).

Anthropometrics

Body mass was assessed to the nearest 0.1kg using scales (model 760, Seca, Hamburg, Germany) and stature was assessed using stadiometers to the nearest 0.1cm (The Leicester Height Measure, Child Growth Foundation, Leicester, United Kingdom). All anthropometric measurements were taken twice while a third measurement was taken in case the first two measurements differed by more than 1% and subsequently the mean between the measures was used in analysis. Body mass index (BMI) was calculated using stature and body mass measurement and then it was converted to standardised BMI z-scores following international Obesity task force (IOTF) classification (Gov.UK, 2018).

Executive functions

The NIH Toolbox is a comprehensive set of neuro-behavioural measurements that assesses cognitive functions from the convenience of an I-Pad 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 made available by Northwestern University for each of the NIH toolbox assessments. To assess the three components of EF, the first author and independent research assistant worked 1:1 with each child, in a quiet space outside the classroom (e.g., the library). Each child was asked to work through three age-appropriate activities from the NIH Toolbox, lasting approximately 15 minutes in total (Northwestern University 2018). Inhibitory control was 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 the arrows pointed in the same direction, whereas on incongruent trials, the middle arrow pointed 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, pressing the chosen button 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 was 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 (animals and food) are presented in the 2-list condition in each series. In each condition, the number of pictures increased with each series to overload a child's working memory progressively. 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 was assessed through the Dimension Change Card Sort, which required the child to match two target pictures with a reference picture by either colour or shape. Prior to the appearance of the reference stimulus, a cue – *shape* or *colour* – appeared on the screen and audibly, indicating to the child what dimension the target should be matched by. The child was instructed to choose as quickly as possible 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.

Randomisation and power

The participating schools were matched by number of students enrolled and then they were randomly allocated to either intervention or control group using a computer-based algorithm. As a result, more schools were allocated to the control group to account for the higher risk of drop out as a consequence of not receiving the intervention. The study was powered as reported in the SAMPLE-PE project protocol paper (Rudd et al., 2020) to assess movement competence change in 3 groups over 3 time points with 90% power at a level of $p<0.05$ adjusting for clustering at class level and allowing a dropout at each time point equal to 20%. As a result, the initial sample calculation aimed to recruit at least 314 participants. It was not possible to perform a sample size and power calculation based on cognitive function outcomes as no meta-analysis reported effect-sizes concerning changes in EF due to PE pedagogy interventions. No study has assessed the effect of Linear pedagogy and Nonlinear pedagogy on EF. However different studies involving PE interventions aiming to increase EF in children presented a number of participants that was similar or lower than 314 children (i.e. 64- 99) (Kolovelonis & Goudas, 2022; Fisher et al., 2011). A sample of 314 children with more than 100 children per intervention group could be considered an adequate sample size for a randomised controlled trial evaluating the effect of PE pedagogy interventions on EF.

Data Analysis

Statistical Approach

Flow diagram (figure 6) indicates the number of children included in the analysis. All calculations were computed with R Studio (Version 1.1.463; R Core Team, 2018). All analyses were conducted in R (R Core Team, 2018) using primarily the *tidyverse* packages (Wickham & Grolemund, 2016). Multilevel mixed-effects models (*nlme* package; Pinheiro, Bates, & R Core Team, 2022) were computed to determine the effects of the intervention on the outcome variables considering time points (level 1; within-person change pre, post, retention) were nested in participants (level 2; between-person) and participants were nested in school classes (level 3). All models were computed using maximum likelihood estimation. We had a hypothesis that the intervention groups would have a significant effect on inhibitory control, working memory and cognitive flexibility when compared to the control group.

The likelihood ratio test uses the comparison of information criteria AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) between models while lower criteria show better model fit. This means, when comparing two adjacent models with different specifications, a negative Δ AIC/BIC indicates better fit to the data for the more complex model indicating the added specification is considered to be meaningful (e.g., added aspect as predictor, random effect). Alpha level was set to .05 for all tests. For all targeted, the following step-by-step procedure was used: (1) unconditional model with random intercepts, (2) random-intercept fixed-slopes model adding time as predictor, (3) random-intercept random-slopes model, (4) adding autocorrelation, (5) random-intercept random-slopes model adding group (experimental, control) and their interaction as additional predictor, and (6) adding control variables sex, age, ethnicity, and deprivation decile to the model. Results of models (1) to (4) are used to describe the data and find model specifications, results of model (5 and 6) are used to test the main hypotheses (effects of group on slopes [trajectories]).

Results

Figure 6 shows the flow of schools and participants through the trial. In total, 12 schools participated in the study (10% response rate). Schools that declined to participate provided different reasons for not taking part (e.g. already involved in other projects, too busy). Of the 410 potentially eligible at baseline (T0), 360 were enrolled into the study (88% response rate) and 359 (99.7% of participants) had valid EF data at either baseline post-intervention and/or follow-up. Reasons for missing data was the children being absent on data collection days. Participant retention in the study from baseline to follow-up was 98%, 95% and 87% for the Linear pedagogy, Nonlinear pedagogy and control group respectively with a larger proportion of control group children leaving school within the study period.

Baseline characteristics

Table 9 shows the demographic characteristics of the study sample by group. The pooled sample comprised 360 children (55% girls) with a mean age of 5.9 (Standard Deviation [SD] = 0.3) years; 56% of the children were white British while 44% were from other ethnicities; 12% reported special educational needs of mild and moderate severity and the vast majority lived in highly deprived areas with 85% of the children living in areas classed as the most deprived in England. Based on the International Obesity Task Force (IOTF) classifications, 17% of children were overweight and 6% were obese. BMI was not assessed in 12% of children due to school absence. Means and standard deviations of all cognitive function variables scores per group are provided in Table 10.

Table 9 Demographic characteristics of children by group

	Linear Pedagogy (n=105)		Nonlinear Pedagogy (n=112)		Control (n=143)	
Baseline Characteristic	Mean (SD) Or %	Missing data	Mean (SD) Or %	Missing data	Mean (SD) Or %	Missing data
Decimal Age (years)	6.0 (0.3)	5	5.9 (0.3)	1	5.9 (0.3)	2
Girls	53%	0	52%	0	58%	0
White British	68%	8	52%	9	50%	5
SEN	8%	1	15%	1	12%	0
Living within the 30% most deprived areas	96%	4	77%	1	89%	3
IOTF BMI	0.4 (1.3)	9	0.5 (1.1)	8	0.3 (1.1)	27
Thinness grade 3	1%		0%		1%	
Thinness grade 2	2%		1%		0%	
Thinness grade 1	6%		4%		6%	
Healthy weight	61%		72%		67%	
Overweight	21%		14%		22%	
Obese	8%		9%		4%	

Executive Function

Inhibitory Control (IC). Table 11 shows age and SEN were significant predictors of inhibitory control. There was a significant time main effect at follow-up but no significant group*time interaction. Post-hoc analyses showed that both experimental groups did not significantly improve when compared to the control group from t0 to t1, (LIN: p = 0.90, NL p = 0.27) as well as from t0 to t2 (LIN: p = .12 NL: p = .16,). (**2-3 t0-t2 0.005)

Working Memory (WM). Table 11 shows age, SEN and deprivation decile were significant predictors of working memory. There was significant time effect post-intervention and follow-up. There was also a significant group*time interaction of the Nonlinear group at post-intervention and follow-up. Post-hoc analyses showed that the Nonlinear group had steeper gains compared to the control group from t0 to t2 (LIN: p = 0.23, NL: p = 0.001) but not from t0 to t1 (LIN = p= 0.26, NL: p=0.10,).

Cognitive Flexibility (CF). Table 11 shows sex, SEN and deprivation decile were significant predictors. There was significant time main effect at follow up. There was also a significant group*time interaction of the Linear group at post-intervention. Post-hoc analyses showed that the Linear group significantly improved compared to the control group from t0 to t1, (LIN p=0.03, NL: p = 0.85,) but not form t0 to t2 (LIN: p = 0.13NL: p = .0.68,).

Table 10 Descriptive executive functions data by group

		Executive Function														
		Inhibitory Control					Working Memory					Cognitive Flexibility				
Group	Time Point	Mean	SE	df	lower.CL	upper.CL	Mean	SE	df	lower.CL	upper.CL	Mean	SE	df	lower.CL	upper.CL
C	0	4.62	0.225	16	4.14	5.1	1.77	0.387	16	0.953	2.59	3.13	0.205	16	2.7	3.56
NL	0	4.93	0.266	14	4.36	5.5	1.96	0.455	14	0.984	2.93	3.38	0.236	14	2.87	3.89
LIN	0	5.03	0.293	14	4.4	5.66	2.31	0.503	14	1.24	3.39	3.4	0.255	14	2.86	3.95
C	1	5.04	0.221	16	4.57	5.51	3.37	0.483	16	2.35	4.4	3.63	0.209	16	3.18	4.07
NL	1	5.66	0.256	14	5.11	6.21	4.55	0.545	14	3.38	5.72	3.94	0.234	14	3.44	4.44
LIN	1	5.49	0.283	14	4.88	6.09	4.62	0.6	14	3.33	5.91	4.64	0.255	14	4.1	5.19
C	2	5.34	0.215	16	4.88	5.79	3.27	0.497	16	2.21	4.32	4.23	0.211	16	3.78	4.68
NL	2	5.94	0.254	14	5.39	6.48	5.19	0.569	14	3.97	6.41	4.62	0.239	14	4.11	5.13
LIN	2	5.41	0.279	14	4.81	6.01	3.15	0.614	14	1.84	4.47	5.03	0.257	14	4.48	5.58

Table 11. Summary table for the results of the mixed models for cognitive functions, adjusting for sex, age, ethnicity, deprivation, body mass index and special educational needs as covariates

	Inhibitory Control	Working Memory	Cognitive Flexibility
(Intercept)	0.027	-10.472	-0.418
	(1.683)	(3.907)	(1.978)
Time Point 1	0.259	1.386***	0.470
	(0.206)	(0.445)	(0.245)
Time Point 2	0.600***	1.506***	0.987***
	(0.140)	(0.388)	(0.248)
Exp. Nonlinear	0.228	0.022	0.231
	(0.312)	(0.654)	(0.335)
Exp. Linear	0.175	0.262	0.112
	(0.327)	(0.693)	(0.348)
Sex	0.262	0.645	0.755***
	(0.170)	(0.393)	(0.199)
Age	0.770***	1.926**	0.528
	(0.278)	(0.646)	(0.327)
Ethnicity	0.220	0.099	0.083
	(0.183)	(0.425)	(0.209)
Deprivation Decile	0.093	0.381**	0.147*
	(0.053)	(0.122)	(0.062)
BMI	-0.069	0.299	-0.022
	(0.071)	(0.164)	(0.084)
SEN	-1.456***	-1.428*	-1.455***
	(0.270)	(0.618)	(0.313)
Time Point 1 * Nonlinear	0.437	1.241*	0.100
	(0.293)	(0.628)	(0.352)
Time Point 2 * Nonlinear	0.361	1.605**	0.190
	(0.202)	(0.557)	(0.358)
Time Point 1 * Linear	0.111	0.915	0.863*
	(0.301)	(0.651)	(0.360)
Time Point 2 * Linear	-0.296	-0.694	0.714
	(0.206)	(0.566)	(0.365)
N	867	874	872
logLik	-1633.519	-2398.222	-1791.510
AIC	3313.037	4842.444	3629.020

Note *SEN Y = 1, SEN N = 0, Girls = 1, Boys = 0, White British = 0 Non-white British = 1*

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

Discussion

This study aimed to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve EF among 5–7-year-old children from deprived areas of Northwest England. The findings of this study suggest that primary PE interventions focussing on motor skills underpinned by Linear pedagogy and Nonlinear pedagogy can support the development of some EF. Participation in Nonlinear pedagogy PE interventions led to an improvement in working memory when compared to participation in the control group at the post-intervention and follow-up timepoints. Participation in Linear pedagogy led to an improvement in cognitive flexibility when compared to the control group at follow-up. Participation in both Linear and Nonlinear pedagogy led to no improvement in inhibitory control. SEN was a significant predictor of all EF; age was a significant predictor of inhibitory control and working memory and gender was a significant predictor of cognitive flexibility. Lastly, deprivation was a significant predictor of working memory and cognitive flexibility. This study was the first to evaluate the effect of Linear pedagogy and Nonlinear pedagogy with children's EF and to compare it to current practice in PE in primary schools. The results obtained in this study extend knowledge about improving EF in primary school PE under different pedagogies.

To our knowledge, there has been no other study that has investigated the effect of Nonlinear pedagogy and working memory in children aged 5-6 years living in an area of deprivation. There is a broad link to studies that have reported interventions focussed on improving motor skill improve working memory (Yi Zhang et al., 2022; Rowe et al., 2019; Koutsandreou et al., 2016). Rather than the principles of Nonlinear pedagogy, some studies report improved working memory when the interventions align with Linear pedagogy whereby it has involved teacher-led instruction of a prescribed movement (Yi Zhang et al., 2022; Rudd et al., 2021). Nonlinear pedagogy is proposed to improve working memory because during the children's experience of exploration and self-discovery there will be information in the environment that will persist, dissolve and newly emerge; working memory will have to sustain this information and manipulate its meaning (Diamond, 2013). Rather than an adult prescribing the information the children should be processing as part of their movement experience, the children are independently dealing with constant changes in an environment that require continual problem solving to find a solution; working memory will enable the identification of nuance and fluency of a goal directed action (Alloway & Alloway, 2010; Cowan & Alloway, 2008).

The study results are that neither Linear nor Nonlinear pedagogy led to improvements to inhibitory control was in contrast to a study of 7-year-old children which showed a Nonlinear training group improved in inhibitory control when compared to a Linear training group (Asadi et al., 2022). Similarly, a study that aligned to the principles of Nonlinear pedagogy variability of practice with children aged 5-10 years improved inhibitory control, found to be mediated by ball skills and levels of outdoor play (Pesce et al., 2016). In the experience of Linear pedagogy, children are given a modelled exemplar of the movement that is required and so there may be limited use of inhibitory control to make changes and choices (Diamond, 2013). When trying new movements and aiming to be successful in their execution, you would expect a child to need to control their thoughts and behaviour to override impulses, however the step-by-step instructions in Linear pedagogy indicate what is appropriate rather than the child independently determining what is needed. In Nonlinear pedagogy, it would have been expected that the opportunity for children to explore different aspects of the task and environment, would have given the children an experience that required them to selectively attend to particular stimuli based upon the goal they are working towards (Diamond, 2013). The result of this study suggests that even when movement experiences may utilise the cognitive skill, it does not transfer to a testable development of that skill. Future research should investigate inhibitory control as an integrative multiple process is associated with self-regulation and use an assessment that measures both skills such as the Heads Shoulders Knees and Toes test (Muir et al., 2023; Montroy et al., 2016; Cameron Ponitz et al., 2008)

This study found Linear pedagogy had a significant effect on cognitive flexibility post-intervention. Cognitive flexibility involves being able to adjust to changing demands and Linear pedagogy breaks the session down into distinct stages that will gradually increase the complexity of the task that the children will need to adjust and respond (Diamond, 2013). The children will have to move from one part of the task to another, using cognitive flexibility to shift their attention to the progressive expectations set by the teacher. The children will be encouraged to identify with specific markers that guide them through the stages of the movement and this shifting of attention throughout the movement may explain the development of cognitive flexibility in the Linear group. However, there are parts of the Linear pedagogy planned sessions that involve simple repetitive movements, and this has previously been reported as reducing the level of cognitively engagement of the movement experience (Tomporowski & Pesce, 2019; Kolovelonis & Goudas., 2022). For this reason, it was expected that Nonlinear pedagogy would lead to improvements in cognitive flexibility, the data shows some trend towards improvement, but this is not statistically significant. Nonlinear pedagogy involves less repetitive movement, and it was expected that the opportunity to make individual choices would encourage a shifting of attention when the children are choosing to engage with the equipment in different ways for example. However, this study shows the stage at which cognitive flexibility is developed aged 5-6 years, may require a more controlled stepping through an activity to elicit a shifting of attention that is age appropriate. It is potentially challenging for the teacher to be able to keep children innovating their movement during tasks. Further research should investigate the effect of Linear and Nonlinear pedagogy on cognitive flexibility in the older age groups at primary school, aged 9-11 years for example.

It has been reported that greater cognitive engagement is elicited during PE when teachers have higher qualifications (Kolovelonis & Goudas., 2022). In SAMPLE-PE it was found that both Linear and Nonlinear pedagogy interventions were delivered with high fidelity to the respective Linear and Nonlinear pedagogical principles (Crotti et al., 2022). This study had several strengths, it was the first study to investigate the effect of Linear and Nonlinear pedagogy approaches on EF, comparing it to current PE practice in primary school. The study contributes to our understanding of the importance of primary school PE being underpinned by a theoretically informed pedagogy. Such findings are particularly relevant for designing primary PE curriculum to support the development needs of children living in areas of deprivation. A further strength was the measurement at both post-intervention and follow-up, this enabled an examination of whether changes detected were maintained or any others emerged. Another strength was that multilevel models accounted for different demographic variables associated with EF. However, this study also has some limitations such as EF being assessed on an iPad for all three skills in succession which could be associated with boredom and the children giving up on the task. Including measures that each had a different format could have kept the children fully engaged with each task. The inhibitory control and cognitive flexibility assessments were relatively easy for the children to complete, leading to a potential ceiling effect. The working memory assessment was quite challenging for the children to complete and led to a number of children scoring 0. A bigger sample size in the intervention groups could have led to trends in improvement emerging more clearly.

The findings of this study suggest that pedagogically informed PE interventions would need to be extended across the school year and supplemented by whole school approaches to close the deficit that exists in the cognitive function of children living in an area of deprivation (Dennis et al., 2022). A broader, embedded view of the movement-cognition relationship informs the art and science of teaching PE; by providing a greater sense of purpose for self-discovery and active engagement by a child in a rich context of opportunities. The origins of pedagogy focussed on ‘instruction of children’ is now balanced by an investigation of ‘interaction’ between the teacher, child, environment and task. When investigating the movement-cognition relationship, it is important to take a broad view of cognition and examine a number of constructs including the relation between EF and self-regulation. Therefore, the next chapter will examine the influence of the SAMPLE-PE interventions on self-regulation.

Chapter 5 - Study 3: The effect of physical education lessons underpinned by motor learning theory (SAMPLE-PE) on self-regulation: a cluster randomised controlled trial in 5-7-year-old children living in an area of deprivation.

Chapter 5 (study 3)	Objectives:

To assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve self-regulation among 5–7-year-old children from deprived areas of Northwest England.	• Examine the effect of Nonlinear or Linear pedagogy compared to current PE delivery within schools on children's self-regulation of 5–7-year-old children from a deprived area of Northwest England.

Thesis study map: chapter 5

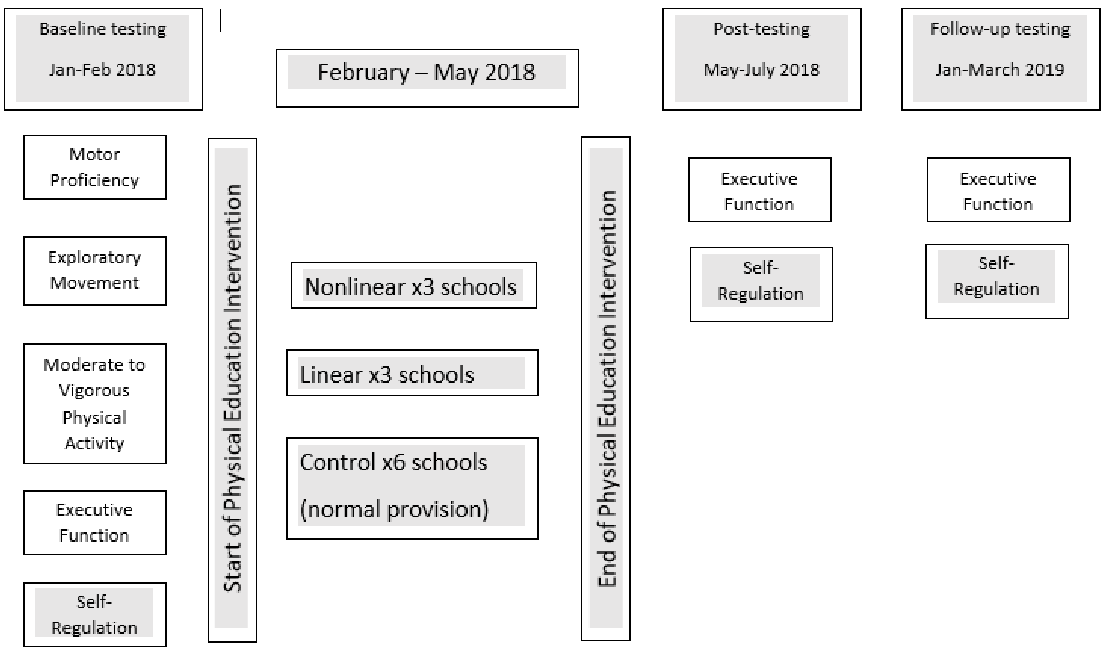

Figure 7 The design of study 3 within the cluster-RCT (greyed)

Introduction

Self-regulation reflects a child's ability to adjust their behaviour, thoughts and emotions to meet the physical, cognitive, social and emotional demands of a situation. Often described as self-control will power, self-regulation is a crucial skill that develops throughout childhood and is essential for managing actions and achieving positive outcomes (McClelland and Cameron, 2011; Posner and Rothbart, 2000; Muir et al., 2023; Montroy et al., 2016). It is conceptually distinct as well as integrative to behaviour and cognitive processes (Diamond, 2016, Posner & Rothbart, 2000, Muraven & Baumeister, 2000; Lakes & Hoyt, 2004). Importantly, self-regulation, along with EF, associated with successful outcomes in primary school education and having a foundational role in overall health and well-being (Pandey et al., 2018; Joseph et al., 2023; EEF, 2024; Muir et al., 2023). However, children living in an area of deprivation often face disruptions in neurodevelopment during critical periods of childhood, negatively impacting self-regulation (Macedo Feijo et al., 2023; Blair & Raver, 2015). These disruptions effect the balance between bottom-up reactivity (impulse control) and top-down regulation (cognitive control) (Palacios-Barrios & Hanson, 2019). (Palacios-Barrios & Hanson, 2019). To address these challenges, interventions that promote self-regulation in disadvantaged contexts are essential to reducing inequalities in academic achievement and overall health (Pandey et al., 2018; Joseph et al., 2023). Such interventions are particularly vital because physical, cognitive, and emotional regulation are all necessary for goal-directed behaviours that lead to success (Pandey et al., 2018).

Research suggests that children living in area of deprivation may respond more effectively to interventions promoting self-regulation (Vasilopoulos & Ellefson, 2021; Diamond & Ling, 2016). Children thrive in environments where they can explore, regulate their actions, and develop autonomy (Alarcon-Espinoza et al., 2022). Interventions grounded in play, autonomy, and agency, alongside positive emotions, have been shown to facilitate self-regulation (Diamond & Lee, 2011; Muir et al., 2023). When embedded within school curricula, these approaches consistently yield positive results (Pandey et al., 2018). To maximize impact, primary school interventions should adopt evidence-based pedagogies that balance explicit instruction with scaffolded opportunities for skill practice, autonomy, and exploration. This structured yet flexible approach enhances self-regulation and supports children's broader development (Muir et al., 2023; EEF, 2024).

A goal-directed behaviour such as practicing motor skills is a problem -solving task. The process of a child's successful or unsuccessful attempts requires perseverance challenging one's self-regulation skills (Tomporowski & Pesce, 2019). At school age, systematic reviews and meta-analyses provide evidence from interventions that the development of motor skills promotes self-regulation (Van Der Fels et al., 2015; Singh et al., 2019, Tomporowski & Pesce, 2019). Intervention characteristics need careful consideration to ensure appropriate challenge and practice that is incremental as the child becomes more familiar and capable of completing the activities (Muir et al., 2023; Diamond & Lee, 2011). Experiences of motor skills through activities such as tennis that are characterised by variability and an unstable environment have been associated with improved self-regulation (Vasilopoulos & Ellefson, 2021). The use of motor skills by a child in sports such as martial arts promote self-regulation because of the required discipline and character growth from the constant evaluation of thoughts and actions (Lakes & Hoyt, 2004; Diamond & Ling, 2016). A structured approach to developing motor skills and sporting experiences needs to also be carefully balanced with providing positive experiences that foster enjoyment and engagement as well as connectedness and social support, which also promote self-regulation (Diamond & Ling, 2016; Muir et al., 2023). Self-regulation is promoted when a child's participation is strong because the child feels they have a voice and are sharing power over a situation where they can independently use their initiative and work collaboratively (Muir et al., 2023; Kangas et al., 2015).

Self-regulation is a context-specific response required when setting goals and autonomously achieving them (Gauti Lazdal et al., 2019; Zimmerman, 2002). The development of motor skills creates an opportunity to set goals and be autonomous and are an essential focus to meet the aims of PE (Ofsted, 2022; Jones et al., 2020; Gao et al., 2021). However, rather than a sole focus on whether a motor skill is mastered using 'high-quality instruction, practice and feedback', it is also important to understand how a specific pedagogical approach used in a PE lesson requires self-regulatory behaviour (Ofsted, 2022; Gauti Lazdal et al., 2019). The expertise of the teacher leading an intervention is very influential in facilitating the use of self-regulatory behaviour (Kolovelonis et al., 2012; Muir et al., 2023). PE needs a clear directive from the teacher to explicitly communicate learning goals and prevent a recreational environment that lacks purpose (Whitehead, 2020; Gauti Lazdal et al., 2019). A challenge for teachers is that there are a number of different pedagogical models, or teaching strategies that they can use to support children's holistic development, and the evidence base can be unclear about which to follow (Arufe-Giraldez et al., 2023). There are two contrasting pedagogical approaches underpinned by motor learning theory, designed to foster motor skills, that provide an interesting perspective of the impact of different PE learning environments on self-regulation; they are Linear and Nonlinear pedagogy.

As noted earlier in the thesis, in Linear pedagogy, children are understood to become skilled movers who can navigate to a goal through clear direction and repetition of a motor skill. The development of a motor skill progresses through three observable stages of learning: cognitive, associative and autonomous (Fitts & Posner, 1967). In the cognitive stage, the child is overwhelmed with information, and they are trying to understand the demands of the goal by being clear on a plan of action. Their execution of the movement skill is effortful, erratic and full of errors. In the associative stage, the child clearly understands the goal of the movement and the systematic approach required; through repeated practice, they aim to reduce the discrepancy between the intended and actual performance. In the autonomous stage, the execution of the goal-directed movement will require minimal conscious processing and be accurate and coordinated. Interventions that have features of Linear pedagogy include the teacher as the main source of instruction and follow a stage-by-stage approach to motor skill development. Linear pedagogy has key features such as explicit instruction, modelling and feedback, all of which could promote self-regulation by children progressively learning how to manage their own learning (Sins et al., 2023). A previous intervention with 207 children aged 5-11 year using some aspects of a Linear pedagogy have been shown to improve children's self-regulation (Lake and Hoyt, 2004). The intervention focused on discipline and self-control, the children were taken through a series of martial arts movements and skills demonstrated by the instructor with an incremental increase in level of challenge. Further research is needed to investigate an explicit delivery of Linear pedagogy in primary school PE lessons to understand the effect on self-regulation in this context.

Nonlinear pedagogy is based upon an ecological perspective whereby, the focus of pedagogy is the design of an informationally rich task and environment wherein children explore functional outcomes (Rudd et al., 2020; Adolph, 2019). In Nonlinear pedagogy, children are encouraged to be independent to create individual level movement solutions which emerge in the task and environments that are carefully designed to represent a performance/game situation. The role of the teacher is to channel the explorations with careful modifications of the task and environment to encourage variability and omit prescription of the solution. Learning occurs through a child's self-organisation and the teacher provides a framework to indirectly introduce, or reduce, noise (stability/instability) in the system that enables a goodness of fit between a child's functional capacities and environment features. Newell's model of movement learning proposed three observable levels of skill differentiation where a child is faced with solving the degrees of freedom problem: coordination, control and skill. Children within the coordination stage, the children solve the problem of reaching a movement goal with rigid and awkward movements where they have locked body segments to reach a rudimentary achievement of the goal. Further experience of the movement moves the child in the control stage where movements are less rigid and smooth as the child becomes comfortable to explore possible solutions. In the skill stage, children exploit affordances in their environment and adapt their movement accordingly when achieving their goal. Nonlinear pedagogy has the potential to promote greater self-regulating autonomy that will be developed through the guided discovery and problem solving (Chow et al., 2021). A previous intervention carried out with 116 children aged 8-9 years that had some Nonlinear pedagogy principles evidenced improvements to children's self-regulation (Pesce et al., 2021). The interventions were games-based, and questions were posed to the children that enabled them to come up with unique solutions to the challenges. Further research is needed to investigate the implementation of an intervention that has a comprehensive coverage of Nonlinear pedagogy principles to understand the effect on self-regulation.

In summary, self-regulation is an important outcome that should be a clear focus of interventions supporting children living in an area of deprivation. Developing motor skills in PE are important to promoting children's self-regulation and this could be impacted by the pedagogy adopted by PE teachers. To date, no study has examined the efficacy of Linear and Nonlinear pedagogy on children's self-regulation living in areas of deprivation. The aim of this study is to assess the efficacy of utilising Linear and Nonlinear pedagogy within PE to improve self-regulation among 5–7-year-old children from deprived areas of Northwest England. This study will compare Linear and Nonlinear pedagogy to current PE delivery within schools and assess the effect of each approach on children's self-regulation. It is hypothesised that Linear and Nonlinear pedagogy will have a greater effect on self-regulation when compared to the control group.

Method

Study Design and Participants

This research was approved by Liverpool John Moores University Research Ethics Committee (Reference 17/SPS/031) and is part of the Skill Acquisition Methods fostering Physical Literacy (SAMPLE-PE) cluster randomised control trial (ClinicalTrials.gov identifier: NCT03551366). Briefly, SAMPLE-PE aimed to investigate the efficacy of PE curricula based upon different pedagogical principles and motor learning theories in promoting physical literacy amongst 5-6-year-old children. The main trial methods of the study have been described elsewhere (Rudd et al., 2020) and in Chapter 4 page 118-121. The present study was designed to analyse the effect of theoretically informed PE pedagogy interventions on self-regulation. Eligible schools were required to be located in a city in Northwest England situated within the most deprived tertile for the English population, based on the school's postcode as ranked by the 2015 English Indices of Deprivation index (Gov.UK, 2018). One hundred and nineteen eligible primary schools were invited to participate in the study via email and telephone. Gatekeeper consent was obtained from 12 eligible government-funded primary schools following an information meeting with the research team, where headteachers were given an in-depth overview of the project. The children from year 1 classes (aged 5-6 years) were then invited to participate in the study via a parent/carer and child invitation pack, including information sheets, parental consent forms, parent and child characteristics questionnaire, child medical information form, and child assent form. If information collated from parents identified children with special education needs (SEN), this was verified by the class teacher. Children who did not return consent and assent forms, signed by both the child and parent, were excluded from all assessments. Children who were not able to participate in PE (e.g., due to medical conditions) were excluded from data analysis.

Using a computer-generated procedure, schools were randomly allocated to one of three groups: 1) Nonlinear pedagogy intervention (n= 3 schools); 2) Linear pedagogy intervention (n = 3 schools) or 3) control group (n= 6 schools). All data was collected in each of the school halls. Baseline data (T0) collection occurred in January-February 2018. Following baseline assessment, intervention schools received a 15-week PE curriculum intervention delivered by trained coaches, while control schools continued usual delivery. All schools were asked to ensure the same amount of PE each week (2 x 60 minutes) for 15 weeks. Post-intervention assessments (T1) were completed within 2 weeks after the intervention period between June and July 2018, while follow-up assessments (T2) took place 6 months after post-intervention assessments between January and early March 2019. The design, conduct and reporting of this study was designed in accordance with the Consolidated Standards of Reporting Trials (CONSORT) (Shulz et al., 2010).

Intervention – Deliverer Training

The Deliverer Training was identical to that described in Study 2 page 128

Linear Pedagogy Intervention Delivery

The Linear Pedagogy approach was detailed in Study 2 page 129

Nonlinear Pedagogy Intervention Delivery

The Nonlinear Pedagogy was approach was detailed in Study 2 page 129

Outcomes and data collection timeline

The outcomes and data collection timeline were detailed in Study 2 page 130

Demographics

Demographics was detailed in Study 2 page 131

Anthropometrics

Anthropometrics was detailed in Study 2 page 131

Self-Regulation

The Strengths and Difficulties Questionnaire (SDQ) is a brief emotional and behavioural screening questionnaire used to measure self-regulation, it has satisfactory validity and reliability in children aged 5-6 years (Mieloo et al., 2012). It consists of 25 questions divided into five subscales, with some items reverse-scored (in italics).

Teachers complete the SDQ by reflecting on the child's attributes over the past six months. Specifically:

Hyperactivity is assessed using 5 items: “restless, overactive, cannot stay still for long”; “Constantly fidgeting or squirming”; “Easily distracted, concentration wanders”; *“Thinks things out before acting”* and *“Sees tasks through the end, good attention span”.*

Conduct problems are assessed using 5 items: “often has temper tantrums or hot tempers”; *“generally obedient, usually does what adults request”;* often fights with other children or bullies them”; often lies or cheats”; and “steals from home, school, or elsewhere”

Peer problems are assessed using 5 items: “rather solitary, tends to play alone”; *“has at least one good friend” “generally liked by other children”;* “picked on or bullied by other children” and “gets on better with adults than with other children”. Finally,

Prosocial behaviours are assessed using 5 items “considerate of other people’s feelings” “shares readily with other children (treats, toys, pencils, etc)” “helpful if someone is hurt, upset of feeling ill”; “kind to younger children” and “often volunteers to help others”.

Each subscale is scored on a 3-point Likert scale: never, somewhat true or certainly true; for all of the items except the five printed above in italics the item is scored 0= not true, 1= somewhat true and 2= certainly true; for the items in italic, the item is scored 2= not true, 1= somewhat true and 0 = certainly true. The score for each of the 5 subscales is generated by summing the scores for the five items ranging from 0-10. The scores for hyperactivity, emotional symptoms, conduct problems and peer problems can be summed to generate the total difficulties score ranging from 0-40. A lower total difficulties score is associated with better self-regulation. Prosocial is a separate total with a maximum score of 10 and a higher score is associated with better outcomes.

A sub-sample of children completed the Response to Challenge Scale which, is an observer-rated measure of children's responses to physical challenges. The sub-sample of children were selected randomly. Children completed the obstacle course individually, it had 12 stations, each station had a progressive level of difficulty. For example, the first task involved a jump from one marker to another whereas the final task involved a jump over a high wall of foam bricks. The researcher modelled the exercise at each station and only gave brief verbal instruction, they did not give praise or encouragement. If the child hesitated or was unable to complete the activity after 3 attempts, they were asked to move onto the next station. The completion of the course was video recorded using GoPro Hero 5 video cameras. The measurement scale has 16 bipolar adjectives (e.g. vulnerable-invincible) that the researcher observed on the video and rated on a 7-point scale. Negatively worded items are reversed prior to aggregation so that possible scores on all subscales ranged from 1-7 with lower scores indicating greater self-regulation. The RCS items reflect three domains of self-regulation: physical, cognitive and affective. The physical subscale has 3-items and focusses on skilfulness and control (e.g. skilful-awkward). The cognitive subscale has 7-items and assesses a child's ability to focus attention and efforts on the task (e.g. focussed-distractible). The affective subscales have 6-items and measures willpower, emotional control, persistence and self-confidence (e.g. persevering – quitting).

Randomisation and power

Randomisation and power were described in Chapter 4 page 133.

Data Analysis

Statistical Approach

For the SDQ descriptive statistics, the mean, standard error and upper and lower confident limit for each group were computed for each timepoint using R Studio (Version 1.1.463; R Core Team, 2018). The calculations for the main SDQ analysis were also computed with R Studio. The analyses of the SDQ were conducted in R (R Core Team, 2018) using primarily the *tidyverse* packages (Wickham & Grolemund, 2016). Multilevel mixed-effects models (*nlme* package; Pinheiro, Bates, & R Core Team, 2022) were computed to determine the effects of the intervention on the outcome variables considering time points (level 1; within-person change pre, post, retention) were nested in participants (level 2; between-person) and participants were nested in school classes (level 3). All models were computed using maximum likelihood estimation. We had a hypothesis that the Linear and Nonlinear group would have a significant effect on self-regulation when compared to the control group.

The likelihood ratio test uses the comparison of information criteria AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) between models while lower criteria show better model fit. This means, when comparing two adjacent models with different specifications, a negative Δ AIC/BIC indicates better fit to the data for the more complex model indicating the added specification is considered to be meaningful (e.g., added aspect as predictor, random effect). Alpha level was set to .05 for all tests. For all targeted, the following step-by-step procedure was used: (1) unconditional model with random intercepts, (2) random-intercept fixed-slopes model adding time as predictor, (3) random-intercept random-slopes model, (4) adding autocorrelation, (5) random-intercept random-slopes model adding group (experimental, control) and their interaction as additional predictor, and (6) adding control variables sex, age, ethnicity, and deprivation decile to the model. Results of models (1) to (4) are used to describe the data and find model specifications, results of model (5 and 6) are used to test the main hypotheses (effects of group on slopes [trajectories]).

For the RCS descriptive statistics, the mean and standard deviation for each group at each timepoint were computed using SPSS. Due to the small sample size, analysis of covariance (ANCOVA) was used to examine the effectiveness of interventions on response to challenge total score, cognitive score, affective score and physical score. The post-test and follow up outcome value were entered as the dependent variable with intervention group as the independent variable. Additionally, gender, ethnicity, SEN, age, deprivation decile and the baseline value were entered as a covariate to control for demographics and the chance of imbalances across groups at baseline. Non-uniformity of variance was checked by examining plots of the residuals of the dependant variable for evidence of heteroscedasticity (Hopkins et al., 2009) and using the Levene's Test for Equality of Variances.

Results

Participant flow

Figure 8 shows the flow of schools and participants through the trial. As outlined previously, in total, 12 schools participated in the study (10% response rate). Schools that declined to participate provided different reasons for not taking part (e.g. already involved in other projects, too busy). Of the 410 potentially eligible children at baseline (T0), 360 were enrolled into the study (88% response rate) and 360 children had valid SDQ data at baseline, 350 children post-intervention and 320 children at follow-up. Reasons for missing data included the teacher being unavailable to complete the questionnaire or administration error. A subsample of children completed the RCS: 140 children completed the RCS at baseline, 93 children post-intervention and 89 children at follow-up. Reasons for missing data were children being absent from school or leaving the school, and due to constraints on data collection time as set by some schools, which made it not possible to complete the RCS with some children within the available time.

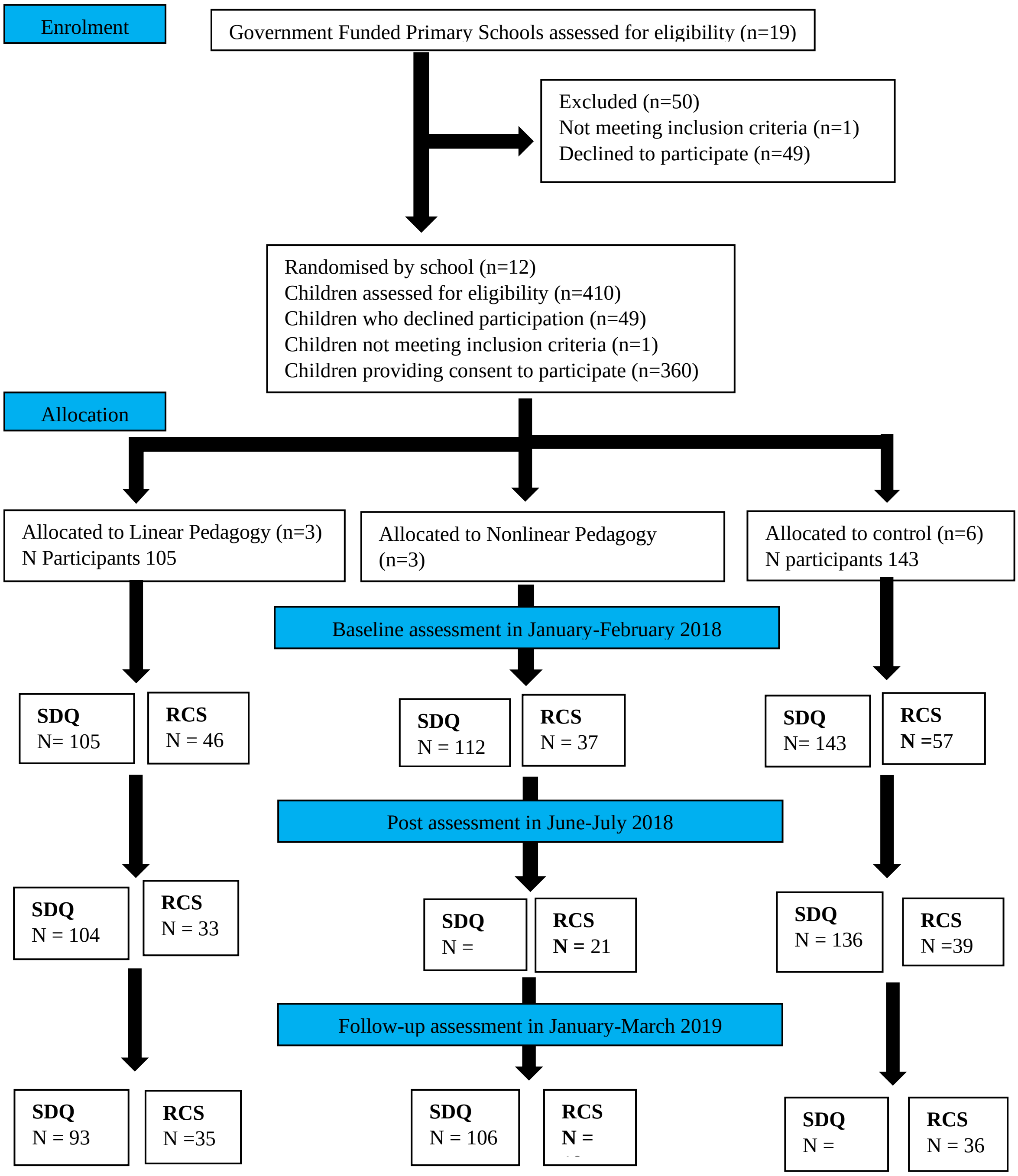

Figure 8 Flow Diagram of the participants included in the self-regulation assessments

Participant Characteristics

Table 12 Demographic characteristics of children by group

	Linear Pedagogy (n=105)		Nonlinear Pedagogy (n=112)		Control (n=143)	
Baseline Characteristic	Mean (SD) Or %	Missing data	Mean (SD) Or %	Missing data	Mean (SD) Or %	Missing data
Decimal Age (years)	6.0 (0.3)	5	5.9 (0.3)	1	5.9 (0.3)	2
Girls	53%	0	52%	0	58%	0
White British	68%	8	52%	9	50%	5
SEN	8%	1	15%	1	12%	0
Living within the 30% most deprived areas (IMD)	96%	4	77%	1	89%	3
IOTF SDS BMI	0.4 (1.3)	9	0.5 (1.1)	8	0.3 (1.1)	27
Thinness grade 3	1%		0%		1%	
Thinness grade 2	2%		1%		0%	
Thinness grade 1	6%		4%		6%	
Healthy weight	61%		72%		67%	
Overweight	21%		14%		22%	
Obese	8%		9%		4%	

Table 12 shows the demographic characteristics of the study sample by group. The pooled sample comprised 360 children (55% girls) with a mean age of 5.9 (Standard Deviation [SD] = 0.3) years; 56% of the children were white British while 44% were from other ethnicities; 12% reported special educational needs of mild and moderate severity and the vast majority lived in highly deprived areas with 85% of the children living in areas classed as the most deprived in England. Based on the International Obesity Task Force (IOTF) classifications, 17% of children were overweight and 6% were obese. BMI was not assessed in 12% of children due to school absence.

Table 13 Descriptive SDQ self-regulation data by group

		Strength and Difficulties Questionnaire									
		Total Difficulties					Prosocial behaviour				
Group	Time Point	Mean	SE	df	lower.CL	upper.CL	Mean	SE	df	lower.CL	upper.CL
C	0	8	1.16	16	5.55	10.5	7.7	0.39	16	6.87	8.52
NL	0	9.52	1.33	14	6.66	12.4	7.54	0.44	14	6.59	8.49
LIN	0	7.17	1.37	14	4.23	10.1	7.34	0.46	14	6.35	8.32
C	1	8.17	1.2	16	5.63	10.7	7.56	0.39	16	6.73	8.39
NL	1	7.51	1.39	14	4.53	10.5	7.61	0.45	14	6.64	8.57
LIN	1	13.5	1.43	14	10.5	16.6	8.11	0.47	14	7.11	9.11
C	2	8.17	1.2	16	5.63	10.7	7.56	0.39	16	6.73	8.39
NL	2	7.66	1.39	14	4.69	10.6	7.51	0.45	14	6.54	8.48
LIN	2	13.5	1.43	14	10.5	16.6	8.11	0.46	14	7.11	9.11

Note: C= Control group; NL = Nonlinear pedagogy group; LIN = Linear pedagogy group.

Table 14 Descriptive SDQ self-regulation data by group

		Baseline			*Post-test*			*Follow-up*		
		N	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*
Total RCS score (0-112)	Control	57	78.89	6.63	39	82.18	7.58	36	80.19	7.33
	Nonlinear	37	79.41	6.44	21	82.38	6.55	18	83.39	5.45
	Linear	46	79.11	6.68	33	80.88	5.84	35	83.23	5.57
Cognitive RCS score (0-42)	Control	57	30.09	2.79	39	31.21	3.11	36	30.03	3.55
	Nonlinear	37	30.51	2.33	21	31.24	2.47	18	31.39	2.38
	Linear	46	29.85	3.58	33	30.42	2.82	35	31.97	2.60
Affective RCS score (0-49)	Control	57	34.26	2.47	39	35.85	3.01	36	35.81	2.87
	Nonlinear	37	34.54	3.97	21	35.67	2.71	18	36.06	2.69
	Linear	46	34.59	2.49	33	35.18	2.46	35	35.74	1.80
Physical RCS score (0-21)	Control	57	14.54	2.38	39	15.14	2.30	36	14.36	2.26
	Nonlinear	37	14.35	2.163	21	15.48	2.400	18	15.94	1.662
	Linear	46	14.67	1.944	33	15.27	1.526	35	15.51	2.120

Note: *N= number of participants, M* = Mean, *SD* = Standard Deviation. Lower values represent higher self-regulation

Table 15. Summary table for the results of the mixed models for self-regulation, adjusting for sex, age, ethnicity, deprivation, body mass index and special educational needs as covariates

	Total Difficulties β and SE	Prosocial Behaviour β and SE
(Intercept)	**14.563***	**7.464****
	(6.017)	(2.442)
Time Point 1	0.235	-0.164
	(0.607)	(0.143)
Time Point 2	0.236	-0.164
	(0.605)	(0.145)
Exp. Nonlinear	1.755	-0.217
	(1.555)	(0.642)
Exp. Linear	-0.431	-0.507
	(1.591)	(0.657)
Sex	**-1.256***	**0.594***
	(0.601)	(0.244)
Age (years)	-1.087	0.006
	(0.987)	(0.400)
Ethnicity	-0.290	0.261
	(0.694)	(0.282)
Deprivation Decile	-0.316	0.077
	(0.185)	(0.075)
BMI (Z-score)	-0.222	-0.084
	(0.246)	(0.100)
SEN	**8.242*****	**-2.161*****
	(0.941)	(0.381)
Time Point 1 * Nonlinear	**-2.315***	0.368
	(0.898)	(0.212)
Time Point 2 * Nonlinear	**-2.152***	0.263
	(0.895)	(0.216)
Time Point 1 * Linear	**6.210*****	**0.893*****
	(0.882)	(0.208)
Time Point 2 * Linear	**6.209*****	**0.893*****
	(0.880)	(0.211)
N	734	734
logLik	-1604.586	-1030.653
AIC	3255.172	2107.306

***Note** SEN Y = 1, SEN N = 0, Girls = 1, Boys = 0, White British = 0 Non-white British = 1*

*** p < 0.001; ** p < 0.01; * p < 0.05

SDQ

Means and standard deviations of total difficulties and prosocial behaviour scores per group are provided in Table 13. Timepoint 0 (t0) is baseline; timepoint 1 (t1) is post-intervention and timepoint 2 (t2) is follow-up.

Total difficulties. Table 15 shows gender (Girls had a lower score) and SEN (having SEN equalled a higher score) were significant predictors of total difficulties. There was a significant group*time interaction in the Linear and Nonlinear group at post-intervention and follow-up: the Nonlinear group made a significant improvement between post intervention and follow up whereas the Linear group significantly declined in the total difficulties score between post intervention and follow up. Post-hoc analyses showed that the Linear group did not significantly improve when compared to the control group from t0 to t1, (LIN: p = 1.18) as well as from t0 to t2 (LIN: p = 1.01). Post-hoc analyses showed that the Nonlinear group significantly improve when compared to the control group from t0 to t1 (NL: p = 0.01) as well as from t0 to t2 (NL: p = 0.01).

Prosocial behaviour. Table 15 shows gender (girls had a higher score) and SEN (having SEN equalled a lower score) were significant predictors of prosocial behaviour. There was a significant group*time interaction in the Linear group at post-intervention and follow-up. There was no significant group*time interaction in the Nonlinear group at post-intervention and follow-up. Post-hoc analyses showed no significant improvements for the Linear or the Nonlinear group when compared to the control group from t0 to t1, (LIN: p = 1.76; NL: p = 0.35) or from t0 to t2 (LIN: p = 2.06; NL: p = 0. 62).

Response to Challenge Scores

Means and standard deviations of total RSC score, cognitive, physical and affective score per group are provided in Table 14. A series of ANCOVAs were conducted to examine the effects of Nonlinear and Linear pedagogies on various components of the RCS scores (total, cognitive, affective, and physical), while controlling for baseline scores, SEN, ethnicity, deprivation decile, sex, and age. Below are the findings for post-test and follow-up assessments:

Response to Challenge Scale: Total scores

After adjusting for covariates, there was a statistically significant difference in post-test total RCS scores between the groups, $F(2, 85) = 4.48$, $p = 0.014$, partial $\eta^2 = 0.095$, indicating a moderate effect size. Post hoc analysis with Bonferroni adjustment revealed no significant difference between the Nonlinear pedagogy group and the control group ($p = 1.000$). However, the Linear pedagogy group showed a significantly higher post test scores compared to the control group (mean difference [small] = 2.94; 95% CI: 0.49, 5.39; $p = 0.013$). No statistically significant difference was found between the groups for follow-up total RCS scores, $F(2, 81) = 1.13$, $p = 0.327$, partial $\eta^2 = 0.027$, indicating a small effect size.

Response to Challenge Scale: Cognitive domain

There was no statistically significant difference between the groups in post-test cognitive RCS scores, $F(2, 85) = 2.96$, $p = 0.057$, partial $\eta^2 = 0.065$, indicating a moderate effect size. A statistically significant difference was observed between the groups in follow-up cognitive RCS scores, $F(2, 81) = 3.24$, $p = 0.044$, partial $\eta^2 = 0.074$, indicating a moderate effect size. Post hoc analysis indicated no significant difference between the Nonlinear pedagogy group and the control group ($p = 1.000$), but the Linear pedagogy group scored significantly higher compared to the control group (mean difference = (medium) 1.50; 95% CI: -2.95, -0.42; $p = 0.042$).

Response to Challenge Scale: Affective domain

There was no statistically significant difference in post-test affective RCS scores between the groups, $F(2, 85) = 2.84$, $p = 0.064$, partial $\eta^2 = 0.063$, indicating a moderate effect size. Similarly, no statistically significant difference was found between the groups for follow-up affective RCS scores, $F(2, 81) = 0.23$, $p = 0.799$, partial $\eta^2 = 0.006$, indicating a small effect size.

Response to Challenge Scale: physical domain

The difference in post-test physical Response to Challenge Scale scores between the groups was not statistically significant, $F(2, 85) = 2.90$, $p = 0.061$, partial $\eta^2 = 0.064$, indicating a moderate effect size. A statistically significant difference was found between the groups in follow-up physical RCS scores, $F(2, 81) = 5.46$, $p = 0.006$, partial $\eta^2 = 0.119$, indicating a moderate to large effect size. Post hoc analysis revealed a significant improvement in the Nonlinear pedagogy group compared to the control group (mean difference = 1.34; 95% CI: -2.34, -0.34; $p = 0.04$), while the Linear pedagogy group showed no significant difference from the control group (mean difference = 0.55; 95% CI: -1.38, 0.29; $p = 0.341$).

Discussion

This study aimed to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve self-regulation among 5–7-year-old children from deprived areas of Northwest England. To our knowledge, this is the first study to explore the effect of Linear and Nonlinear pedagogies on self-regulation. Our analyses of the SDQ also had three main findings: first, participation in Nonlinear pedagogy led to an improvement in the SDQ total difficulties score of self-regulation at the post-intervention and follow-up timepoints. Second, participation in Linear pedagogy led to a deterioration in the SDQ total difficulties score of self-regulation at the post-intervention and follow-up timepoints. Finally, participation in Linear pedagogy led to an improvement in the SDQ pro social behaviour score of self-regulation at the post-intervention and follow-up timepoints. The analysis of the RCS had three main findings: first, participation in the Linear pedagogy group led to a small improvement in the RCS total score at post-test when compared to the control group. Secondly, participation in the Linear group led to a moderate improvement in the RCS cognitive score at follow-up when compared to the control group. Thirdly, participation in the Nonlinear pedagogy group led to a moderate improvement in the RCS physical score at follow-up when compared to the control group. There was no difference in the affective subscale score between the intervention and control groups.

Consistently, in this study, both the RCS and SDQ showed that when compared to the control group, Linear and Nonlinear pedagogy effect different aspects of self-regulation. Linear and Nonlinear pedagogy were hypothesised to have an effect on children's self-regulation because they are underpinned by motor learning theory and previous studies have found interventions focussed on improving children's motor skills have a beneficial effect on self-regulation (Miller et al., 2023). By assessing different constructs of self-regulation, this study gives insight into why a pedagogy focussed on promoting motor skills may promote children's self-regulation. The PE lessons that the control group will have experienced, should involve activities that are developmentally appropriate and promote cognitive, social, physical and emotional skills (Crotti et al., 2022). However, PE teachers do not necessarily have the knowledge of pedagogy to foster these skills and potentially therefore require less self-regulatory abilities (Backman & Barker, 2020).

To date, there has been no other study that has investigated the effect of Linear and Nonlinear pedagogy on the total difficulties element of self-regulation assessed using the SDQ. The total difficulties score is formed from five scales: emotional symptoms, conduct problems, hyperactivity/inattention and peer relationship problems and the score is generated by summing the score from all the subscales. Positive effects on total difficulties score within the Nonlinear pedagogy group could be attributed to a number of factors including: the children are given the chance to decide for themselves how they want to engage in the movement environment, such as the opportunity to choose the level of difficulty (Robinson et al., 2015). Children are also provided with opportunities to self-evaluate their own progress and the teacher stimulates the children's thinking by suggesting prompts and questions that will develop the children's own internal dialogue that helps them to regulate their behaviour (Barkley, 2012; Hautakangas et al., 2022). In Nonlinear pedagogy, children also have the opportunity to make decisions about how to be successful in a motor skill activity, this type of experiences has previously been found to help children develop their self-regulation (Hautakangas et al., 2022).

Prosocial behaviour involves an ability to control behaviour and engage in goal-directed activities alongside others (Li et al., 2022). Eisenburg et al., (2006) reported that prosocial behaviour increases with age and the development stage that the children are at, in this study could have had influenced the results. In this study, Linear pedagogy was associated with an improvement in prosocial behaviour when compared to the control group. This may be explained by the fact that in Linear pedagogy, a child will need to recognise how the actions of others align with the goal, potentially disengage with their own part of the activity and formulate a plan of action to help others achieve the goal (Blake et al., 2015). Crotti et al., (2022) reported that Linear pedagogy had higher incidences of Game Play which, could indicate the children had more opportunities to work as a team and learn how to behave alongside one another. Another study also found that experiencing positive emotions promoted prosocial behaviour (Li et al., 2022). It could be that in Linear pedagogy; the children are experiencing many more positive emotions of the goals achieved; they are potentially set at much more regular intervals during the sessions and goals are broken down into small milestones that can be achieved. However, it would have also been expected that the novelty and diversity of Nonlinear pedagogy would have promoted positive emotions and subsequent use of self-regulation processes (Audriffen & Andre, 2015; Pesce, 2016). Future research would need to assess the level of interaction between children during the Linear and Nonlinear pedagogy PE lessons to make an exact conclusion of the different levels of interaction between children in each pedagogy (Li et al., 2022).

To date, there has been no other study that has investigated the effect of Linear and Nonlinear pedagogy on the Response to Challenge Scale assessment of self-regulation. Positive effects on the RCS physical score in the Nonlinear group could indicate that when compared to the control group, Nonlinear pedagogy has greater responsiveness to the physical individual needs of the children, important for the development of self-regulation (Hautakangas et al., 2022). Nonlinear pedagogy promotes the inherent problem solving of movement that potentially enables the enhancement of processes underpinning a child's regulatory behaviour (Adolph & Hoch, 2018). Physically, the children are encouraged to vary their movement significantly during the Nonlinear pedagogy lessons, trying out multiple different ways to achieve a goal. It could be that in the control group, there is greater repetitiveness of the same movement across multiple sessions that requires less self-regulation. The focus on motor skills in Nonlinear pedagogy ensures the children experience a complexity of movement that potentially creates greater challenge of physical self-regulation (Miller et al., 2023)

Linear pedagogy has less opportunity for children to participate in solving a problem, often the answer is given to the children through modelling by the teacher. However, the RCS showed that Linear pedagogy improved the total score and cognitive domain of self-regulation. It could be that the experience of making less choices by themselves helped the children to learn about the boundaries they need to control their behaviours, and this didactic approach gave the children the parameters they need to inhibit impulsive responses, plan and adapt their approach to achieving a motor skill goal (Vink et al., 2020). Other studies that have used a teaching strategy to help children how to learn with control of their emotions and behaviours shows the scaffolding of each task instructed in Linear pedagogy would promote a control of the actions taken by the child in a step-by-step manner (Bronson, 2000). The focus on motor skills in Linear pedagogy may help the children to develop their control over an action by breaking it down into clear stages from the start to the end of the movement. Finally, it is interesting to consider the impact of Linear pedagogy across both assessments of self-regulation: Linear pedagogy might have led to a deterioration in the SDQ total difficulties score because its structured approach could inadvertently amplify rigidity or stress for children already struggling with behavioural or emotional challenges. However, the same explicit instruction could improve the RCS cognitive score by providing clear frameworks and strategies which help children respond effectively to tasks. The different findings across both Linear and Nonlinear pedagogy, indicate that future research should explore the potential of using a combination of pedagogical approaches through a multi-model curriculum in order to achieve a broad range of learning outcomes that focus on children's holistic development in PE (Casey & MacPhail., 2018). One common element between linear and nonlinear pedagogy is that they both aim to achieve the same learning outcomes, which is essential for supporting a multi-model curriculum (Casey & MacPhail, 2018). For teachers to effectively integrate these pedagogical approaches, it is important that the key features of each are clearly defined. This clarity enables educators to engage with the unique concepts each model offers, allowing them to adapt and evolve their teaching methods accordingly (Casey & MacPhail, 2018). Moving forward, research should investigate how each pedagogy can undergo a process of ongoing development and refinement. This would help identify which elements are most likely to be widely and clearly adopted by teachers, particularly in terms of their value for linking movement and cognition (Casey et al., 2021). A key strength of models-based practice is its potential to blend different pedagogies, providing educators with the flexibility and autonomy necessary to deliver lessons effectively while still achieving intended learning outcomes (Casey et al., 2021). In terms of viability, for teachers to have the confidence to work with such flexibility and autonomy, they need to exit their training with a great sense of confidence in their own knowledge base of different pedagogical approaches.

Strengths and limitations

The study included several strengths, it was the first study to investigate the effect of Linear and Nonlinear pedagogy approaches on self-regulation, comparing it to current PE practice in primary school. The direct assessment of self-regulation through movement via the RCS is a strength of this study. A further strength was the measurement at both post-intervention and follow-up, the follow up assessments allowed for medium term improvements to be assessed. Another strength was that multilevel models accounted for different demographic variables associated with self-regulation.

It is important to note the limitations: the SDQ is a proxy measure of self-regulation completed by teachers. Also, the generalisability of the study's results is limited by the age and demographic characteristics of the sample. The study focussed exclusively on children aged 5-7 years living in areas of deprivation, which may not fully represent the diverse range of children's experiences and developmental trajectories.

Conclusions

In conclusion, the findings from this study show that among children aged 5-6 years living in an area of deprivation, pedagogical interventions based upon motor learning theory have a differential effect on self-regulation. The explicit instructions in Linear pedagogy may have taught the children important early lessons on how to self-regulate their behaviour during a motor skill that they can clearly identify the control required at the different stages of the action. In contrast the level of exploration and autonomy in Nonlinear pedagogy may have created the opportunity to experience problem-solving activities that require self-control to achieve the motor skill goal.

Such findings are particularly relevant for designing primary PE curriculum to support the development needs of children living in deprived areas. It is important for future research to examine the effect of PE pedagogy in children from different areas of deprivation, age groups and cultural contexts to determine whether the effects hold across varied populations. This broader understanding will further inform the development of tailored interventions to support children’s self-regulation.

Chapter 6 Synthesis

Introduction to the chapter

This chapter will be a synthesis of findings from across the thesis. I will seek to summarise the aims, outcomes, strengths and limitations of the studies presented in this thesis. Furthermore, the chapter will include a discussion of the studies' contributions and implications for research, policy and practice, proposing avenues for future research. The last section of the chapter will be a personal reflection about my PhD journey.

Aims and objectives

This thesis was part of a wider RCT called the SAMPLE-PE project (Rudd et al., 2020). The aim of SAMPLE-PE was to better understand how UK primary school PE pedagogy can support PA behaviours and affective, physical and cognitive skills of children living in an area of deprivation. The overarching aim of this PhD thesis was to explore the influence of different aspects of movement on cognition among children aged 5-7 years living in an area of deprivation. As part of the RCT, there were three data collection points at baseline (Study 1), post-test (Study 2 and 3) and follow-up. Study two aimed to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve EF among 5–7-year-old children living in areas of deprivation. Study three aimed to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve self-regulation among children aged 5-7 years living in an area of deprivation.

The objectives and key questions of this thesis were to:

Study one:

- Examine how demographic factors are associated with executive function.
- Investigate the association of each measure of movement (PA dose, movement proficiency, and divergent movement) with executive function.
- Examine how the combination of PA and motor competence variables are associated with executive function.
- Include an ecological approach to the measure of movement that assesses a child's exploration of divergent movement solutions

A key question in this study was that after controlling for demographic factors, which movement variable(s) had the strongest association with EF? Also, does a combination of PA and motor competence variables have a stronger association with EF? Demographics, motor competence, and a combination of motor competence and PA were hypothesised to be significant predictors of EF.

Study two:

- Examine the effect of Nonlinear or Linear pedagogy compared to current PE delivery in schools on executive function of 5–7-year-old children from a deprived area of Northwest England.

A key question in this study was: when compared to the control group does a pedagogy underpinned by motor learning theory have a greater effect on EF? It was hypothesised that Linear and Nonlinear pedagogy would have a greater effect on EF when compared to the control group.

Study Three:

- Examine the effect of Nonlinear or Linear pedagogy compared to current PE delivery within schools on the self-regulation of 5–7-year-old children from a deprived area of Northwest England.

A key question in this study was: when compared to the control group does a pedagogy underpinned by motor learning theory have a greater effect on self-regulation? It was hypothesised that Linear and Nonlinear pedagogy would have a greater effect on self-regulation when compared to the control group.

Unique contribution to the literature

Study 1

- *This study extends the assessment of movement quality showing an association between exploratory movement and executive function of children aged 5-6 years living in an area of deprivation*
- *A consideration of the unique and combined associations between physical activity dose and movement competence with executive function of children aged 5-6 years living in an area of deprivation*

Study 2

- *The first study to investigate the effect of PE interventions guided by Linear and Nonlinear pedagogy on children's executive functions.*
- *This study highlights the importance of a pedagogical approach underpinned by motor learning theory adopted by a PE teacher to support the development of movement and cognitive outcomes.*

Study 3

- *The first study to investigate the effect of PE interventions guided by Linear and Nonlinear pedagogy on children's self-regulation.*
- *The first study to assess self-regulation using the Response to Challenge Scale with children aged 5-6 years living in an area of deprivation*
- *This study highlights that a combined 'multi-model' pedagogy should be the focus of PE teacher training to elicit the greatest benefits on cognitive outcomes.*

Summary of key findings

Study 1: Associations of physical activity dose and movement quality with executive functions in children aged 5-6 years living in an area of deprivation.

It is well documented that there is a disparity of the EF skills of children living in an area of deprivation (Haft & Hoeft, 2017; Lawson et al., 2018; Mooney et al., 2021). To improve the academic trajectory of children living in an area of deprivation it is crucial to identify controllable factors that may reduce the gap in EF skills (Merz et al., 2019; Waters et al., 2021). Previously, there has been contrasting findings in the literature; there are some studies that report PA dose has the greater association with EF (Hillman et al., 2008; Donnelly et al., 2016; Van Waelvelde et al., 2019); others focussed on the effect of motor skills (Van der Fels., 2015; Tomporowski & Pesce, 2019); whilst another body of research that has sought to identify the benefit of other movement qualities such as motor creativity on EF (Vasilopoulos et al., 2023). The aim of the first study in this thesis was to address this issue by using cross-sectional data to investigate the associations of PA dose and movement quality with EF in children aged 5-6 years living in an area of deprivation. Three different modes of movement assessment were used: movement proficiency and divergent movement ability (collectively understood as motor competence) and PA dose with EF. Demographics, motor competence, and a combination of motor competence and PA were hypothesised to be significant predictors of EF assessed using the NIH toolbox in a sample of 360 children aged 5-6 years living in an area of deprivation. After controlling for demographics, it was found that motor competence and PA variables better predict EF when considered together. Tomporowski and Pesce (2019) explained that there is an interaction between energy expenditure and the allocation of mental resources required during skill acquisition. When exertion levels are balanced with skill demands, EF are engaged to assess and adjust performance. However, if the physical or skill challenge is too low or too high, it may cause fatigue or loss of focus, hindering EF. Thus, optimizing the balance between motor competence and PA is essential for effectively engaging EF.

When considered individually, demographics, motor proficiency and divergent movement were significant predictors of EF, whilst PA variables were not. The model with movement proficiency explained 16% of EF variance ($r^2 = 0.16$ 95% CI = 0.08–0.26). This finding was consistent with the findings of a previous study by Cook et al. (2019), who found that motor skills were associated with EF and PA dose was not. This suggests that a careful balance needs to be struck in primary school PE, that the competing demand of the curriculum aims, should not lead to a dominance of PA dose, neglecting a key focus on movement competence. A novel finding from this study was that divergent movement competence exhibited the strongest positive association with EF ($r^2 = 0.19$ 95% CI = 0.12–0.28). This is consistent with the motor creativity literature that has reported an association with EF (Scribinetti et al., 2011; Crenshaw, 2020). Divergent movement is understood to be an aspect of motor creativity that focusses on how a child explores functional movement outcomes and diverges from habitual behaviours and routines (Hulteen et al., 2023). This is an exploratory movement capability that can be explained from an ecological perspective, which views cognition as an activity across the whole system whereby EF are embedded in the self-organisation processes and mutual relations between a child and the dynamics of their environment (Adolph & Hoch, 2019). This suggests that the process of using EF should not be considered as a black box computer system housed in the brain.

Study 2: The effect of physical education lessons underpinned by motor learning theory (SAMPLE-PE) on children's executive function

In areas of deprivation, parents rely on school as the key environment where their children will be physically active and gain associated health and development benefits (Eyre et al., 2022). 'Quality' PE has been reported to promote the development of EF (Alvarez-Bueno et al., 2017; Garcia-Hermoso et al., 2021). One way of ensuring quality PE is by implementing a curriculum with a strong theoretical basis so that lessons are developmentally appropriate, systematic and progressive (Rudd et al., 2020). Linear pedagogy and Nonlinear pedagogy are underpinned by motor learning theory and have demonstrated positive effects on motor skill development, one of the main goals of the National Curriculum (Marzoni et al., 2022; Chow et al., 2006). Children's motor skills have been positively associated with the development of EF (Van der Fels et al., 2015; Tomporowski & Pesce, 2019). However, little is known about the impact of Linear and Nonlinear pedagogy on EF. Therefore, the aim of study two was to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve EF among 5–7-year-old children from deprived areas of Northwest England.

It was found that participation in Nonlinear pedagogy when compared to the control group, led to an improvement in working memory at the post-intervention and follow-up timepoints. This contributes to the literature that has emphasised how when explaining working memory performance both the child and their environment need to be considered (Hambrick et al., 2020). This is different to traditional approaches to research on working memory that focusses on how internal cognitive structures and processes make up a system of working memory separate from the external environment (Hambrick et al., 2020). Previously interventions have identified features such as the level of challenge, playfulness, enjoyment and cognitive enrichment have a more positive effect on children's working memory (Yi-Zhang et al., 2022; Diamond & Ling, 2016; Takacs & Kassai, 2019). In Nonlinear pedagogy, cognitive enrichment may come from task variability that encourages children to explore and adapt their own solutions. Instructions focus less on conscious control of each movement stage and more on overall movement effects, promoting self-organization. Working memory here involves understanding the entire task over time, integrating previous and upcoming actions (Diamond, 2013). Linear pedagogy may not have been effective at promoting working memory because the amount of information given to the children at each stage of the task will not require re-organising or manipulating individual responses.

Study two also found that Linear pedagogy led to an improvement in cognitive flexibility at the follow-up timepoint. Cognitive flexibility, which develops after inhibitory control and working memory, may explain why positive effects appeared at follow-up rather than immediately post intervention (Diamond, 2013). In Linear pedagogy, the increasing complexity of tasks prompts children to adjust, and shift focus between movement components. This challenge may encourage them to "think outside the box" by testing and refining approaches to match an ideal model (Diamond, 2013). It was a surprising result that neither Linear pedagogy nor Nonlinear pedagogy had an effect on inhibitory control. This is in contrast to previous literature that has reported interventions which promote variability of practice that would align to Nonlinear pedagogy principles had a positive effect on inhibitory control (Pesce et al., 2016). The process of motoric stopping that would have occurred in Linear pedagogy when the children were aligning their movements to the steps outlined would have expected to promote inhibitory control (Traut et al., 2021).

Study 3: The effect of physical education lessons underpinned by motor learning theory (SAMPLE-PE) on children's self-regulation

Self-regulation operates across several levels of function and its development during early childhood is understood to be predictive of short and long-term outcomes such as academic achievement and life choices (Montroy et al., 2016). Early childhood is viewed as being a rapid period of change and there needs to be further understanding of the dynamic interaction between development areas. Motor competence and self-regulation share fundamental processes including goal-directed activity, planning sequenced actions and control over body movements (Miller et al., 2023). While cross-sectional data shows there is a positive association between motor competence and self-regulation (Veldman et al., 2023), there is, however, limited literature that has identified the benefit of motor skill interventions on self-regulation (Veldman et al., 2023). Key characteristics of an intervention that may promote self-regulation include a mastery climate and a child-centered environment that enables children to select their own goals, foster autonomy and master increasingly difficult motor skills (Miller et al., 2023). There has been no previous study that has investigated the effect of PE pedagogy that are underpinned by motor learning theory (Linear and Nonlinear) on self-regulation. This study aimed to assess the efficacy of utilizing Linear and Nonlinear pedagogy within PE to improve self-regulation among 5–7-year-old children from deprived areas of Northwest England. In this study it was hypothesised that Nonlinear pedagogy would have a greater effect on self-regulation because the key features of the intervention align with the findings of previous studies (Miller et al., 2023).

In the total sample of 360 children the SDQ was used to measure self-regulation at baseline, post-test and follow-up, and the intervention groups were compared to a control group. In a subsample, the Response to Challenge Scale was used as a physical assessment of self-regulation measured at the same timepoints. It was found that the children in the Nonlinear pedagogy intervention made significant improvements in their SDQ total difficulties score at post-test and follow-up. Nonlinear pedagogy also led to an improvement in the RCS physical score at follow-up when compared to the control group. Nonlinear pedagogy uses guided discovery to enhance self-regulating autonomy and competence (Chow et al., 2021). Autonomy is key for self-regulation, requiring motivation to be self-driven rather than controlled (Legault & Inzlicht, 2013). Linear pedagogy did not have an effect on the SDQ total difficulties score of self-regulation, potentially because there was not enough autonomy whereby the movement behaviours were directed by the adult. However, when self-regulation was measured using the RCS Linear pedagogy was found to lead to an improvement in the total score at post-test when compared to the control group and RCS cognitive score at follow-up. The physical challenges of linear pedagogy seem to have an effect on self-regulation whereby the children are learning to work within specific parameters to regulate their physical actions.

Another finding of this study was that Linear pedagogy led to an improvement in the pro-social behaviour score of the SDQ. This part of the scale assesses the children’s ability to identify actions that benefit others and relate well with peers (Silva et al., 2015). The features of Linear pedagogy can be compared to traditional practices in PE that are associated with the goal to inspire participation in competitive sport, requiring the skill of teamwork whereby the group of children share a clear common goal (Gov.UK, 2024). From a self-regulation perspective, it could be that the performance of the sport in a team, will help the children to understand how others are reacting to their behaviour and learn to support one another through a process of socially shared regulation (Braund & Timmons, 2021; Heatherton, 2011).

Synthesis and Integration of Findings

Assessment of movement and cognition

It is essential that an assessment is accurate and meaningful, connected well to the experiences under investigation. Some assessments only measure one dimension at a time, rather than collecting information holistically about the construct (Downs et al., 2020): especially when assessing broad constructs such as movement and cognition, it is essential to ensure the assessments capture all elements and relates to contextual factors. Assessments should be authentic to daily life scenarios to understand how movement and cognition perform in typical environments. Movement and cognitive skills vary significantly across ages and developmental stages and so assessments should account for age, experience, and baseline abilities, especially when these capacities are still developing. This thesis included some novel assessments alongside more established forms of assessment that enabled a broader view of movement and cognition of children aged 5-6 years living in an area of deprivation.

Unlike traditional assessments of movement competence that may emphasise standardised outcomes, the Divergent Movement assessment recognises individual differences in movement solutions. This reflects real-world experiences to date for children at this age where their PA will be in environments that are changeable and varied, where fixed, repetitive movements are not ecologically valid. It also aligns with the Nonlinear pedagogy under investigation to support an explanation of why this approach to PE has an impact on EF and self-regulation. As discussed previously, divergent movement and Nonlinear pedagogy can be explained from ecological approach of understanding an individual's ability to create movement solutions in varied settings. This provides a platform for exploring how children are using EF during a movement. The scoring focuses on the variety of responses rather than a strict adherence to the demonstration of a specific movement. The child is awarded a higher score for coming up with unique ways to complete a task and varying movements. It is challenging the view of which aspect of a movement experience requires EF.

The Response to Challenge Scale assesses self-regulation as it occurs in real-time in a situational context, observing how a child reacts to progressively challenging and novel tasks (Lakes, 2012). This offers a direct measure of self-regulation rather than the SDQ as a proxy measure where the teacher makes inferences about the child in response to different statements about self-regulation. The RCS enables an investigation of self-regulation as a multi-dimensional construct, assessing physical, affective and cognitive domains. Rather than the SDQ that breaks down self-regulation into different categories, the findings of the RCS are transferrable to other research that has investigated the same domains.

The varying level of challenge of each task in the obstacle course was carefully adapted to ensure it was age appropriate, requiring the child to adapt to setbacks when their initial attempts were not successful. The instructions and feedback from the leading adult were kept to an absolute minimum to ensure consistencies in completion of the obstacle course by each child, creating challenges the child had to complete independently of support. A physical assessment is appropriate for creating this level of difficulty for a child to face because of the enjoyment level children have in trying different movement challenges. It is also possible to capture their multiple attempts at the task and the varying degree of difficulty throughout the course made it a positive experience for the children. Future research should establish the convergent validity of the RCS with other assessments of self-regulation.

Movement Qualities

There are so many different arguments in the literature that can often present the quantity and quality of movement having a distinct role for why PA can benefit EF. However, this thesis showed that the strongest association with EF occurs when movement is viewed holistically, combining quality and quantity, considering PA dose and movement competence. When trying to achieve the aim of PE of promoting cognitive development, this study moves the focus away from simply getting children active and brings into focus, a need for pedagogy underpinned by theory that has the goal of developing children's motor competence.

In previous discussions of motor competence, the acquisition of motor proficiency has been the dominant focus, and this thesis has emphasised that a child's exploratory movement capability is also an important movement quality when investigating the association with EF. As mentioned earlier, exploratory movement does not prescribe one uniform movement, instead children are encouraged to explore their own functional movement solutions (Rudd et al., 2020). The focus of this thesis was children living in an area of deprivation and the importance of divergent movement is a notable finding that should influence the priorities of their PE experience, especially when this group of children are less likely to get opportunities in their free time to experience exploratory movements in the outdoors for example (Seers et al., 2022).

There are a number of different features of a task that are associated with developments in EF, exploratory movement requires information-gathering activity that in real time, can guide adaptive actions (Adolph & Hoch, 2019). When thinking about the association with EF, the child is having to behave with initiative and face the challenge of achieving goals that they set (Rodriguez, 2022). Exploratory movement relates to how we need to be flexible and adapt which, could require higher-order thinking skills (Adolph, 2008). Adaptive actions are generative and creative, involving problem solving (Adolph & Hoch, 2018). Flexibility involves using a variety of actions to achieve the same functional outcome and requires the transfer of existing information to a new situation (Adolph & Hoch, 2018). As indicated earlier, rather than focussing on EF as an internal process housed in a computer-like system in the brain, the finding in this thesis that exploratory movement has a stronger association, adds to the literature that discusses EF as part of a whole system of body-environment relations. In exploratory movement children need to determine which actions are functional and which are not, to do this they have to generate, detect and use perceptual information. Exploratory movement emphasises a movement quality that the same action cannot be repeated in the same way in every situation because a child's body, environment and tasks are in continual flux. EF may be required to meet the demands of novelty and variability of movement as a quality that needs to be considered when planning interventions and considering features of pedagogy such as instruction giving and task demands.

As discussed earlier, also having a focus on motor proficiency creates an effective level of challenge and demands goal-setting behaviours that will involve EF

(Tomporowski & Pesce, 2019). This thesis has supported the view outlined in a number of meta-analyses and systematic reviews that motor skill learning benefits EF (Van Der Fels et al., 2015; Zeng et al., 2017; Gandotra et al., 2021; Tomporowski & Pesce, 2019) and this association is particularly significant for children under the age of 13 years (Van Der Fels et al., 2015). One mechanism suggested earlier is that motor skills and EF rely on overlapping neurological processes and regions, particularly in the prefrontal cortex and cerebellum (Shi & Feng 2022; Diamond, 2000). Motor proficiency activities demand control and precision that activate these areas, effectively strengthening neural networks that support EF skills like planning, problem-solving, and impulse control (Diamond, 2000). The cerebellum, traditionally associated with motor control, also plays a role in cognitive functions like attention and timing, suggesting a neurological overlap that supports both motor and EF development (Stoodley & Schmahmann, 2009). Other suggestions are that motor proficiency require sequencing of tasks, so when children are practicing these steps, they are also strengthening their ability to retain, process and manipulate information (Alloway & Alloway, 2010). As highlighted earlier, motor proficiency tasks like learning a sport or practicing a dance routine have been shown to engage EF (Oppici et al., 2020). In tasks that involve stopping, changing, or adjusting movements, for example in martial arts the process involves restraining automatic impulses in favour of more considered responses (Giordano et al., 2021). SAMPLE-PE used categories of motor skills and associated sports and activities to structure the intervention, for example dance was the first of three sections of the curriculum.

The importance of Physical Education

Eyre et al. (2022) reported that in schools for an area of deprivation, there are multiple barriers in the implementation of PE. As previously noted, it is a challenging time for PE, with competing pressures to achieve a number of outcomes. There is the pressure to reduce the decline in PA across childhood into adolescence and maximise enjoyment to sustain participation (Haas et al., 2021). Maximising enjoyment is associated with a move away from traditional PE to games-based activity (Mo et al., 2024). It is also a challenge of curricular PE to reduce time between tasks where children are sitting or standing to listen to instructions and time-off task taking turns to participate to ensure recommended amounts of time spent in MVPA (Crotti et al., 2022). There is a suggestion that PE teachers prioritise PA dose and its associated health benefits, rather than learning in the subject (Larsson & Nyberg, 2017; Saether et al., 2023). This study highlighted that children's opportunity to be physically active needs carefully designed activities to optimise the effect on cognitive development and subsequent academic achievement.

PE is said to be a subject with an identity crisis whereby staff are unclear how to avoid activities and traditions that have come under criticism (Kirk, 2010; Saether et al., 2023). As described earlier, for children living in an area of deprivation, PE is their first experience of structured PA because they have often had limited access to equipment and greenspace (Ofsted, 2023; Brockman et al., 2009). It is essential for physical educators to challenge traditions and consider specific teaching approaches that can benefit multiple aspects of children's development of skills. This study shows that a PE curriculum needs a clear design that encompasses multiple movement qualities, not just a focus on one aspect in isolation, rather a combined approach to targeting PA dose and movement competence.

The importance of pedagogy

This thesis shows that a pedagogy underpinned by motor learning theory that supports the development of EF and self-regulation when compared to control group schools. Teachers and sports coaches delivering the sessions in the control group likely did not have substantial knowledge of pedagogy and that may explain why there was lower incidence of motor content, discovery and skill practice in those sessions (Crotti et al., 2022). The key features of Nonlinear and Linear pedagogy can provide a toolkit of ideas for teachers that, identifies ways in which PE experiences can support the development of EF and self-regulation. This thesis has challenged the view of pedagogy as instruction of children and rather the focus should be on the design of the environment and session to create quality interactions.

In Nonlinear pedagogy, it is interesting to consider how a child uses the environment and opportunities the task presents to manage the cognitive demands of the task (Hambrick et al., 2020). Working memory is required when a child needs to consider alternative actions, making relations between ideas (Diamond, 2013). This process aligns with the experience of Nonlinear pedagogy where the goal is to amplify exploratory behaviours and through an experience of variability encourage adaptive behaviours that lead to individual functional solutions (Correia et al., 2018). It is interesting to consider the processes that underpin the acquisition of new coordination patterns (Chow et al., 2021): when trying to reach the goal of finding a function movement solution, the child is having to consider alternative ideas as they adjust and make sense of new information as they trial different approaches to the task, potentially exploiting a self-organisation process that will involve working memory and self-regulation.

As described earlier, Nonlinear pedagogy does not focus on developing cognitive capacities from an asymmetrical view of cognition as a central controller but rather as an intertwined relationship between cognitive, perceptual and motor systems (Correia et al., 2018). There is a mutuality between the learner and their environment where cognitive processes are part of a human movement system navigating the information that is available in a search for different movement solutions (Chow et al., 2021). There is an influx of information and connections that can be made between different individual, task and environment constraints. An important feature of Nonlinear pedagogy is that in terms of input and output, there is a non-proportionate relationship (Chow et al., 2021). Working memory may support spontaneous changes to coordination and movement patterns that emerge (Diamond, 2013). It is critical to a child’s ability to be creative and see connections, Nonlinear pedagogy promotes such an individualised approach to learning (Diamond, 2013; Chow et al., 2021).

The focus on meaningful contexts in Nonlinear pedagogy may challenge a child to connect with past and future plans to reach a goal (Diamond, 2013). Rather than focusing on repetition, Nonlinear pedagogy encourages a “noisy” learning environment, allowing children to explore different ways to achieve movement goals, which promotes decision-making and problem-solving, requiring self-regulation (Chow et al., 2011). As referenced earlier, using a constraints-led approach, teachers act as facilitators, adjusting elements like equipment or space to guide students toward exploring diverse movement patterns, supporting both physical and cognitive growth (Chow et al., 2021). A principle of Nonlinear pedagogy is that a small change to a task may lead to significant change in the behaviours that emerge. The key is autonomous behaviour of making choices and engaging in personally meaningful activities (Legault & Inzlicht, 2013). Nonlinear pedagogy embraces the chaos of a child’s exploratory activity to produce an individualised movement pattern that meets the goal of the task (Chow et al., 2011). It could be the autonomy and fluctuations in the stability of the neurobiological systems during this experience supports the development of working memory and self-regulation (Chow et al., 2011).

Linear pedagogy follows a traditional structure that progresses from a warm-up, to drills, and then performance of the sport or game that will have a clear goal, before a cool down (Crotti et al., 2022). Linear pedagogy involves clearly defined steps and sequences in skill acquisition. This structure helps children understand task expectations and potentially reduces cognitive load by focusing on one skill at a time supporting self-regulation (Seufert, 2018). It appears the number of changes in the task to incrementally adjust the instructions in Linear Pedagogy has potentially also had a positive effect on cognitive flexibility. Small changes in task settings can result in significant alterations in behaviour, promoting shifts in attention and self-regulation.

Linear pedagogy emphasizes repeated practice of a skill before progressing to the next stage. This helps children rehearse specific movements until they become more automatic, learning to focus on relevant cues and ignore distractions, a crucial component of self-regulation (Best & Miller, 2010). Linear pedagogy also gradually increases task complexity; therefore, children can build foundational skills before tackling more challenging aspects, which supports cognitive flexibility as they learn to integrate new skills into previously mastered ones. This incremental approach allows children to monitor and regulate their progress, building their confidence and self-regulatory abilities as they recognize improvements in their skills (Tomporowski et al., 2008).

As mentioned earlier, information processing theory references ideal movement patterns so optimal movements are modelled. Linear pedagogy often involves immediate corrective feedback, allowing children to adjust their performance according to the teacher's guidance. This feedback helps them develop self-monitoring skills, which are essential for self-regulation. Through this process, children learn to adjust their behaviours based on external cues, internalizing these self-corrective processes over time (Zimmerman & Kitsantas, 2002). Linear pedagogy often includes clear, sequential goals, such as mastering one technique before moving to the next. These goals provide motivation and help children learn to set and achieve objectives, reinforcing planning and goal-directed behaviour, which are key for self-regulation (Schunk & Zimmerman, 1997).

The clear parameters of what is expected of one another may foster children collaborating with others while navigating their paths to skill development, benefiting from peer feedback (Renninger, 2010). In Linear pedagogy, the instruction will direct a child's attention internally towards their own body part, that will be standardised for all children in the group rather than an external focus on their movements in the environment that is much more individualised (Gottiwald et al., 2023). The purpose of the instructions is to support the development of skill acquisition, but it may have also had a consequence for how the children relate to one another by sharing the same focus on their body position. The children are becoming aware of the parts of their motor behaviour as a gauge against a norm they are sharing with others (Heatherton, 2011).

Combining different aspects of the Pedagogical Models

This PhD has shown that two contrasting pedagogical models benefit EF in different ways; this supports the view of Casey & MacPhail, (2018) that PE practice may need a broader theoretical frame of reference, involving a hybrid pedagogy which combines multiple models. A multi-model approach could create the right level of challenge and innovation PE needs (Lund & Tannehill, 2014). Casey & MacPhail (2018) suggested that one instructional model on its own cannot provide a depth of learning required to effectively meeting PE outcomes.

A feature shared between Linear and Nonlinear pedagogy is that they have the same learning outcomes which is key to a multi-model curriculum (Casey & MacPhail, 2018). The components of each pedagogy would need to be clear for teachers so that they can take ownership of the new ideas each pedagogy presents to shape and reshape their practice (Casey & MacPhail, 2018). Future research should explore how each of the pedagogies investigated in this PhD need to go through a ‘development-refinement cycle’ to understand which key aspect will be consistently adopted by multiple teachers with clarity of their benefit to the movement-cognition relationship (Casey et al., 2021). The benefit of models-based practice is that the combination of pedagogies could give the teacher the freedom and flexibility they need for successful delivery that meets learning outcomes (Casey et al., 2021). There is the potential that different aspects of Linear and Nonlinear pedagogy align with a teacher’s existing way of delivering PE, to be effective, it is important that the introduction of a pedagogy does not just feel like a new blueprint way of doing something that creates an uncertainty of its value (Casey et al., 2021). Teachers need to engage in continuous professional development that helps them to reflect on how a pedagogical approach blends with their own values and build on their existing approach. There needs to be regular opportunities to reflect on pedagogical approaches because over time, teachers will form habits and ways of doing activities that could be adjusted and flexed to adopt effective features of pedagogy. It could be that future research on the benefits of Linear and Nonlinear pedagogy to EF and self-regulation could include some reflective practice of the teachers to identify key features that are having the desired effect.

Strengths of this thesis

This thesis was part of a cluster randomised controlled trial that is the gold standard for evaluation. A major strength of this thesis is that validated tools were used to assess PA dose, motor competence, EF and self-regulation. Furthermore, a novel tool the Response to Challenge scale was adapted to include a direct assessment of self-regulation. An important strength of study 1 was that is measured both children's PA dose and movement competencies. A major strength was the inclusion of TGMD-3 and accelerometer-based measurement of habitual PA and the use of novel raw acceleration metrics that could facilitate the comparison with other studies. A novel tool, the divergent movement assessment was also included that provided a holistic view of movement competence.

Another strength of this thesis was that study 2 and 3 were the first studies to investigate how PE interventions based on Linear pedagogy and Nonlinear pedagogy could effect EF and self-regulation, which is vital to inform future PE-based interventions and applied pedagogic practice that meets the overall aims of PE in the UK. The comprehensive investigation of EF and self-regulation across the thesis is considered another strength. This thesis was comprehensive and methodical in the way it gathered data. Lastly, methodological strengths of study 2 and 3 include the use of the clustered randomised controlled trial design, allowing a clear comparison between the control and intervention conditions, and statistical models accounting for data being nested in addition to modelling in a range of covariates.

Limitations

Specific limitations have been highlighted in each chapter; however, some overarching issues will be discussed here.

There are some challenges when carrying out assessments with 5-6-year-old children. For example, the inhibitory control and cognitive flexibility task involved quite repetitive activities for the children and a number of them were observed to lose focus during the activity. When assessing working memory, the computer programme took the children through a series of practice tasks which did not contribute to the score, it then started the actual task that had fewer instructions than the practice which a number of children found very challenging. This resulted in a large proportion of the children scoring a 0 as their raw score of working memory. There needed to be a more accessible element to the task for the children that were going to find this task difficult.

Measuring deprivation is complex because its multi-dimensional including economic, social, health, educational and environmental aspects and deprivation is dynamic whereby an area might improve due to investment or another might decline because of job losses and data is only collected every few years. Turning a lived experience into measurable numbers is a challenge. Deprivation decile is a ranking not a score so it is measuring the most deprived relative to others, not necessarily deprived in absolute terms and this means in a wealthier country, even the “most deprived” areas might still have higher living standards than the “least deprived” in a poorer country. Deciles average data across small areas, but wealthy and deprived households can live side by side, local pockets of deprivation can be hidden if the area overall is measuring as ok. Reducing deprivation to a single decile can oversimplify multidimensional issues like health, education or housing.

In the analysis, I haven't explored mediation to determine whether improvements in motor competence led to improvements in EF and self-regulation. This was beyond the scope of this thesis but should be explored in future research. Also, in the analysis, to account for missing data, multiple imputation methods were employed in study one because 262 children out of a total of 360 presented valid PA measurement. The reasons behind missing PA measurement included not wearing the monitor enough to obtain valid PA measurement and losing the accelerometer during the assessment period. A further limitation that has been beyond the scope of this PhD to address is that there needs to be a video analysis of teaching sessions to identify the key features of Linear and Nonlinear pedagogy that influence EF. Within study 2 and 3, theoretical suggestions have been proposed of the potential mechanisms of how each pedagogy can promote different aspects of EF that now need to be tested through observations of the delivery.

Implications for future research

Future longitudinal research is needed to determine the direction of causation between movement qualities and EF. More research is also warranted to assess the association between divergent movement and EF over a longer time period to understand the relationship in different age groups. It would also be interesting to include measures of academic performance to provide a comprehensive understanding of the key features of PE that support academic achievement.

Future research should investigate the implementation of both pedagogies over a longer period of time, for example a full academic year and compare the difference effect for children of different ages. It would be interesting to identify key features of the pedagogies, such as the number of task changes to explore further the mechanism supporting the different EF. Future research should also endeavour to explore which specific aspect of the intervention has an effect on self-regulation. It could be that features of the intervention other than the acquisition of a motor skill are having an effect on self-regulation, such as self-navigating interactions with peers and managing their emotions surrounded by an environment that is constantly changing (Miller et al., 2023).

A key next step in future research is to test out identifiable aspects of the implementation including the role of the teacher and the activity of the children in each pedagogy to understand non-negotiable features that benefit EF and self-regulation (Kirk, 2013). There needs to be more unpacking of the key aspects of the pedagogy that are having an effect on EF through video analysis of the session delivery or reflective checklists where the teachers are involved in identifying the features having an effect. An observation tool such as the SOFIT+ could be used to capture detailed information about pedagogy, instruction quality and the types of movements practiced. SOFIT+ tracks teacher behaviours including how they instruct, demonstrate, manage and provide feedback, giving insights into pedagogical strategies. It includes an analysis of task design and relevance, assessing how instructional content and the learning environment influence the child’s engagement.

Implications for policy and practice

Trained teachers are crucial to the promotion of EF and self-regulation (Keenan et al., 2019), yet currently in the UK PE in primary schools is often delivered by externally hired multi-sports coaches. In view of this, future polices should assure that primary PE will be delivered by teachers who have had training in PE pedagogy. It has also been reported that following their training teachers report an unfamiliarity with technical terms and evidence-based interventions (Keenan et al., 2019). PE teachers should be trained to be aware of the process of developing EF and self-regulation so that they can relate to areas of their practice that have the capacity to promote the skills it involves. The Education Endowment Foundation already publishes accessible documents for primary school teachers about the importance of EF and self-regulation. A key next step is for documents published by such organisations accessed by primary school teachers is to illustrate the link between movement qualities and pedagogical approaches that support the development of EF and self-regulation.

This PhD has shown the importance of pedagogies underpinned by motor learning theory and it would suggest reviewing the content of teacher training to ensure teachers confidence in delivering such evidence-based interventions. The result in this study showed that there is no one pedagogical model that is suitable for all a child's learning and development needs and that a combination of different features of a pedagogy may need to be considered (Ferraz et al., 2023). A teacher would need to be knowledgeable of the different pedagogies and their theoretical rationale in order to make important decisions about which part of the different approaches best suit the needs of the students (Ferraz et al., 2023). There has been a longstanding view that the training of PE for primary school teachers is 'insufficient' and 'ineffective' (Harris, Cale & Musson, 2011; Randall, 2022). The solutions to this involve increasing the PE content in teacher training, focussing on the holistic benefits of child development and reflection on different pedagogical approaches. There needs to be ongoing professional development that empowers staff to develop confidence in their pedagogical approach. The use of PE specialists should take the role of modelling lessons and collaborative planning. This PhD has provided evidence that can be used to demonstrate how PE should be valued equally to core subjects and the role of PE pedagogy to support all areas of child development needs to be understood by all stakeholders.

To support a teacher with learning about each pedagogical approach, which would entail reading a vast amount of literature, there is a need for stronger, more accessible summaries of the key features of each pedagogy that indicate how they align to each aspect of a child's development needs. This thesis has identified key features of Nonlinear and Linear pedagogy that should be considered in the pedagogical approach by a teacher. From a Nonlinear perspective, variability of the environment and task should be utilised to embrace the noise and chaos of children's explorations. Rather than low expectations of children from an area of deprivation they should be encouraged to be autonomous in creating individual, functional movement solutions (EEF, 2024). Linear pedagogy emphasises the importance of predictability and structure that enables the practice of previously learnt steps and progression of task complexity in small steps.

Finally, there are potential opportunities both within curricular and extra-curricular time in a school that could meet the objective of promoting divergent movement. For example, it could be that certain approaches to implementing structured play-based activities during break and lunch time could be adapted to include divergent movement opportunities (Saether et al., 2023). Nonlinear pedagogy provides a framework within PE lessons to promote divergent movement.

Personal Reflection

The completion of my PhD has been an ambition that I have held for a long time. I have had to be really resilient throughout to prevent doubting my ability to get to the end. From the outset, I loved the teamwork required of the SAMPLE-PE project. We helped each other through challenging times, such as the relentless requirements of the data collection. There have been significant moments of celebration, that showed that perseverance certainly pays off. The publication of study one was the culmination of years of drafting and re-drafting. Again, it would not have been possible without the team effort of those involved. I couldn't help but compare myself to others around me in the team, I was in awe of their capabilities. This was my greatest challenge to overcome, to truly believe that I was capable!

There were many activities that pushed me out of my comfort zone. I was most proud of conquering the statistical analysis required of study one during the pandemic. I gained significant experience and vastly improved my data handling skills. The stage of scoring and coding the data we had collected got me through a challenging time personally, when diagnosed with Skin Cancer. I threw myself into watching the videos of the assessments we had created, then scoring each one. The task took months, but it was very satisfying and a great team achievement. I love writing, yet lack confidence in what I write, so submitting drafts for supervisors to review, has always been uncomfortable! I have learnt so much about writing in this discipline that I feel able to transfer my skills to other areas of my profession. I also feel the PhD helped me to grow in confidence in delivering presentations, a skill I would now say is my strength. I thoroughly enjoyed observing the approaches of others at the conferences we attended and appreciated refining my own way of putting together a successful presentation. A highlight was presenting at the conference in Verona. For me, a really special and memorable occasion was when gave an online presentation to the audience at James' new University in Norway.

I have vastly improved my subject knowledge and skills. Although, I am aware there is much more to learn, I have enjoyed exploring different theoretical viewpoints of EF, motor competence and PE pedagogy. The learning process was continually nurtured by discussions with supervisors, reading relevant literature and participating in conferences that I was lucky enough to attend. My interest in the ecological approach has only increased and this is hopefully something I can engage with in the future. My challenge was almost at times, reading too in-depth and I learnt how I must have clear outputs for my efforts to pay off.

I also, thoroughly enjoyed the practical side of the project, working in partnership with primary schools. I was grounded and inspired by the work of schools in areas of deprivation, moved by the challenges some children face. I now work in a partnership focussing on adult learners facing similar difficulties in trying to achieve an education and I thoroughly enjoy working with other professionals trying to support individuals from an area of deprivation.

I had the opportunity to work with a vast number of different assessments and I learnt a lot about the use of validated tools and the value of novel assessments. I developed a deeper understanding of the strengths and limitations of each assessment tool. For example, the NIH toolbox, came highly recommended, yet the practicalities of the assessments with the children had significant limitations. I now have a deeper knowledge, of how novel tools can be adapted to meet the research objectives. In future, if I was to assess EF again, I would explore alternative forms of assessment. It felt very rewarding to be the first study to use the Response to Challenge Scale and exploratory movement assessment with this group of children. I now also fully appreciate how intensive and complex it is to plan and complete multiple assessments of children within a cluster randomised control trial.

I developed wider skills during my PhD, I learnt how to cope with high levels of stress, and this prepared me for a future role in leadership, where I have to use my ability to organise my time efficiently, and manage large volumes of work. These skills, along with prioritising my workload were very important to me particularly during the early stages of my PhD. Lastly, I had the opportunity to meet a large network of people who are a constant source of inspiration to challenge me to better myself in my academic career. The way we have helped each other, is something that I will be eternally grateful.

Conclusion

The findings from this thesis suggest that a combined approach of supporting PA dose and movement competence is required in interventions aimed at promoting EF among children living in an area of deprivation. This outcome impacts the previous literature that has commonly investigated the individual effect of different movement qualities. It informs PE curriculum to ensure a careful balance of PA dose and movement competence and for PE teachers to fully understand the different movement qualities that make up a child’s movement competence. As well as motor proficiency, an opportunity for a child to explore divergent movement is associated with EF among children living in an area of deprivation.

This thesis provides a unique contribution in evaluating how Linear and Nonlinear PE pedagogies underpinned by motor learning theories could effect EF and self-regulation. Nonlinear pedagogy had an effect on working memory and self-regulation, Linear pedagogy had an effect on cognitive flexibility and self-regulation. This contributes to an understanding of how different experiences of learning a motor skill can support the development of EF and self-regulations. Key features of the different pedagogies have been identified in this thesis. Future interventions aimed at supporting the development of EF and self-regulation among children in deprived areas should consider multicomponent interventions that include a number of the different qualities of pedagogies underpinned by motor learning theory. Future longitudinal research is needed to examine the trajectory of the associations between movement competence and EF and determine causal links between movement qualities and EF. An analysis of observations of Linear and Nonlinear pedagogy would help to pinpoint the key features of the approaches that are having an effect on EF and self-regulation.

References

Adams, J.A., (1971). A closed-loop theory of motor learning. *Journal of Motor Behaviour,* 3(2), 111–150. https://doi.org/10.1080/00222895.1971.10734898

Adams, D.L. (1999). Develop better motor skill progressions with Gentile's Taxonomy of tasks. *Joperd*, 70(8).

Adolph, K.E. (2008). Learning to Move. *Current Directions in Psychological Science,* 17(3), 213-218. https://doi.org/10.1111/j.1467-8721.2008.00577.x

Adolph, K. & Robinson, S.R. (2015). Motor Development. In Liben, L. & Muller, U. (2015). *Cognitive processes.* London: Wiley.

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

Adolph, K.E. (2020) Oh, Behave! *Infancy,* 25(4), 374-392. https://doi.org/10.1111/infa.12336

Ahmed, F.S. & L.S. Miller., (2011). Executive function mechanisms of theory of mind. *Journal of autism and developmental disorders.* 41(5), 667-678. DOI: 10.1007/s10803-010-1087-7

Alarcon-Espinoza, M., Sanduvete-Chaves, S., Anguera, M.T., García, P.S. & Chacón-Moscoso, S. (2022). Emotional Self-Regulation in Everyday Life: A Systematic Review. *Quantitative Psychology and Measurement,* 13. https://doi.org/10.3389/fpsyg.2022.884756

Alloway, T.P. & Alloway, R.G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of experimental child psychology.* 106(1), 20-9. DOI: 10.1016/j.jecp.2009.11.003.

Alloway, T.P. (2011). A comparison of working memory profiles in children with ADHD and DCD. Child Neuropsychology, *A Journal on Normal and Abnormal Development in Childhood and Adolescence.* 17(5), 483-494. https://doi.org/10.1080/09297049.2011.553590

Alvarez, J.A. & Emory, E. (2006). Executive Function and the Frontal Lobes: A Meta-Analytic Review. *Neuropsychology Review.* 16, 17-42. https://doi.org/10.1007/s11065-006-9002-x

Alvarez-Bueno, C., Pesce, C., Cavero-Redondo, I., Sánchez-López, M., Garrido-Miguel, M., Martínez-Vizcaíno, V. (2017). Academic Achievement and Physical Activity: A Meta-analysis. *Paediatrics.* 140(6). doi: 10.1542/peds.2017-1498.

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.

Anson, J.G., Elliott, D., Davids, K. (2005). Information Processing and Constraints-based Views of Skill Acquisition: Divergent or Complementary? *Motor Control* 9(3), 217-41. DOI:10.1123/mcj.9.3.217

Araújo, D., & Davids, K. (2009). Ecological approaches to cognition and action in sport and exercise: Ask not only what you do, but where you do it. *International Journal of Sport Psychology,* 40(1), 5–37. https://psycnet.apa.org/record/2009-04771-002

Arufe-Giráldez, V., Sanmiguel-Rodríguez A., Ramos-Álvarez O., & Navarro-Patón R. (2023). News of the Pedagogical Models in Physical Education-A Quick Review. *Int J Environ Res Public Health.* 31;20(3),2586. doi: 10.3390/ijerph20032586. PMID: 36767953; PMCID: PMC9916296.

Asadia, M., Shamsipour Dehkordib, P. & Entezari, M. (2022). Effects of Linear and Non-linear Pedagogy on Motor and Cognitive Creativity. *International Journal of Motor Control and Learning,* 5(1), 1-9.

Audriffen, M. & Andre, N. (2015). The strength model of self-control revisited: Linking acute and chronic effects of exercise on executive functions. *Journal of Sport and Health Science*, 4(1), 30-46. https://doi.org/10.1016/j.jshs.2014.09.002

Aviles, C., Navia, J.A., Ruiz-Perez, L.M. & Zapertero-Ayuso, J.A. (2020). How enaction and ecological approaches can contribute to sports and skill learning. *Frontiers in Psychology,* 11. https://doi.org/10.3389/fpsyg.2020.523691

Backman, E. & Barker, D. M. (2019). Re-thinking pedagogical content knowledge for physical education teachers – implications for physical education teacher education. *Physical Education and Sport Pedagogy*, 25(5), 451–463. doi: 10.1080/17408989.2020.1734554.

Baddeley, A. (1986). *Working Memory.* Oxford: Oxford University Press

Baddeley, A. (1992). Working memory. *Science*, 255(5044), 556-559. doi: 10.1126/science.1736359

Baggetta, P., & Alexander, P. A. (2016). Conceptualization and operationalization of executive function. *Mind, Brain, and Education, 10*(1), 10–33. https://doi.org/10.1111/mbe.12100

Baker, E.R., Liu Q. & Huang, R. (2019). A View from the Start: A Review of Inhibitory Control Training in Early Childhood. *Inhibitory Control Training - A Multidisciplinary Approach.* DOI:10.5772/intechopen.88700

Bakrania, K., Yates, T., Rowlands, A. V., Esliger, D. W., Bunnewell, S., Sanders, J., Davies, M., Khunti, K., & Edwardson, C. L. (2016). Intensity Thresholds on Raw Acceleration Data: Euclidean Norm Minus One (ENMO) and Mean Amplitude Deviation (MAD) Approaches. *PloS one*, 11(10), e0164045. https://doi.org/10.1371/journal.pone.0164045

Barkley, R. A. (2012). *Executive functions: What they are, how they work, and why they evolved.* The Guilford Press. https://psycnet.apa.org/record/2012-15750-000

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

Baumeister, R.F. (1991). *Meanings of Life.* New York: Guilford.

Bedard, C., St John, L., Bremer, E., Graham, J. D., & Cairney, J. (2019). A systematic review and meta-analysis on the effects of physically active classrooms on educational and enjoyment outcomes in school age children. *PloS one*, 14(6), e0218633. https://doi.org/10.1371/journal.pone.0218633

Berg, V., Rogers, S.L., McMahon, M., Garrett, M. & Manley, D. (2020). A Novel Approach to Measure Executive Functions in Students: An Evaluation of Two Child-Friendly Apps. *Educational Psychology*, 11. https://doi.org/10.3389/fpsyg.2020.01702

Bernstein, N.A. (1967) *The Co-Ordination and Regulation of Movements*. Oxford: Pergamon Press.

Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive Functions after Age 5. *Changes and Correlates. Developmental review,* 29(3), 180–200. https://doi.org/10.1016/j.dr.2009.05.002

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

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between Executive Function and Academic Achievement from Ages 5 to 17 in a Large, Representative National Sample. *Learning and individual differences,* 21(4), 327–336. https://doi.org/10.1016/j.lindif.2011.01.007

Best, J. R., & Miller, P. H. (2010). A Developmental Perspective on Executive Function. *Child Development,* 81, 1641-1660. https://doi.org/10.1111/j.1467-8624.2010.01499.x

Bidzan-Bluma, I., & Lipowska, M. (2018). Physical Activity and Cognitive Functioning of Children: *A Systematic Review. International journal of environmental research and public health*, 15(4), 800. https://doi.org/10.3390/ijerph15040800

Bierman, K. L., Nix, R. L., Greenberg, M. T., Blair, C., & Domitrovich, C. E. (2008). Executive functions and school readiness intervention: impact, moderation, and mediation in the Head Start REDI program. Development and psychopathology, 20(3), 821–843. https://doi.org/10.1017/S0954579408000394

Billore, S., Anisimova, T. & Vrontis, D. (2023). Self-Regulation and goal-directed behaviour: a systematic literature review, public policy recommendations, and research agenda. *Journal of Business Research*, 156, 113435. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4407061

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., Granger, D. A., Willoughby, M., Mills-Koonce, R., Cox, M., Greenberg, M. T., Kivlighan, K. T., Fortunato, C. K., & FLP Investigators (2011). Salivary cortisol mediates effects of poverty and parenting on executive functions in early childhood. *Child development*, 82(6), 1970–1984. https://doi.org/10.1111/j.1467-8624.2011.01643.x

Blair, C., & Raver, C. C. (2015). School readiness and self-regulation: a developmental psychobiological approach. *Annual review of psychology*, 66, 711–731. https://doi.org/10.1146/annurev-psych-010814-015221

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

Blake, P.R., Piovesan, M., Montinari, N., Warneken, F.& Gino, F. (2015). Prosocial norms in the classroom: The role of self-regulation in following norms of giving, *Journal of Economic Behaviour & Organization,* 115, 18-29. https://doi.org/10.1016/j.jebo.2014.10.004.

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

Bonetti, S., Blanden, J. & Husain, F. (2020). Analysis of the early year's workforce and its impact on children's outcomes. Available at: https://www.nuffieldfoundation.org/project/analysis-of-the-early-years-workforce-and-its-impact-on-childrens-outcomes (Accessed 24 October 2024)

Braund, H., Timmons, K. Operationalization of self-regulation in the early years: comparing policy with theoretical underpinnings. *ICEP* 15, 8 (2021). https://doi.org/10.1186/s40723-021-00085-7

Brock, L. L., Murrah, W. M., Cottone, E. A., Mashburn, A. J., & Grissmer, D. W. (2018). An after-school intervention targeting executive function and visuospatial skills also improves classroom behaviour. *International Journal of Behavioural Development*, 42(5), 474-484. https://doi.org/10.1177/0165025417738057

Brockman, R., Jago, R., Fox, K.R., Thompson, J.L., Cartwright, K. & Page, A.S. (2009). "Get off the sofa and go and play" Family and socioeconomic influences on the physical activity of 10-11-year-old children. *BMC Public Health,* 9(253). doi:10.1186/1471-2458-9-253.

Bronson, M. B. (2000). Self-regulation in early childhood: *Nature and nurture*. Guilford Press.

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.

Burrows, L., O'Sullivan, M., Halbert, G. & Scott, E. (2020). The aims and outcomes challenge: preparing physical education teacher educators and teachers for twenty-first century redesign imperatives and accountability requirements, in MacPhail, A. & Lawson, H. (2020). *School Physical Education and Teacher Education.* London: Routledge.

Button, C., Davids, K. & Bennett, S. (2008). *Dynamics of Skill Acquisition.* Human Kinetics

Button, C., Siefert, L., Chow, J., Araujo, D. & Davids, K. (2020). *Dynamics of Skill Acquisition: An Ecological Dynamics Approach.* Champaign, Illinois: Human Kinetics.

Cameron Ponitz, C.E., McClelland, M.M., Jewkes, A.M., McDonald Connor, C., Farris, C.L. & Morrison, F.J. (2008). Touch your toes! Developing a direct measure of behavioural regulation in early childhood. *Early Childhood Research Quarterly,* 23 (2) 141-158, https/doi.org/10.1016/j.ecresq.2007.01.004

Cañas, J., Quesada, J. F., Antolí, A., & Fajardo, I. (2003). Cognitive flexibility and adaptability to environmental changes in dynamic complex problem-solving tasks. *Ergonomics,* 46(5), 482–501. https://doi.org/10.1080/0014013031000061640

Casey, B.J., Giedd, J.N. & Thomas, K.M. (2000). Structural and functional brain development and its relation to cognitive development. Biological Psychology, 54, 241-257. https://doi.org/10.1016/S0301-0511(00)00058-2

Casey, A., & MacPhail, A. (2018). Adopting a models-based approach to teaching physical education. *Physical Education and Sport Pedagogy,* 23(3), 294–310. https://doi.org/10.1080/17408989.2018.1429588

Casey, A., MacPhail, A., Larsson, H., & Quennerstedt, M. (2021). Between hope and happening: Problematizing the M and the P in models-based practice. *Physical*

Education and Sport Pedagogy, 26(2), 111–122. https://doi.org/10.1080/17408989.2020.1789576

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.

CCF. (2023). What is the Connectome Coordination Facility? Available at: https://www.humanconnectome.org/. (Accessed 24 October 2024).

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

Chen, J., Zhou, X., Wu, X., Ye, S., Zhou, X. & Gao, Z. (2023). Effects of exergaming on executive functions of children: a systematic review and meta-analysis from 2010 to 2023. *Arch Public Health* 81, 182 https://doi.org/10.1186/s13690-023-01195-z

Chow, J.Y., Davids, K., Button, C., Shuttleworth, R., Renshaw, I. & Araujo, D. (2006). Nonlinear pedagogy: a constraints-led framework for understanding emergence of game play and movement skills. *Nonlinear dynamics, psychology, and life sciences.* 10. 71-103.

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

Chow, J.Y., Davids, K., Button, C. & Renshaw, I. (2015). *Nonlinear Pedagogy in Skill Acquisition: An Introduction*. Imprint Routledge. London. https://doi.org/10.4324/9781315813042

Chow, J.Y., Komar, J.& Seifert, L. (2021). The Role of Nonlinear Pedagogy in Supporting the Design of Modified Games in Junior Sports. *Frontiers in Psychology*. (12). DOI=10.3389/fpsyg.2021.744814

Chow, J.Y., Davids, K., Button, C., & Renshaw, I. (2021). *Nonlinear Pedagogy in Skill Acquisition: An Introduction* (2nd ed.). Routledge. https://doi.org/10.4324/9781003247456

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

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(5), e12820. https://doi.org/10.1111/desc.12820

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(5), e12820. https://doi.org/10.1111/desc.12820

Cowan, N. (2014). Working memory underpins cognitive development, learning, and education. *Educational Psychology Review*, 26(2), 197–223. https://doi.org/10.1007/s10648-013-9246-y

Cowan, N. & Alloway, T. (2008). Development of working memory in childhood. *The Development of Memory in Infancy and Childhood.* Imprint Psychology Press.

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 pre-schoolers’ 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

Contreras-Osorio, F., Campos-Jara, C., Martínez-Salazar, C., Chirosa-Ríos, L., & Martínez-García, D. (2021). Effects of Sport-Based Interventions on Children's Executive Function: A Systematic Review and Meta-Analysis. *Brain sciences*, 11(6), 755. https://doi.org/10.3390/brainsci11060755

Contreras-Osorio, F., Campos-Jara, C., Martínez-Salazar, C., Chirosa-Ríos, L., & Martínez-García, D. (2021). Effects of Sport-Based Interventions on Children's Executive Function: A Systematic Review and Meta-Analysis. Brain sciences, 11(6), 755. https://doi.org/10.3390/brainsci11060755

Contreras-Osorio, F., Ramirez-Campillo, R. Cerda, E., Campos-Jara, R., Martínez, C., Araneda, R., Ebner-Karestinos, D., Arellano-Roco, C. & Campos, C. (2022). Effects of Sport-Based Exercise Interventions on Executive Function in Older Adults: A Systematic Review and Meta-Analysis. *International Journal of Environmental Research and Public Health*. 19. 10.3390/ijerph191912573.

Correia, V., Carvalho, J.H., Araujo, D. Pereira, E. & Davids, K. (2018). Principles of nonlinear pedagogy in sport practice. *Physical Education and Sport Pedagogy*. 24. 1-16. 10.1080/17408989.2018.1552673.

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

Cowan, N. & Morey, C.C. (2009). Visual working memory depends on attentional filtering. *Trends in Cognitive Science,* 23(10, 139-141. https://doi.org/10.1016/j.tics.2006.02.001

Cowan N. (2014). Working Memory Underpins Cognitive Development, Learning, and Education. *Educational psychology review,* 26(2), 197–223. https://doi.org/10.1007/s10648-013-9246-y

Cowan, N. (2013). Working memory underpins cognitive development, learning and education. *Education Psychology Review,* 3 (26), 197-223. doi: 10.1007/s10648-013-9246-y

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.

Crenshaw, K. Investigating the Link Between Executive Function and Creativity in School Aged Children. (2020). Available at: https://egrove.olemiss.edu/cgi/viewcontent.cgi?article=2371&context=hon_thesis (Accessed 24 October 2024).

Crotti M, Rudd J, Roberts S, Fitton Davies K, O'Callaghan L, Utesch T, et al. (2022) Physical activity promoting teaching practices and children's physical activity within physical education lessons underpinned by motor learning theory (SAMPLE-PE). *PLoS ONE* 17(8): e0272339. https://doi.org/10.1371/journal.pone.0272339

Crova, C., Struzzolino, I., Marchetti, R., Masci, I., Vannozzi, G., Forte, R., & Pesce, C. (2014). Cognitively challenging physical activity benefits executive function in overweight children. *Journal of sports sciences,* 32(3), 201–211. https://doi.org/10.1080/02640414.2013.828849

Cuartas, J., Gershoff, E.T., Bailey, D. & McCoy, D.C. (2022). Physical punishment and child, adolescent and adult outcomes in low and middle-income countries: protocol for systematic review and meta-analysis. *Systematic Reviews,* 11. https://doi.org/10.1186/s13643-022-02154-5

Dajani, D.R. & Uddin, L.Q. (2014). Demystifying cognitive flexibility: implications for clinical and developmental neuroscience. *Trends in Neuroscience,* 38 (9), 571-578. doi: 10.1016/j.tins.2015.07.003

Hu, T., Zhang, D., Wang, J., Mistry, R., Ran, G., & Wang, X. (2014). Relation between emotion regulation and mental health: a meta-analysis review. *Psychological reports*, 114(2), 341–362. https://doi.org/10.2466/03.20.PR0.114k22w4

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

Davis, E.E., Pitchford, N.J. & Limback, E. (2011). The interrelation between cognitive and motor development in typically developing children aged 4–11 years is underpinned by visual processing and fine manual control. https://doi.org/10.1111/j.2044-8295.2011.02018.x

de Greeff, J. W., Bosker, R. J., Oosterlaan, J., Visscher, C., & Hartman, E. (2018). Effects of physical activity on executive functions, attention and academic performance in preadolescent children: a meta-analysis. *Journal of science and medicine in sport, 21(5),* 501–507. https://doi.org/10.1016/j.jsams.2017.09.595

Dennis, E., Manza, P. & Volkow, N.D. (2022). Socioeconomic status, BMI and brain development in children. *Translational Psychiatry,* 12(33). doi: 10.1038/s41398-022-01779-3

Department for Education. (2013). *National curriculum in England: physical education programmes of study*. Available at: https://www.gov.uk/government/publications/national-curriculum-in-england-physical-education-programmes-of-study/national-curriculum-in-england-physical-education-programmes-of-study (Accessed 24 October 2024).

Department of Education. (2020). *Enhancing physical education provision and improving access to sport and physical activity in school.* Available at: https://assets.publishing.service.gov.uk/media/65fd68f9f1d3a0001d32adbc/Enhancing_physical_education_provision_and_improving_access_to_sport_and_physical_activity_in_school.pdf (Accessed 24 October 2024).

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

Diamond, A. (2003). Close Interrelation of Motor Development and Cognitive Development and of the Cerebellum and Prefrontal Cortex. *Child Development 71* (1) 44-56. https://doi.org/10.1111/1467-8624.00117

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T.

Knight (Eds.), *Principles of frontal lobe function.* (pp. 466–503). Oxford Academic: Oxford University. https://doi.org/10.1093/acprof:oso/9780195134971.003.0029

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. (2016). Why improving and assessing executive functions early in life is critical. In Griffin, A., McCardle, P. & Freund, L.S. (2016). *Executive Function in Preschool-Age Children: Integrating Measurement, Neurodevelopment and Translational Research.* American Psychological Association. https://doi.org/10.1037/14797-002

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science (New York, N.Y.), 333(6045),* 959–964. https://doi.org/10.1126/science.1204529

Diamond, A. & Ling, D.S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience*, *18,* 34-48, ISSN 1878-9293. https://doi.org/10.1016/j.dcn.2015.11.005.

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

Diamond, A., & Ling, D. S. (2020). Review of the evidence on, and fundamental questions about, efforts to improve executive functions, including working memory. *In*: J. M. Novick, M. F. Bunting, M. R. Dougherty, & R. W. Engle (Eds.), Cognitive and working memory training: *Perspectives from psychology, neuroscience, and human development* 143–431. Oxford University Press. https://doi.org/10.1093/oso/9780199974467.003.0008

Dick, A.S. (2014). The development of cognitive flexibility beyond the preschool period: An investigation using a modified Flexible Item Selection Task. Journal of Experimental Child Psychology, 125, 13-34. https://doi.org/10.1016/j.jecp.2014.01.021.

Doebel, S., & Zelazo, P. D. (2015). A meta-analysis of the Dimensional Change Card Sort: Implications for developmental theories and the measurement of executive function in children. *Developmental review*, 38, 241–268. https://doi.org/10.1016/j.dr.2015.09.001

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

Duncan, M., Cunningham, A. & Eyre, E. (2019), A combined movement and story-telling intervention enhances motor competence and language ability in pre-schoolers to a greater extent than movement or story-telling alone. *European Physical Education Review*, 25(1). 221-235. http://dx.doi.org/10.1177/1356336X1771577

Duku, E. & Vaillancourt, T. (2014). Validation of the BRIEF-P in a sample of Canadian preschool children. *Child neuropsychology*, 20(3), 358–371. https://doi.org/10.1080/09297049.2013.796919

Education Endowment Foundation. (2024). *Setting and Streaming*. Available at: https://educationendowmentfoundation.org.uk/education-evidence/teaching-learning-toolkit/setting-and-streaming#:~:text=Closing%20the%20disadvantage%20gap,be%20misallocated%20to%20lower%20sets. (Accessed 24 October 2024)

Education Endowment Foundation. (2024). *Self-Regulation and Executive Function.* Available at: https://educationendowmentfoundation.org.uk/early-years/evidence-store/self-regulation-and-executive-function (Accessed: 24 October 2024).

Eisenberg, N., Fabes, R. A., & Spinrad, T. L. (2006). Prosocial Development. In N. Eisenberg, W. Damon, & R. M. Lerner (Eds.), *Handbook of child psychology: Social, emotional, and personality development* (6th ed., pp. 646–718). John Wiley & Sons, Inc.

Elam, J. S., Glasser, M. F., Harms, M. P., Sotiropoulos, S. N., Andersson, J. L. R., Burgess, G. C., Curtiss, S. W., Oostenveld, R., Larson-Prior, L. J., Schoffelen, J. M., Hodge, M. R., Cler, E. A., Marcus, D. M., Barch, D. M., Yacoub, E., Smith, S. M., Ugurbil, K., & Van Essen, D. C. (2021). The Human Connectome Project: A retrospective. *NeuroImage*, 244, 118543. https://doi.org/10.1016/j.neuroimage.2021.118543

Eriksen, B.A., Eriksen, C.W. (1974). Effects of noise letters upon the identification of a target letter in a non-search task. *Perception & Psychophysics*, 16, 143–149. https://doi.org/10.3758/BF03203267

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

Esmaili, M., Farhud, D. D., Poushaneh, K., Baghdassarians, A., & Ashayeri, H. (2023). Executive Functions and Public Health: A Narrative Review. *Iranian journal of public health*, 52(8), 1589–1599. https://doi.org/10.18502/ijph.v52i8.13398

Evans, G.W. & Kim, P. (2013). Childhood Poverty, Chronic Stress, Self-Regulation, and Coping. *The Society for Research in Child Development.* https://doi.org/10.1111/cdep.12013C

Eyre, E. L. J., Adeyemi, L. J., Cook, K., Noon, M., Tallis, J., & Duncan, M. (2022). Barriers and Facilitators to Physical Activity and FMS in Children Living in Deprived Areas in the UK: Qualitative Study. *International journal of environmental research and public health,* 19(3). https://doi.org/10.3390/ijerph19031717

Faghiri, A., Stephen, J.M., Wang, Y.P., Wilson, .W. & Calhoun, V.D. (2017). Changing brain connectivity dynamics: from early childhood to adulthood. *Human Brain Mapping*, 39(3), 1108-1117. doi: 10.1002/hbm.23896

Fairclough, S. J., Noonan, R., Rowlands, A. V., Van Hees, V., Knowles, Z., & Boddy, L. M. (2016). Wear Compliance and Activity in Children Wearing Wrist- and Hip-Mounted Accelerometers. *Medicine and science in sports and exercise,* 48(2), 245–253. https://doi.org/10.1249/MSS.0000000000000771

Fairclough, S.J., Taylor, S.L., Rowlands, A., Boddy, L. & Noonan, R. (2019). Average acceleration and intensity gradient of primary school children and associations with indicators of health and wellbeing. *Journal of Sports Sciences.* 37. 10.1080/02640414.2019.1624313.

Fairclough, S. J., Rowlands, A. V., Del Pozo Cruz, B., Crotti, M., Foweather, L., Graves, L. E. F., Hurter, L., Jones, O., MacDonald, M., McCann, D. A., Miller, C., Noonan, R. J., Owen, M. B., Rudd, J. R., Taylor, S. L., Tyler, R., & Boddy, L. M. (2023). Reference values for wrist-worn accelerometer physical activity metrics in England children and adolescents. *The international journal of behavioural nutrition and physical activity,* 20(1), 35. https://doi.org/10.1186/s12966-023-01435-z

Farah, M.J. (2017). The neuroscience of socioeconomic status: correlates, causes and consequences. *Neuron,* 96(1), 56-71. doi: 10.1016/j.neuron.2017.08.034.

Fathirezaie Z, Matos S, Khodadadeh E, Clemente FM, Badicu G, Silva AF, Zamani Sani SH, Nahravani S. (2022). The Relationship between Executive Functions and Gross Motor Skills in Rural Children Aged 8–10 Years. *Healthcare.* 10(4):616. https://doi.org/10.3390/healthcare10040616

Ferraz, R., Branquinho, L., Sortwell, A., Teixeira, J.E., Forte, P., & Marinho, D.A. (2023) Teaching models in physical education: current and future perspectives. *Montenegrin Journal of Sports Science and Medicine*, 19 (1), 53–60. https://doi.org/10.26773/mjssm.230307

Ferris, L. T., Williams, J. S., & Shen, C. L. (2007). The effect of acute exercise on serum brain-derived neurotrophic factor levels and cognitive function. *Medicine and science in sports and exercise,* 39(4), 728–734. https://doi.org/10.1249/mss.0b013e31802f04c7

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

Fisher, A., Boyle, J.M., Paton, J.Y., Tomporowski, P., Watson, C., McColl, J.H. & Reilly, J.J. (2011). Effects of a physical education intervention on cognitive function in young children: randomized controlled pilot study. BMC Paediatrics, 11, 97 https://doi.org/10.1186/1471-2431-11-97

Fiske, A. & Holmboe, K. (2019). Neural substrates of early executive function development. *Developmental Review,* 52, 42-62. doi: 10.1016/j.dr.2019.100866.

Fitts, P. M. & Posner, M. I. (1967*). Human performance*. Oxford: Brooks/Cole.

Fletcher, T. & Mandigo, J. (2012). The primary schoolteacher and physical education: A review of research and implications for Irish physical education. *Irish Educational Studies.* 31. 10.1080/03323315.2012.710063.

Foulkes, J. D., Knowles, Z., Fairclough, S. J., Stratton, G., O'Dwyer, M., Ridgers, N. D., & Foweather, L. (2015). Fundamental movement skills of preschool children in Northwest England. *Perceptual and motor skills*, 121(1), 260–283. https://doi.org/10.2466/10.25.PMS.121c14x0

Furley, P., Schutz, L.M. & Wood, G. (2023). A critical review of research on executive functions in sport and exercise. *International Review of Sport and Exercise Psychology*. DOI:10.1080/1750984X.2023.2217437

Fuster, J.M. (2002). Frontal lobe and cognitive development. *Journal of Neurocytology,* 31, 373-385.

Funahashi, S. & Andreau, J.M. (2013). Prefrontal cortex and neural mechanisms of executive function. *Journal of Physiology – Paris.* 107(6), 471-482. doi: 10.1016/j.jphysparis.2013.05.001

Gallotta, M. C., Emerenziani, G. P., Iazzoni, S., Meucci, M., Baldari, C., & Guidetti, L. (2015). Impacts of coordinative training on normal weight and overweight/obese children's attentional performance. *Frontiers in human neuroscience,* 9, 577. https://doi.org/10.3389/fnhum.2015.00577

Gao, Z., Wen, X., Fu, Y., Lee, J.E. & Zeng, N. (2021). Motor Skill Competence Matters in Promoting Physical Activity and Health. *Motor Skill Competence Matters in Promoting Physical Activity and Health.* https://doi.org/10.1155/2021/9786368

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

Gandotra, A., Koyuk, S., Sattar, Y. & Bizonics, V. (2021). A meta-analysis of the relationship between motor skills and executive functions in typically-developing children. *Journal of Cognition and Development.* 23(8), 1-28. DOI:10.1080/15248372.2021.1979554

Garcia-Hermoso, A., Ramirez-Velez, R., Lubans, D.R. & Izquierdo, M. (2021). Effects of physical education interventions on cognition and academic performance outcomes in children and adolescents: a systematic review and meta-analysis. *British Journal of Sports Medicine,* 55, 1224-1232. doi:10.1136/bjsports-2021-104112

Laxdal, A.G., Mjåtveit, A., Leibinger, E. Haugen, T. & Giske, R. (2019). Self-regulated Learning in Physical Education: An Analysis of Perceived Teacher Learning Support and Perceived Motivational Climate as Context Dependent Predictors in Upper Secondary School. *Scandinavian Journal of Educational Research.* DOI:10.1080/00313831.2019.1689164

Gauti Lazdal, A., Mjaveit, A., Leibinger, E. & Haugen, T. (2019). Self-regulated learning in physical education: an analysis of perceived teacher learning support and perceived motivational climate as context dependent predictors in upper secondary school. *Scandinavian Journal of Educational Research.* DOI:10.1080/00313831.2019.1689164

Gerst, E. H., Cirino, P. T., Fletcher, J. M., & Yoshida, H. (2015). Cognitive and behavioural rating measures of executive function as predictors of academic outcomes in children. *Child Neuropsychology*, 23(4), 381–407. https://doi.org/10.1080/09297049.2015.1120860

Gibson, J.J. (1979). *The Ecological Approach to Visual Perception: Classic Edition.* Boston: Houghton Mifflin.

Gibson, J.J. (1986). *The Theory of Affordances.* Boston: Houghton Mifflin.

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

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development.* Oxford: Oxford University Press

Goldstein, S., Naglieri, J.A., Princiotta, D. & Otero, T. (2014). *Introduction: A History of Executive Functioning as a Theoretical and Clinical Construct.* In: Goldstein, A. & Naglieri, J.A. (2014). *Handbook of Executive Functioning*. New York: Springer. DOI:10.1007/978-1-4614-8106-5_1

Goodman, R. (1997). The strengths and difficulties questionnaire: a research note. *Journal of Child Psychology and Psychiatry,* 38(5), 581-586. doi: 10.1111/j.1469-7610.1997.tb01545.x.

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,* 617, 351-359. https://doi.org/10.1038/s41586-023-05964-2

Gothe, N., Pontifex, M. B., Hillman, C., & McAuley, E. (2013). The acute effects of yoga on executive function. *Journal of physical activity & health,* 10(4), 488–495. https://doi.org/10.1123/jpah.10.4.488

Gottwald, J. M., Achermann, S., Marciszko, C., Lindskog, M., & Gredebäck, G. (2016). An Embodied Account of Early Executive-Function Development. *Psychological science*, 27(12), 1600–1610. https://doi.org/10.1177/0956797616667447

Gottwald, V., Davies, M., & Owen, R. (2023). Every story has two sides: evaluating information processing and ecological dynamics perspectives of focus of attention in skill acquisition. *Frontiers in sports and active living,* 5. https://doi.org/10.3389/fspor.2023.1176635

Gov.UK (2018). *English indices of deprivation. DOI: English indices of deprivation. Available at:* https://www.gov.uk/government/collections/english-indices-of-deprivation (Accessed 24 October 2024)

Gov. UK (2024). *PE and Sport Premium for Schools.* Available at: https://www.gov.uk/guidance/pe-and-sport-premium-for-primary-schools (Accessed 24 October 2024)

Gov.UK (2024). *The National Curriculum.* Available at: https://www.gov.uk/national-curriculum (Accessed 24 October 2024).

Gray, R. (2023). How We Learn to Move.

Grissom, N. M., & Reyes, T. M. (2019). Let's call the whole thing off: Evaluating gender and sex differences in executive function *Neuropsychopharmacology,* 44(7), 1344. https://doi.org/10.1038/s41386-019-0367-y

Griffiths, A., Toovey, R., Morgan, P. E., & Spittle, A. J. (2018). Psychometric properties of gross motor assessment tools for children: a systematic review. *BMJ open,* 8(10), e021734. https://doi.org/10.1136/bmjopen-2018-021734

Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of motor behaviour,* 36(2), 212–224. https://doi.org/10.3200/JMBR.36.2.212-224

Gunzenhauser, C., & Nückles, M. (2021). Training Executive Functions to Improve Academic Achievement: Tackling Avenues to Far Transfer. *Frontiers in psychology,* 12, 624008. https://doi.org/10.3389/fpsyg.2021.624008

Gu, Q., Zou, L., Loprinzi, P.D., Quan, M. & Huang, T. (2019). Effects of Open Versus Closed Skill Exercise on Cognitive Function: A Systematic Review. *Frontiers in Psychology*, 10. DOI=10.3389/fpsyg.2019.01707

Guilford, J. P. (1956). The structure of intellect. *Psychological Bulletin*, *53*(4), 267–293. https://doi.org/10.1037/h0040755

Gurbin, T. (2015). Enlivening the machinist perspective: humanising the information processing theory with social and cultural influences. *Procedia Social and Behavioural Sciences.* 197, 2331-2338. https://doi.org/10.1016/j.sbspro.2015.07.263

Haas, P., Yang, C. H., & Dunton, G. F. (2021). Associations Between Physical Activity Enjoyment and Age-Related Decline in Physical Activity in Children-Results from a Longitudinal Within-Person Study. *Journal of sport & exercise psychology,* 43(3), 205–214. https://doi.org/10.1123/jsep.2020-0156

Hackman, D.A, Gallop, R., Evans, G. & Farah, M.J. (2015). Socioeconomic status and executive function: developmental trajecories and mediation. *Developmental Science,* 18(5). DOI:10.1111/desc.12246

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

Han, X., Zhao, M., Kong, Z. & Xie, J. (2022). Association between fundamental motor skills and executive function in preschool children: a cross-sectional study. *Frontiers in Psychology, 13.* DOI 10.3389/fpsyg.2022.978994

Harris, J., Cale, L. & Musson, H. (2011). The predicament of primary physical education: a consuequence of 'insufficient' ITT and 'ineffective' CPD? Physical education and Sport Pedagogy, 17(4), 367-381. https://doi.org/10.1080/17408989.2011.582489.

Hautakangas, M., Kumpulainen, K., & Uusitalo, L. (2022). Children developing self-regulation skills in a Kids' Skills intervention programme in Finnish Early Childhood Education and Care. *Early Child Development and Care,* 192(10), 1626–1642. https://doi.org/10.1080/03004430.2021.1918125

Heatherton T. F. (2011). Neuroscience of self and self-regulation. *Annual review of psychology*, 62, 363–390. https://doi.org/10.1146/annurev.psych.121208.131616

Heilmann, F., Weinberg, H., & Wollny, R. (2022). The Impact of Practicing Open- vs. Closed-Skill Sports on Executive Functions-A Meta-Analytic and Systematic

Review with a Focus on Characteristics of Sports. *Brain sciences*, 12(8), 1071. https://doi.org/10.3390/brainsci12081071

Hildebrand, M., VAN Hees, V. T., Hansen, B. H., & Ekelund, U. (2014). Age group comparability of raw accelerometer output from wrist- and hip-worn monitors. *Medicine and science in sports and exercise*, 46(9), 1816–1824. https://doi.org/10.1249/MSS.0000000000000289

Hill, C. R., & Hughes, J. N. (2007). An examination of the convergent and discriminant validity of the Strengths and Difficulties Questionnaire. *School Psychology Quarterly*, 22(3), 380–406. https://doi.org/10.1037/1045-3830.22.3.380

Hillman, C., Erickson, K. & Kramer, A. (2008). Be smart, exercise your heart: exercise effects on brain and cognition. *Nature Reviews Neuroscience,* 9, 58–65 https://doi.org/10.1038/nrn2298

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

Hudson, K. N., Ballou, H. M., & Willoughby, M. T. (2020). Short report: Improving motor competence skills in early childhood has corollary benefits for executive function and numeracy skills. *Developmental science*, 24(4), e13071. https://doi.org/10.1111/desc.13071

Hughes, C., Ensor, R., Wilson, A., & Graham, A. (2010). Tracking executive function across the transition to school: a latent variable approach. *Developmental neuropsychology*, 35(1), 20–36. https://doi.org/10.1080/87565640903325691

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

Inzlicht, M., Werner, K. M., Briskin, J. L., & Roberts, B. W. (2021). Integrating Models of Self-Regulation. *Annual review of psychology,* 72, 319–345. https://doi.org/10.1146/annurev-psych-061020-105721

Ishihara, T., Drollette, E.S., Ludyga, S., Hillman, C.H. & Kamijo, K. (2021). The effects of acute aerobic exercise on executive function: A systematic review and meta-analysis of individual participant data. *Neuroscience & Bio-behavioural Reviews,* 128, 258-269. https://doi.org/10.1016/j.neubiorev.2021.06.026.

Jacobson, L., Williford, A. & Pianta, R. (2011). The Role of Executive Function in Children's Competent Adjustment to Middle School. *Child neuropsychology,* 17. 255-80. 10.1080/09297049.2010.535654.

Jebeile, H., Kelly, A.S., O'Malley, G. & Baur, L.A. (2022). Obesity in children and adolescents: epidemiology, causes, assessment, and management. *The Lancet Diabetes & Endocrinology,* 10(5), 351-365. https://doi.org/10.1016/S2213-8587(22)00047-X.

Jones, S.M., Bailey, R., Barnes, S.P. & Partee, A. (2016). *Executive Function Mapping Project: Untangling the Terms and Skills Related to Executive Function and Self-Regulation in Early Childhood.* Available at: https://www.acf.hhs.gov/sites/default/files/documents/opre/ef_mapping_executivesummary_101416_final_508.pdf (Accessed 24 October 2024).

Jones, D., Innerd, A., Giles, E. L., & Azevedo, L. B. (2020). Association between fundamental motor skills and physical activity in the early years: A systematic review and meta-analysis. *Journal of sport and health science*, 9(6), 542–552. https://doi.org/10.1016/j.jshs.2020.03.001

Joseph, A., J., Sylva, K., Sammons, P. & Siraj, I. (2023). Drivers of the socio-economic disadvantage gap in England: Sequential pathways that include the home learning environment and self-regulation as mediators. *British Journal of Educational Psychology*, 94(1), 22-40. https://doi.org/10.1111/bjep.12629

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

Kangas, J., Ojala, M. & Venninen, T. (2015). Children's Self-Regulation in the Context of Participatory Pedagogy in Early Childhood Education. Early Education and Development. 26(5). DOI: 10.1080/10409289.2015.1039434.

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

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

Kauffman, S.A. (1993). *The Origins of Order. Self-Organisation and Selection in Evolution.* Oxford: Oxford University Press.

Keenan, L., Conroy, S., O'Sullivan, A. & Downes, M. (2019). Executive functioning in the classroom: Primary school teachers' experiences of neuropsychological issues and reports. *Teaching and Teacher Education*, 86. https://doi.org/10.1016/j.tate.2019.102912.

Kelso, J.A. (1997). *The Self-Organization of Brain and Behaviour. Dynamic Patterns.* The MIT Press.

Kim, H., Duran, C. A. K., Cameron, C. E., & Grissmer, D. (2018). Developmental Relations Among Motor and Cognitive Processes and Mathematics Skills. *Child development*, 89(2), 476–494. https://doi.org/10.1111/cdev.12752

Kirk, D. (2010). *Physical Education Futures.* London: Routledge.

Kirk D. (2019). *Precarity, Critical Pedagogy and Physical Education.* London: Routledge.

Koepp, A. E., Gershoff, E. T., Castelli, D. M., & Bryan, A. E. (2022). Pre-schoolers' executive functions following indoor and outdoor free play. *Trends in neuroscience and education*, 28, 100182. https://doi.org/10.1016/j.tine.2022.100182

Koester, D. (2023) The cognitive future of motor control and learning. *Frontiers in Sports and Active Living,* 5. doi: 10.3389/fspor.2023.1181808

Kolovelonis, A., Goudas, M., Hassandra, M. & Dermitzaki, I. (2012). Self-regulated learning in physical education: Examining the effects of emulative and self-control practice. *Psychology of Sport and Exercise.* 13. 383–389. 10.1016/j.psychsport.2012.01.005.

Kolovelonis, A. & Goudas, M. (2022). Physical education students' calibration accuracy and academic achievement: a longitudinal study. *Issues in Educational Research*, 32(2), 575-592 https://www.iier.org.au/iier32/kolovelonis-abs.html

Kopp, C. B. (1991). Young children's progression to self-regulation. *In M. Bullock (Ed.), The development of intentional action: Cognitive, motivational, and interactive processes* (pp. 38–54). Karger.

Korucu, I., Ayturk, E., Finders, J. K., Schnur, G., Bailey, C.S., Tominey, S. L. & Schmitt, S. A. (2022). Self-Regulation in Preschool: Examining Its Factor Structure and Associations with Pre-academic Skills and Social-Emotional Competence. Frontiers in Psychology, 12. DOI=10.3389/fpsyg.2021.717317.

Koskulu-Sancar, S., Blom, E., van de Weijer-Bergsma, E., Grandfield, E., Verhagen, J. & Mulder, H. (2023). Techers mater in early childhood: the relation between teachers' behaviours and executive function development in toddlerhood. *Infant and Child Development.* 33 (3). DOI: https://doi.org/10.1002/icd.2474

Koutsandréou, F., Wegner, M., Niemann, C., & Budde, H. (2016). Effects of Motor versus Cardiovascular Exercise Training on Children's Working Memory. *Medicine and science in sports and exercise*, 48(6), 1144–1152. https://doi.org/10.1249/MSS.0000000000000869

Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1982). *On the Control and Coordination of Naturally Developing Systems.* In J. A. S. Kelso, & J. E. Clark (1982). *The Development of Movement Control and Coordination*. New York: Wiley.

Kurgansky, A. V. (2022). Assessment of executive functions in children aged 3–6 years: Current state, challenges, and perspectives. *Neuroscience and Behavioural Physiology*, 52(2), 297–307. https://doi.org/10.1007/s11055-022-01237-z

Lakes, K. D., & Hoyt, W. T. (2004). Promoting self-regulation through school-based martial arts training. *Journal of Applied Developmental Psychology*, 25(3), 283–302. https://doi.org/10.1016/j.appdev.2004.04.002

Lakes K. D. (2012). The Response to Challenge Scale (RCS): The Development and Construct Validity of an Observer-Rated Measure of Children's Self-Regulation. *The International journal of educational and psychological assessment*, 10(1), 83–96. https://pubmed.ncbi.nlm.nih.gov/25750758/

Larsson, H., & Nyberg, G. (2017). 'It doesn't matter how they move really, as long as they move.' Physical education teachers on developing their students' movement capabilities. *Physical Education and Sport Pedagogy*, 22(2), 137–149. https://doi.org/10.1080/17408989.2016.1157573

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.* https://doi.org/10.1371/journal.pone.0202964

Lawson, G.M., Hook, C.J. & Farah, M.J. (2018). A meta-analysis of the relationship between socioeconomic status and executive function performance among children. *Developmental Science*, 21(2). doi: 10.1111/desc.12529.

Lee, J., Zhang, Chu, A. & Gu. (2020). Effects of a fundamental motor skill-based afterschool program on children's physical and cognitive health outcomes. *International Journal of Environmental Research and Public Health,* 17(3). DOI:10.3390/ijerph17030733

Legault, L., & Inzlicht, M. (2013). Self-determination, self-regulation, and the brain: Autonomy improves performance by enhancing neuroaffective responsiveness to self-regulation failure. *Journal of Personality and Social Psychology,* 105(1), 123–138. https://doi.org/10.1037/a0030426

Lewis, A. & Smith, D. (2009). Defining higher order thinking. *Theory into Practice.* 32(3). https://doi.org/10.1080/00405849309543588

Likhitweerawong, N., Khorana, J., Boonchooduang, N., Phinyo, P., Patumanond, J., & Louthrenoo, O. (2022). Association between executive function and excess weight in pre-school children. *PloS one,* 17(10), e0275711. https://doi.org/10.1371/journal.pone.0275711

Li, W., Mao, Y. & Hu, B. (2022). Will exposure to different consequences of prosocial behaviour always lead to subsequent prosocial behaviour among adolescents: An experimental study of short videos. Frontiers in Psychology, 13. DOI=10.3389/fpsyg.2022.927952.

Liu, S., Yu, Q., Li, Z., Cunha, P. M., Zhang, Y., Kong, Z., Lin, W., Chen, S., & Cai, Y. (2020). Effects of Acute and Chronic Exercises on Executive Function in Children and Adolescents. A Systemic Review and Meta-Analysis. *Frontiers in psychology*, 11, 554915. https://doi.org/10.3389/fpsyg.2020.554915

Loaiza, V.M. & Souza, A.S. (2024). Active maintenance in working memory reinforces bindings for future retrieval from episodic long-term memory. *Memory & Cognition.* https://doi.org/10.3758/s13421-024-01596-7

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. *Paediatrics, 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 Behaviour 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., Brand, S., Holsboer-Trachsler, E., & Pühse, U. (2016). Acute effects of moderate aerobic exercise on specific aspects of executive function in different age and fitness groups. *A meta-analysis. Psychophysiology*, 53(11), 1611–1626. https://doi.org/10.1111/psyp.12736

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

Lund, J. & Tannehill, D. (2014). *Standards-Based Physical Education Curriculum Development.* Jones and Bartlett Publishers.

Lupien, S., McEwen, B., Gunnar, M. & Heim, C. (2009). Effects of stress throughout the lifespan on the brain, behaviour and cognition. Nature Reviews Neuroscience, 10, 434–445 (2009). https://doi.org/10.1038/nrn2639

Lynch, B. A., Kaufman, T. K., Rajjo, T. I., Mohammed, K., Kumar, S., Murad, M. H., Gentile, N. E., Koepp, G. A., McCrady-Spitzer, S. K., & Levine, J. A. (2019). Accuracy of Accelerometers for Measuring Physical Activity and Levels of Sedentary Behaviour in Children: A Systematic Review. *Journal of primary care &*

community health, 10, 2150132719874252. https://doi.org/10.1177/2150132719874252

Macedo Feijó, D. M., Pires, J. F., Gomes, R. M. R., Carlo, E. J. F., Viana, T. N. L., Magalhães, J. R., Santos, A. C. T., Rodrigues, L. D., Oliveira, L. F., & Dos Santos, J. C. C. (2023). The impact of child poverty on brain development: does money matter? *Dementia & neuropsychologia*, 17, e20220105. https://doi.org/10.1590/1980-5764-DN-2022-0105

Mackes, N.K., Golm, D., Sarkar, S., Kumsta, R., Rutter, M., Fairchild, G., Mehta, M.A. & Sonuga-Barke, E.J. (2020). Early childhood deprivation is associated with alterations in adult brain structure despite subsequent environmental enrichment. PNAS, 117(1), 641-649. doi: 10.1073/pnas.1911264116.

Malambo, C., Nová, A., Clark, C., & Musálek, M. (2022). Associations between Fundamental Movement Skills, Physical Fitness, Motor Competency, Physical Activity, and Executive Functions in Pre-School Age Children. *A Systematic Review. Children (Basel, Switzerland*), 9(7). https://doi.org/10.3390/children9071059

Malcolm, D., Marcen, C. & Pullen, E. (2023). The World Health Organisation, physical activity and the contradictions of neoliberal health promotion. *International Journal of Sport Policy and Politics*, 16(4). https://doi.org/10.1080/19406940.2023.2242874

Mattson, M.P. (2014). Superior pattern processing is the essence of the evolved human brain. *Frontiers in Neuroscience*, 8(265). https://doi.org/10.3389/fnins.2014.00265

McClelland, M. M., & Cameron, C. E. (2019). Developing together: The role of executive function and motor skills in children's early academic lives. *Early Childhood Research Quarterly,* 46, 142–151. https://doi.org/10.1016/j.ecresq.2018.03.014

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

Marinšek M. & Lukman, N. (2022). Teaching strategies for promoting motor creativity and motor skill proficiency in early childhood. *Economic Research*, 35(1), 2645-2653, DOI:10.1080/1331677X.2021.1974306

Marmot, M., Goldblatt, P. & Allen, J. (2010). Fair Society, Healthy Lives. The Marmot Review.

Marzoni, M., Bahram, A., Ghadiri, F. & Yaali, R. (2022). 'The comparison of effectiveness Linear and Nonlinear Pedagogy on manipulation Motor Skills performance of children'. *Motor Behaviour*, 13(45), pp. 91-112. doi: 10.22089/mbj.2019.6200.1703

McClelland, M. M., & Cameron, C. E. (2011). Self-regulation and academic achievement in elementary school children. *New directions for child and adolescent development*, 133, 29–44. https://doi.org/10.1002/cd.302

McEwen, C. A., & McEwen, B. S. (2017). Social structure, adversity, toxic stress, and intergenerational poverty: An early childhood model. *Annual Review of Sociology*, 43, 445–472. https://doi.org/10.1146/annurev-soc-060116-053252

McCoy, D. C. (2019). Measuring young children's executive function and self-regulation in classrooms and other real-world settings. *Clinical Child and Family Psychology Review*, 22(1), 63–74. https://doi.org/10.1007/s10567-019-00285-1

McNeill, J., Howard, S. J., Vella, S. A., Santos, R. & Cliff, D. P. (2018). Physical activity and modified organized sport among preschool children: Associations with cognitive and psychosocial health. *Mental Health and Physical Activity*, 15 45-52. DOI: http://dx.doi.org/10.1016/j.mhpa.2018.07.001

Meijer, A., Königs, M., Vermeulen, G. T., Visscher, C., Bosker, R. J., Hartman, E., & Oosterlaan, J. (2020). The effects of physical activity on brain structure and neurophysiological functioning in children: A systematic review and meta-analysis. *Developmental cognitive neuroscience*, 45, 100828. https://doi.org/10.1016/j.dcn.2020.100828

Merz, E. C., Wiltshire, C. A., & Noble, K. G. (2019). Socioeconomic inequality and the developing brain: Spotlight on language and executive function. *Child Development Perspectives*, 13(1), 15–20. https://doi.org/10.1111/cdep.12305

Mieloo, C., Raat, H., van Oort, F., Bevaart, F., Vogel, I., Donker, M. & Jansen, W. (2012). Validity and Reliability of the Strengths and Difficulties Questionnaire in 5–6 Year Olds: Differences by Gender or by Parental Education? *PloS one*. 7. e36805. 10.1371/journal.pone.0036805.

Miguel, P.M., Meaney, M.J. & Silveira, P.P. (2023). New Research Perspectives on the Interplay Between Genes and Environment on Executive Function Development. *Biological Psychiatry*, 94, (2), 131-141. ISSN 0006-3223. https://doi.org/10.1016/j.biopsych.2023.01.008.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychological Review, 63(2), 81–97. https://doi.org/10.1037/h0043158

Miller, G.A., Galanter, E. & Pribram, K.H. (1968). *Plans and the Structure of Behaviour*. *Systems Research for Behavioural Science*, Routledge. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315130569-53/plans-structure-

Miller, A. L., Palmer, K. K., Wang, L., Wang, C., Riley, H. O., McClelland, M. M., & Robinson, L. E. (2023). Mastery-oriented motor competence intervention improves behavioural but not cognitive self-regulation in head start pre-schoolers: Randomized controlled trial results. *Scandinavian journal of medicine & science in sports*, 33(5), 725–736. https://doi.org/10.1111/sms.14294

Miller, E. K. & Wallis, J. D. (2009). Executive Function and Higher-Order Cognition: Definition and Neural Substrates. In: Squire LR (ed.) *Encyclopaedia of Neuroscience*, 4, 99-104. Oxford: Academic Press.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A. & Wager, D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: a latent variable analysis. *Cognitive Psychology,* 41(1), 49-100. doi: 10.1006/cogp.1999.0734.

Mo, W., Saibon, J., Yaming, L. Jiequan, L. & He, Y. (2024). Effects of game-based physical education program on enjoyment in children and adolescents: a systematic review and meta-analysis. *BMC Public Health.* 24. 10.1186/s12889-024-18043-6.

Montroy, J. J., Bowles, R. P., Skibbe, L. E., McClelland, M. M., & Morrison, F. J. (2016). The development of self-regulation across early childhood. *Developmental Psychology*, 52(11), 1744–1762. https://doi.org/10.1037/dev0000159

Mooney, K.E., Prady, S.L., Barker, M.M., Pickett, K.E. & Waterman, A.H. (2021) The association between socioeconomic disadvantage and children’s working memory abilities: A systematic review and meta-analysis. *PLoS ONE* 16(12): e0260788. https://doi.org/10.1371/journal.pone.0260788

Moreau, D. (2013). Motor expertise modulates movement processing in working memory. *Acta Psychologica.* 142(3), 356-361. doi: 10.1016/j.actpsy.2013.01.011.

Moreau, D., & Conway, A. R.A. (2013). Cognitive enhancement: A comparative review of computerized and athletic training programs. *International Review of Sport and Exercise Psychology*, 6(1), 155–183. https://doi.org/10.1080/1750984X.2012.758763

Moreau, D. & Chou, E. (2019). *The Acute Effect of High-Intensity Exercise on Executive Function*: A Meta-Analysis, *Perspectives on Psychological Science,* 14(5) https://doi.org/10.1177/1745691619850568

Morris, J.L., Daly-Smith, A., Archbold, V.SJ. Wilkins, E.L.& McKenna, J. 92019). The Daily Mile™ initiative: Exploring physical activity and the acute effects on executive function and academic performance in primary school children. *Psychology of Sport and Exercise,* 45. https://doi.org/10.1016/j.psychsport.2019.101583.

Mulvey, K. L., Taunton, S., Pennell, A. Ali, B. (2018). Head, Toes, Knees, SKIP! Improving Preschool Children’s Executive Function Through a Motor Competence Intervention. *Journal of Sport and Exercise Psychology.* 40. 1-7. 10.1123/jsep.2018-0007.

Mura, G., Vellante, M., Egidio Nardi, A., Machado, S. & Carta, M.G. (2015). Effects of school-based physical activity interventions on cognition and academic achievement: a systematic review. *CNS & Neurological Disorders*, 14(9), 1194-1208. DOI: 10.2174/1871527315666151111121536

Muir, R.A., Howard, S.J. & Kervin, L. (2023). Interventions and Approaches Targeting Early Self-Regulation or Executive Functioning in Preschools: A Systematic Review. Educational Psychology Review, 35(27). https://doi.org/10.1007/s10648-023-09740-6

Munakata, Y., Snyder, H. & Chatham, C. (2012). Developing Cognitive Control: Three Key Transitions. *Current directions in psychological science*. 21. 71-77. 10.1177/0963721412436807.

Muntaner-Mas, A., Mazzoli, E., Abbott, G., Mavilidi, M. F., & Galmes-Panades, A. M. (2022). Do Physical Fitness and Executive Function Mediate the Relationship between Physical Activity and Academic Achievement? *An Examination Using Structural Equation Modelling. Children (Basel, Switzerland)*, 9(6), 823. https://doi.org/10.3390/children9060823

Muraven, M., & Baumeister, R. F. (2000). Self-regulation and depletion of limited resources: Does self-control resemble a muscle? *Psychological Bulletin*, 126(2), 247–259. https://doi.org/10.1037/0033-2909.126.2.247

Nesbitt, K., Farran, D. & Fuhs, M. (2015). Executive Function Skills and Academic Achievement Gains in Prekindergarten. Contributions of Learning-Related Behaviours. *Developmental psychology*. 51(7). DOI: 10.1037/dev0000021.

Newell, K. M. (1986*). Constraints on the Development of Coordination*. In Wade, M.G. & Whiting, H.T.A. *Motor Development in Children: Aspects of Coordination and Control*. The Netherlands: Martinus Nijhoff, Dordrecht.

NHS. (2024). *Health Survey for England, 2022 Part 2.* Available at: https://digital.nhs.uk/data-and-information/publications/statistical/health-survey-for-england/2022-part-2/childrens-overweight-and-obesity (Accessed 24 October 2024).

NIH Toolbox (2024). *Over 50 Neurobehavioral Assessments in One iPad App.* Available at: https://nihtoolbox.org/ (Accessed: 24 October 2024).

Ni Chróinín, D., Fletcher, T. & O'Sullivan, M. (2017). Pedagogical principles of learning to teach meaningful physical education. *Physical Education and Sport Pedagogy.* 23. 1-17. 10.1080/17408989.2017.1342789.

Nieto-López, M., Sánchez-López, M., Visier-Alfonso, M.E., Martínez-Vizcaíno, V., Jiménez-López, E. & Alvarez-Bueno, C. (2020). Relation between physical fitness and executive function variables in a preschool sample. Paediatric Research, 88, 623-628. https://doi.org/10.1038/s41390-020-0791-z

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, 126(2), 220–246. https://doi.org/10.1037/0033-2909.126.2.220

Noonan, R.J., Boddy, L., Fairclough, S. & Knowles, Z.R. (2017). Parental perceptions on children's 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.

Nunes de Santana, A. N., Roazzi, A., & Nobre, A. P. M. C. (2022). The relationship between cognitive flexibility and mathematical performance in children: A meta-analysis. *Trends in neuroscience and education*, 28, 100179. https://doi.org/10.1016/j.tine.2022.100179

Oberauer, K. (2019). Working memory and attention – a conceptual analysis and review. *Journal of Cognition,* 2(1). https://doi.org/10.5334/joc.58

O'Callaghan, L., Foweather, L., Crotti, M., Oppici, L., Pesce, C., Boddy, L., Fitton Davies, K. & Rudd, J. (2024). Associations of physical activity dose and movement quality with executive functions in socioeconomically disadvantaged children aged 5–6 years. *Psychology of Sport and Exercise*, 70. https://doi.org/10.1016/j.psychsport.2023.102546.

Ofsted. (2022). *Research Review Series: PE.* Available at: https://www.gov.uk/government/publications/research-review-series-pe/research-review-series-pe (Accessed 24 October 2024).

Ofsted. (2023*). Levelling the playing field: the physical education subject report*. Available at: https://www.gov.uk/government/publications/subject-report-series-pe/levelling-the-playing-field-the-physical-education-subject-report (Accessed 24 October 2024).

Oppenheim, C. & Archer, N. (2021). *The Role of Early Childhood Education and Care in Shaping Life Chances.* Available at: https://www.nuffieldfoundation.org/publications/early-childhood-education-care-shaping-life-chances (Accessed 24 October 2024)

Oppici, L., Rudd, J.R., Buszard, T. & Spittle, S. (2020). Efficacy of a 7-week dance (RCT) PE curriculum with different teaching pedagogies and levels of cognitive challenge to improve working memory capacity and motor competence in 8–10 years old children. Psychology of Sport and Exercise, 50. https://doi.org/10.1016/j.psychsport.2020.101675.

Oppici, L., Frith, E., & Rudd, J. (2020). A perspective on implementing movement sonification to influence movement (and eventually cognitive) creativity. *Frontiers in Psychology, 11,* Article 2233. https://doi.org/10.3389/fpsyg.2020.02233

Orangi, B.M., Yaali, R., Bahram, A., van der Kamp, J. & Aghdasi, M.T. (2021). The effects of linear, nonlinear, and differential motor learning methods on the emergence of creative action in individual soccer players. *Psychology of Sport and Exercise*, 56. https://doi.org/10.1016/j.psychsport.2021.102009.

Orth, D., van der Kamp, J., Memmert, D., & Savelsbergh, G. J. P. (2017). Creative Motor Actions as Emerging from Movement Variability. *Frontiers in psychology,* 8, 1903. https://doi.org/10.3389/fpsyg.2017.01903

Owen L.L.W., & Manning J.R. (2024). High-level cognition is supported by information-rich but compressible brain activity patterns. *PNAS*, 121(35). https://doi.org/10.1073/pnas.2400082121

Pagona, B., & Costas, M. (2008). The Development of Motor Creativity in Elementary School Children and Its Retention. *Creativity Research Journal*, 20(1), 72–80. https://doi.org/10.1080/10400410701842078

Palacios-Barrios, E. E., & Hanson, J. L. (2019). Poverty and self-regulation: Connecting psychosocial processes, neurobiology, and the risk for psychopathology. *Comprehensive Psychiatry*, 90, 52–64. https://doi.org/10.1016/j.comppsych.2018.12.012

Pandey, A., Hale, D., Das, S., Goddings, A. L., Blakemore, S. J., & Viner, R. M. (2018). Effectiveness of Universal Self-Regulation-Based Interventions in Children and Adolescents: A Systematic Review and Meta-analysis. *JAMA paediatrics*, 172(6), 566–575. https://doi.org/10.1001/jamapediatrics.2018.0232

Pascual, A., Moyano Muñoz, N., & Quílez Robres, A. (2019). The Relationship Between Executive Functions and Academic Performance in Primary Education: Review and Meta-Analysis. *Frontiers in psychology*, 10, 1582. https://doi.org/10.3389/fpsyg.2019.01582

Perry, R.E. & Braren, S.H. (2018). Socioeconomic risk and school readiness: longitudinal mediation through children’s social competence and executive function. *Frontiers in Psychology*, 9. https://doi.org/10.3389/fpsyg.2018.01544

Pezzulo, G., & Cisek, P. (2016). Navigating the Affordance Landscape: Feedback Control as a Process Model of Behaviour and Cognition. *Trends in cognitive sciences*, 20(6), 414–424. https://doi.org/10.1016/j.tics.2016.03.013

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. (2016). Variability of practice as an interface between motor and cognitive development. *International Journal of Sport and Exercise Psychology*, 17(2), 1-20. DOI:10.1080/1612197X.2016.1223421

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.

Petersen, I. T., Hoyniak, C. P., McQuillan, M. E., Bates, J. E., & Staples, A. D. (2016). Measuring the development of inhibitory control: The challenge of heterotypic continuity. *Developmental review*, 40, 25–71. https://doi.org/10.1016/j.dr.2016.02.001

Phillips, S.M., Summerbell, C., Hobbs, M. Muir, C., Hillier-Brown, F.C., Hesketh K.R., & Saxena, S., (2021). A systematic review of the validity, reliability, and feasibility of measurement tools used to assess the physical activity and sedentary behaviour of pre-school aged children. International Journal of Behavioural Nutrition and Physical Activity. 18, 141. https://doi.org/10.1186/s12966-021-01132-9

Piaget, J. (1967*). Biology and Knowledge*. Paris: Gallimard

Piaget, J. (1973). *The child and reality: Problems of genetic psychology.*

Pickering, S.J. (2006). *Working Memory and Education.* Academic Press: London.

Posne, M. I., & Rothbart, M. K. (2000). Developing mechanisms of self-regulation. *Development and psychopathology*, 12(3), 427–441. https://doi.org/10.1017/s0954579400003096

Posner, M. I., & Snyder, C. R. R. (1975). *Attention and cognitive control*. In R. Solso (Ed.), *Information processing and cognition: The Loyola symposium.* Hillsdale: Lawrence Erlbaum

Randall, V. (2022). 'We want to, but we can't: pre-service teachers' experiences of learning to teach primary physical education. Oxford Review of Education, 349,(2), 209-228. https://doi.org/10.1080/03054985.2022.2040471

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.

Raja, V., & Anderson, M. L. (2019). Radical Embodied Cognitive Neuroscience. *Ecological Psychology,* 31(3), 166–181. https://doi.org/10.1080/10407413.2019.1615213

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.

Renninger, K. A. (2010). Working with and cultivating the development of interest, self-efficacy, and self-regulation. In D. D. Preiss & R. J. Sternberg (Eds.), Innovations in educational psychology: *Perspectives on learning, teaching, and human development*, 107–138. Springer Publishing Company.

Renshaw, I. & Chow, J.Y. (2018). A constraint-led approach to sport and physical education pedagogy. *Physical Education and Sport Pedagogy.* 24. 1-14. 10.1080/17408989.2018.1552676.

Reyes-Amigo, T., Bezerra, A., Gomez-Mazorra, M., Boppre. G., Martins, C., Carrasco-Beltran, H., Cordero-Roldan, E., & Mota, J. (2022). Effects of high-intensity interval training on executive functions in children and adolescents: A Systematic Review and Meta-analysis. *Physical Activity Review*, vol. 10(2), 10(2): 77-87. doi: 10.16926/par.2022.10.23

Richardson, M.J., Shockley, K., Fajen, B.R. & Riley, M.A. (2008). Ecological psychology: six principles for an embodied-embedded approach to behaviour. In Calvo, P. & Gomila, A. (2008). *Handbook of Cognitive Science: An Embodied Approach. London*: Elsevier

Ridgers, N.D., & Fairclough, S.J. (2011). Assessing free-living physical activity using accelerometery: Practical issues for researchers and practitioners. *European Journal of Sport Science*, 11(3), 205-213. https://doi.org/10.1080/17461391.2010.501116

Robinson, L. E., Stodden, D. F., Barnett, L. M., Lopes, V. P., Logan, S. W., Rodrigues, L. P., & D'Hondt, E. (2015). Motor Competence and its Effect on Positive Developmental Trajectories of Health. *Sports medicine (Auckland, N.Z.)*, 45(9), 1273–1284. https://doi.org/10.1007/s40279-015-0351-6

Robson, D. A., Allen, M. S., & Howard, S. J. (2020). Self-regulation in childhood as a predictor of future outcomes: A meta-analytic review. *Psychological Bulletin*, 146(4), 324–354. https://doi.org/10.1037/bul0000227

Rodríguez, C. (2022). The construction of executive function in early development: The pragmatics of action and gestures. *Human Development*, 66(4-5), 239–259. https://doi.org/10.1159/000526340

Roscoe, C.M.P., James, R.S. & Duncan, M.J. (2019). Accelerometer-based physical activity levels, fundamental movement skills and weigh status in British preschool children from a deprived area. *European Journal of Pediatrics*, 178, 1043-1052. https://doi.org/10.1007/s00431-019-03390-z

Roscoe C. M. P., Taylor, N., Weir, N., Flynn, R. J. and Pringle, A. (2024). Impact and Implementation of an Early Years Fundamental Motor Skills Intervention for Children 4–5 Years. *Children*. 11(4), 416. https://doi.org/10.3390/children11040416

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

Rowe, A., Titterington, J., Holmes, J., Henry, L., & Taggart, L. (2019). Interventions targeting working memory in 4-11-year-olds within their everyday contexts: A systematic review. *Developmental review:* DR, 52, 1–23. https://doi.org/10.1016/j.dr.2019.02.001

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 northwest 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

Rudd, J., Foulkes, J., O' Sullivan, M. & Woods, C. (2021). *A 'Fundamental' Myth of Movement With a 'Functional' Solution. Myths of Sport Coaching.* Sequoia Books

Sæther, S., Borgen, J. S., & Leirhaug, P. E. (2023). *Structuring play in physical education. Sport, Education and Society,* 1–13. https://doi.org/10.1080/13573322.2023.2283782

Sánchez-López, M., Cavero-Redondo, I., Álvarez-Bueno, C., Ruiz-Hermosa, A., Pozuelo-Carrascosa, D.P., Díez-Fernández, A., Gutierrez-Díaz del Campo D., Jesús Pardo-Guijarro, M. & Martínez-Vizcaíno, V. (2018). Impact of a multicomponent physical activity intervention on cognitive performance: The MOVI-KIDS study. *Scandinavian Journal of Medicine & Science in Sports, 2*9(5), 766-775. https://doi.org/10.1111/sms.13383

Sankalaite, S., Huizinga, M., Dewandeleer, J., Xu, C., de Vries, N., Hens, E., & Baeyens, D. (2021). Strengthening Executive Function and Self-Regulation Through Teacher-Student Interaction in Preschool and Primary School Children: *A Systematic Review. Frontiers in psychology,* 12, 718262. https://doi.org/10.3389/fpsyg.2021.718262

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

Schirmbeck, K., Rao, N., & Maehler, C. (2020). Similarities and differences across countries in the development of executive functions in children: A systematic review. *Infant and Child Development*, 29(1), Article e2164. https://doi.org/10.1002/icd.2164

Schmidt, R.A. (1975) A schema theory of discrete motor skill learning. *Psychological Review*. 82(4), 225-260. DOI: https://doi.org/10.1037/h0076770

Schmidt, R. A., & Wrisberg, C. A. (2008). *Motor learning and performance: A situation-based learning approach (4th ed.).* Human Kinetics.

Schmidt, M., Jäger, K., Egger, F., Roebers, C. M., & Conzelmann, A. (2015). Cognitively Engaging Chronic Physical Activity, But Not Aerobic Exercise, Affects Executive Functions in Primary School Children: A Group-Randomized Controlled Trial. *Journal of sport & exercise psychology*, 37(6), 575–591. https://doi.org/10.1123/jsep.2015-0069

Seers, H. (2022). H*ow the natural environment can support children and young people.* Available at: https://publications.naturalengland.org.uk/publication/6705674179575808 (Accessed: 24 October 2024).

Schulz, K.F., Altman, D.G., Moher, D. (2010). Statement: updated guidelines for reporting parallel group randomised trials. *BMC Medicine*, 8(18). https://doi.org/10.1186/1741-7015-8-18

Scionti, N., Cavallero, M., Zogmaister, C., & Marzocchi, G. M. (2020). Is Cognitive Training Effective for Improving Executive Functions in Pre-schoolers? A Systematic Review and Meta-Analysis. *Frontiers in psychology*, 10, 2812. https://doi.org/10.3389/fpsyg.2019.02812

Scibinetti P., Tocci, N. & Pesce, C. (2011). Motor Creativity and Creative Thinking in Children: The Diverging Role of Inhibition. *Creativity Research Journal* - CREATIVITY RES J. 23. 262-272. 10.1080/10400419.2011.595993.

Shah, R.K. (2021). Conceptualising and defining pedagogy. *Journal of Research & Method in Education.* 11(1), 6-29. DOI: 10.9790/7388-1101020629

Shi, P. & Feng, X. (2022). Motor skills and cognitive benefits in children and adolescents: relationship, mechanism and perspectives. *Frontiers in Psychology*, 13. https://doi.org/10.3389/fpsyg.2022.1017825

Shea, C. H., & Wulf, G. (2005). Schema Theory: A Critical Appraisal and Re-evaluation. *Journal of Motor Behaviour*, 37(2), 85–101. https://doi.org/10.3200/JMBR.37.2.85-102

Silva T. B. F., Osório, F. L. & Loureiro, S.R. (2015). SDQ: Discriminative validity and diagnostic potential. *Frontiers in Psychology,* 6. DOI=10.3389/fpsyg.2015.00811

Silva, C., Sousa-Gomes, V., Fávero, M., Oliveira-Lopes, S., Merendeiro, C.S., Oliveira, J. & Moreira, D. (2022). Assessment of preschool-age executive functions: A systematic review. *Clinical Psychology & Psychotherapy.* https://doi.org/10.1002/cpp.2718

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

Sins, P., de Leeuw, R., de Brouwer, J. & Vrieling-Teunter, E. (2023). Promoting explicit instruction of strategies for self-regulated learning: evaluating a teacher professional development program in primary education. *Metacognition Learning* 19, 215–247 (2024). https://doi.org/10.1007/s11409-023-09368-5

Sitaresmi, D. & Kurniastuti, I. (2024). Development of a self-direction game handbook to improve inhibitory control for 10–12-year-olds. *International Journal of Indonesian Education and Teaching*. 8. 61-77. 10.24071/ijiet.v8i1.6751.

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 manual: 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.

Smart, P., Clowes, R. & Heersmink, R. (2017), "Minds Online: The Interface between Web Science, Cognitive Science and the Philosophy of Mind". *Foundations and Trends® in Web Science,* Vol. 6: No. 1-2, pp 1-232. http://dx.doi.org/10.1561/1800000026

Smith, L.B. & Thelen, E. (1994). *A Dynamic Systems Approach to the Development of Cognition and Action.* The MIT Press. ISBN: 9780262200950

Song, W., Feng, L., Wang, J., Ma, F., Chen, J., Qu, S., & Luo, D. (2022). Play Smart, Be Smart? Effect of Cognitively Engaging Physical Activity Interventions on Executive Function among Children 4~12 Years Old: *A Systematic Review and Meta-Analysis. Brain sciences,* 12(6), 762. https://doi.org/10.3390/brainsci12060762

Souissi, S., Chamari, K., & Bellaj, T. (2022). Assessment of executive functions in school-aged children: A narrative review. *Frontiers in psychology,* 13, 991699. https://doi.org/10.3389/fpsyg.2022.991699

Stein, M., Auerswald, M., & Ebersbach, M. (2017). Relationships between Motor and Executive Functions and the Effect of an Acute Coordinative Intervention on

Executive Functions in Kindergartners. *Frontiers in psychology*, 8, 859. https://doi.org/10.3389/fpsyg.2017.00859

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. *Brazilian 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). Holistic 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

Sullivan, L. (2021) *Is Physical Education in Crisis? Leading a much-needed change in Physical Education.* Radstock: Scholarly.

Takacs, Z. K., & Kassai, R. (2019). The efficacy of different interventions to foster children's executive function skills: A series of meta-analyses. *Psychological Bulletin*, 145(7), 653–697. https://doi.org/10.1037/bul0000195

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

Toplak, M. E., West, R. F., & Stanovich, K. E. (2013). Practitioner review: do performance-based measures and ratings of executive function assess the same construct? *Journal of child psychology and psychiatry, and allied disciplines*, 54(2), 131–143. https://doi.org/10.1111/jcpp.12001

Tulsky, D. S., Carlozzi, N., Chiaravalloti, N. D., Beaumont, J. L., Kisala, P. A., Mungas, D., Conway, K., & Gershon, R. (2014). NIH Toolbox Cognition Battery (NIHTB-CB): list sorting test to measure working memory. *Journal of the International Neuropsychological Society*, 20(6), 599–610. https://doi.org/10.1017/S135561771400040X

Turner, G., Israelsson, J., Reynolds, N., Umeh, E., O'Connor, L., Loveless, B., Ford, J., Vaughan, J. & Hands, A. (2024). Addressing access to greenspace and health inequalities in England: policy content analysis and systematic literature review. *The Lancet*, 404(1). https://doi.org/10.1016/S0140-6736(24)01990-1

Turvey, M., Shaw, R. & Mace, W. (1978). Issues in the Theory of Action: Degrees of Freedom, Coordinative Structures and Coalitions.

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

UNESCO. (2024). *Promoting Quality Physical Education Policy*. Available at: https://www.unesco.org/en/quality-physical-education (Accessed 24 October, 2024).

Ursache, A., Noble, K. G., & Paediatric Imaging, Neurocognition and Genetics Study (2016). Socioeconomic status, white matter, and executive function in children. *Brain and behaviour,* 6(10), e00531. https://doi.org/10.1002/brb3.531

Utesch, T. & Bardid, F. (2019). Motor competence, in Hackfort, D., Schinke, R.J. & Strauss, B. (2019) *Dictionary of sports psychology*. Amsterdam: Academic press, 186.

Valeh, F., Saberi kakhki, A. & Alirezayi Noghondar, F. (2020). The comparison of Linear and Nonlinear pedagogy on the learning of table tennis forehand stroke. *International Journal of Physical Education, Sports and Health,* 7(6), 106-111. https://doi.org/10.22271/kheljournal.2020.v7.i6b.1904

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 der Veer, I. P. A., Verbecque, E., Rameckers, E. A. A., Bastiaenen, C. H. G., & Klingels, K. (2022). How can instructions and feedback with external focus be shaped to enhance motor learning in children? A systematic review. *PloS one,* 17(8), e0264873. https://doi.org/10.1371/journal.pone.0264873

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

Van Waelvelde, H., Vanden Wyngaert, K., Mariën, T., Baeyens, D. & Calders, P. (2019). The relation between children's aerobic fitness and executive functions: A systematic review. *Infant and Child Development,* 33(5). https://doi.org/10.1002/icd.2163

Vargas-Vitoria, R., Faúndez-Casanova, C., Cruz-Flores, A., Hernandez-Martinez, J., Jarpa-Preisler, S., Villar-Cavieres, N., González-Muzzio, M. T., Garrido-González, L., Flández-Valderrama, J., & Valdés-Badilla, P. (2023). Effects of Combined Movement and Storytelling Intervention on Fundamental Motor Skills, Language Development and Physical Activity Level in Children Aged 3 to 6 Years: *Study Protocol for a Randomized Controlled Trial. Children (Basel, Switzerland),* 10(9), 1530. https://doi.org/10.3390/children10091530

Vasilopoulos, F. & Ellefson, M.R. (2021) Investigation of the associations between physical activity, self-regulation and educational outcomes in childhood. *PLoS ONE* 16(5). https://doi.org/10.1371/journal.pone.0250984

Vasilopoulos, F., Jeffrey, H., Wu, Y., Dumontheil, I., (2023). Multi-level meta-analysis of whether fostering creativity during physical activity interventions increases their impact on cognitive and academic outcomes during childhood. Scientific Reports, 13, 8383. https://doi.org/10.1038/s41598-023-35082-y

Vazou, Spyridoula., Pesce, C., Lakes, Kimberley. & Smiley-Oyen, A. (2016). More than one road leads to Rome: A narrative review and meta-analysis of physical activity intervention effects on cognition in youth. *International Journal of Sport and Exercise Psychology*. 17. 10.1080/1612197X.2016.1223423.

Veldman, S. L., Hammersley, M. L., Howard, S. J., Stanley, R. M., Okely, A. D. & Jones, R. A. (2023). Associations of gross motor skills with self-regulation and executive function in preschool-aged children. *Australasian Journal of Early Childhood,* 48(3), 234-246. https://doi.org/10.1177/18369391231175524

Vella-Brodrick, D. A., & Gilowska, K. (2022). Effects of nature (greenspace) on cognitive functioning in school children and adolescents: A systematic review. *Educational Psychology Review,* 34(3), 1217–1254. https://doi.org/10.1007/s10648-022-09658-5

Veraksa, A., Tvardovskaya, A., Gavrilova, M., Yakipova, V. & Musalek, M. (2021). Associations between executive function and physical fitness in preschool children. *Frontiers in Psychology,* 12. doi: 10.3389/fpsyg.2021.674746

Verburgh, L., Königs, M., Scherder, E. J., & Oosterlaan, J. (2014). Physical exercise and executive functions in preadolescent children, adolescents and young adults: a meta-analysis. *British journal of sports medicine,* 48(12), 973–979. https://doi.org/10.1136/bjsports-2012-091441

Vink, M., Gladwin, T.E., Geeraerts, S., Pas, P., Bos, D., Hofstee, M., Durston, S. & Vollebergh, W. (2020). Towards an integrated account of the development of self-regulation from a neurocognitive perspective: A framework for current and future longitudinal multi-modal investigations. *Developmental Cognitive Neuroscience,* 45. 100829, ISSN 1878-9293. https://doi.org/10.1016/j.dcn.2020.100829.

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

Vugteveen, J., de Bildt, A., Theunissen, M., Reijneveld, S. A., & Timmerman, M. (2021). Validity Aspects of the Strengths and Difficulties Questionnaire (SDQ)

Adolescent Self-Report and Parent-Report Versions Among Dutch Adolescents. *Assessment*, 28(2), 601-616. https://doi.org/10.1177/1073191119858416

Wade M., McLaughlin, K.A., Buzzell, G.A., Fox, N.A., Zeanah, C.H. & Nelson, C.A. (2023). Family-based care buffers the stress sensitizing effect of early deprivation on executive functioning difficulties in adolescence. *Child Development*, 94. DOI: 10.1111/cdev.13863

Walker, S. P., Wachs, T. D., Grantham-McGregor, S., Black, M. M., Nelson, C. A., Huffman, S. L., Baker-Henningham, H., Chang, S. M., Hamadani, J. D., Lozoff, B., Gardner, J. M., Powell, C. A., Rahman, A., & Richter, L. (2011). Inequality in early childhood: risk and protective factors for early child development. *Lancet (London, England)*, 378(9799), 1325–1338. https://doi.org/10.1016/S0140-6736(11)60555-2

Wang, M., Yang, X., Yu, J., Zhu, J., Kim, H. D., & Cruz, A. (2023). Effects of Physical Activity on Inhibitory Function in Children with Attention Deficit Hyperactivity Disorder: A Systematic Review and Meta-Analysis. *International journal of environmental research and public health,* 20(2), 1032. https://doi.org/10.3390/ijerph20021032

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

Wassenberg, R., Feron, F. J., Kessels, A. G., Hendriksen, J. G., Kalff, A. C., Kroes, M., Hurks, P. P., Beeren, M., Jolles, J., & Vles, J. S. (2005). Relation between cognitive and motor performance in 5- to 6-year-old children: results from a large-scale cross-sectional study. *Child development,* 76(5), 1092–1103. https://doi.org/10.1111/j.1467-8624.2005.00899.x

Waters, N., Ahmed, S., Tang, S., Morrison, F. & Davis-Kean, P. (2021). Pathways from Socioeconomic Status to Early Academic Achievement: The Role of Specific Executive Functions. *Early Childhood Research Quarterly*. 54. 321-331. 10.1016/j.ecresq.2020.09.008.

Weaver, J. (2015). Motor Learning Unfolds Over Different Timescales in Distinct Neural Systems. *PLoS Biology,* 13(12). https://doi.org/10.1371/journal.pbio.1002313

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

Whitall, J., Bardid, F., Getchell, N., Pangelinan, M., Robinson, L. E., Schott, N., & Clark, J. E. (2020). Motor development research: II. The first two decades of the 21st century shaping our future. *Journal of Motor Learning and Development*, 8(2), 363-390. https://doi.org/10.1123/jmld.2020-0007

Whitehead, M. (2020). *Aims of Physical Education. Learning to Teach Physical Education in the Secondary School, 5th Ed.* Routledge. eBook ISBN9780429264436

Wickham, H. & Grolemund, G. (2017). *R for Data Science: Import, Tidy, Transform, Visualize, and Model Data.* O'Reilly Media

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Developmental Psychology,* 44(2), 575–587. https://doi.org/10.1037/0012-1649.44.2.575

Wickham, S., Whitehead, M., Taylor-Robinson, D., & Barr, B. (2017). The effect of a transition into poverty on child and maternal mental health: a longitudinal analysis of the UK Millennium Cohort Study. *The Lancet. Public health,* 2(3), e141–e148. https://doi.org/10.1016/S2468-2667(17)30011-7

Willoughby, M., Hudson, K., Hong, Y. & Wylie, A, (2021). Improvements in motor competence skills are associated with improvements in executive function and math problem-solving skills in early childhood. *Developmental Psychology,* 57(9),1463-1470. doi: 10.1037/dev0001223. PMID: 34929091

Wilson, T. D. (2002). *Strangers to ourselves: Discovering the adaptive unconscious.* Belknap Press/Harvard University Press.

Wood, M. A., Mellalieu, S.D., Araújo, D., Woods, C.T. & Davids, K. (2022). Learning to coach: an ecological dynamics perspective. *International journal of sports science & coaching.* https://journals.sagepub.com/doi/epdf/10.1177/1747

WHO. (2020). *Guidelines on physical activity and sedentary behaviour.* Available at: https://www.who.int/publications/i/item/9789240015128 (Accessed 24 October 2024).

World Health Organisation. (2022). Promoting physical activity through schools. Available at: https://iris.who.int/bitstream/handle/10665/354605/9789240049567-eng.pdf?sequence=1 (Accessed 24 October 2024).

Wulf, G. (2012). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology*, 6(1), 77–104. https://doi.org/10.1080/1750984X.2012.723728

Xiong, S., Li, X. & Tao, K. (2017). Effects of structured physical activity program on Chinese young children's executive function and perceived physical competence in a day care center. *BioMed Research International,* doi: 10.1155/2017/5635070.

Xue, Y., Yang, Y. & Huang, T. (2019). Effects of chronic exercise interventions on executive function among children and adolescents: a systematic review with meta-analysis. *British Journal of Sports Medicine,* 53(22), 1397-1404. doi: 10.1136/bjsports-2018-099825.

Yao, S., Zhang, C, Zhu, X., Jing, X., McWhinnie, C.M. & Abela, J.R.Z. (2009). Measuring adolescent psychopathology: psychometric properties of the self-report strengths and difficulties questionnaire in a sample of Chinese adolescents. *The Journal of Adolescent Health,* 45(1), 55-62. doi: 10.1016/j.jadohealth.2008.11.006.

Yi Lee, M.C., Chow, J.Y., Button, C. & Tan, C.W.K. (2017). Nonlinear pedagogy and its role in encouraging twenty-first century competencies through physical education: a Singapore experience. *Asia Pacific Journal of Education,* 37(4), 483-499. DOI:10.1080/02188791.2017.1386089

Youth Sport Trust. 2002. *The STEP Tool*. Available at: https://www.youthsporttrust.org/media/ihdab2uj/yst_60min_cover_and_challenge_cards_final_insideout.pdf (Accessed 24 October 2024)

Youth Sport Trust. (2024). *PE and School Sport – The Annual Report 2024.* Available at: https://www.youthsporttrust.org/media/tjgf20tp/yst_pe_school_sport_report_2024_final.pdf (Accessed 24 October 2024).

Zatorre, R.J., Fields, R.D. & Johansen-Berg, H. (2012). Plasticity in gray and white: neuroimaging changes in brain structure during learning. *Nature Neuroscience,* 15(4), 528-536. doi: 10.1038/nn.3045.

Zavitz, E. & Price, N.S.C. (2019). Understanding sensory information processing through simultaneous multi-area population recordings. *Frontier of Neural Circuits,* 12. https://doi.org/10.3389/fncir.2018.00115

Zelazo, P. D., Frye, D., & Rapus, T. (1996). An age-related dissociation between knowing rules and using them. *Cognitive Development, 11*(1), 37–63. https://doi.org/10.1016/S0885-2014(96)90027-1

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

Zelazo, P.D., Blair, C.B. & Willoughby, M.T. (2016). Executive Function: Implications for Education. *Institute of Education Sciences.* https://files.eric.ed.gov/fulltext/ED570880.pdf

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

Zhang, J.Y., Shen, Q.Q., Wang, D.L., Hough, J.M., Xia, T., Qiu, S., Wang, X.Y., Zhou, S.B., Yang, W.W., Heng, S.Y., Lu, C.C., Cui, L. & Yin, H.C. (2022). Physical activity intervention promotes working memory and motor competence in preschool children. *Frontiers in Public Health,* 10. https://doi.org/10.3389/fpubh.2022.984887

Zimmerman, B.J. (2002). Becoming a self-regulated learner: an overview. *Theory into Practice.* 41(2). https://doi.org/10.1207/s15430421tip4102_2

Appendices

Appendix A

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

Predictor		**Estimate**	**Std.error**	**p value**
Intercept	Complete cases	-5.18	6.67	0.438
	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
SEN	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		

Appendix B

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 Imputed	-4.00 -3.32	1.03 0.91	<0.001 <0.001
Deprivation decile	Complete cases Imputed	2.92 3.15	0.98 0.98	0.003 0.002
R^2 of the model	Complete cases (n=239) Imputed	0.190 0.160		

Appendix C

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

Predictor		Estimate	Std.error	p value
Intercept	Complete cases	-7.37	7.43	0.322
	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		

Appendix D

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		

Appendix E

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		

Appendix F

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		

Appendix G

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		

Appendix H

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		

Appendix I

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**
Intercept	Complete cases	-5.83	8.00	0.467
	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		

Appendix J

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		

Appendix K

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
Intercept	Complete cases	-6.30	7.99	0.432
	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		

Appendix L

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
Intercept	Complete cases	3.14	12.31	0.799
	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		

Appendix M

Response to Challenge Scale items by subscale

Cognitive subscale

Attentive	1	2	3	4	5	6	7	Inattentive
Self-disciplined	1	2	3	4	5	6	7	Unrestrained
Involved in task	1	2	3	4	5	6	7	Resistant
Focused	1	2	3	4	5	6	7	Distractible
Weak-willed	1	2	3	4	5	6	7	Strong-willed
Engaged	1	2	3	4	5	6	7	Disengaged

Affective subscale

Invincible	1	2	3	4	5	6	7	Vulnerable
Assertive	1	2	3	4	5	6	7	Timid
Quitting	1	2	3	4	5	6	7	Persevering
Motivated	1	2	3	4	5	6	7	Unmotivated
Confident	1	2	3	4	5	6	7	Insecure
Uncontrolled emotions	1	2	3	4	5	6	7	Control over emotions
Fearless	1	2	3	4	5	6	7	Fearful

Physical subscale

Athletic	1	2	3	4	5	6	7	Unfit
Clumsy	1	2	3	4	5	6	7	Coordinated
Skilful	1	2	3	4	5	6	7	Awkward

Appendix N

Summary table for the results of the mixed models for self-regulation adjusting for sex, age, ethnicity and deprivation as covariates

	Total Difficulties	Prosocial Behaviour
(Intercept)	14.285*	6.050*
	(6.373)	(2.466)
Time Point 1	0.167	-0.136
	(0.532)	(0.137)
Time Point 2	0.168	-0.136
	(0.531)	(0.138)
Exp. Non-Linear	1.517	-0.154
	(1.768)	(0.592)
Exp. Linear	-0.834	-0.359
	(1.794)	(0.603)
Sex	-1.981**	0.937***
	(0.621)	(0.241)
Age	-0.868	0.168
	(1.044)	(0.406)
Ethnicity	0.505	0.077
	(0.723)	(0.277)
Deprivation Decile	-0.213	0.077
	(0.195)	(0.075)
Time Point 1 * Non-Linear	-2.178**	0.200
	(0.817)	(0.211)
Time Point 2 * Non-Linear	-2.025	0.103
	(0.815)	(0.214)
Time Point 1 * Linear	6.209***	0.909***
	(0.813)	(0.210)
Time Point 2 * Linear	6.208	0.909***
	(0.810)	(0.211)
N	814	814
logLik	-1785.625	-1157.935
AIC	3613.250	2357.870

Appendix O

Summary table for the results of the mixed models for inhibitory control adjusting for sex, age, ethnicity, deprivation, BMI and SEN as covariates

	Model 1	Model 2	Model 3	Model 4
(Intercept)	4.829	4.615	0.291	0.027
	(0.148)	(0.219)	(1.709)	(1.683)
Time Point 1	0.540***	0.456*	0.420*	0.259
	(0.117)	(0.188)	(0.190)	(0.206)
Time Point 2	0.716***	0.725***	0.716***	0.600***
	(0.088)	(0.138)	(0.140)	(0.140)
Exp. NonLinear		0.337	0.310	0.228
		(0.340)	(0.350)	(0.312)
Exp. Linear		0.434	(0.409)	0.175
		(0.356)	(0.369)	(0.327)
Sex			0.422*	0.262
			(0.167)	(0.170)
Age			0.667*	0.770***
			(0.282)	(0.278)
Ethnicity			0.154	0.220
			(0.186)	(0.183)
Deprivation Decile			0.042	0.093
			(0.053)	(0.053)
BMI				-0.069
				(0.071)
SEN				-1.456***
				(0.270)
Time Point 1 * NonLinear		0.276	0.311	0.437
		(0.279)	(0.281)	(0.293)
Time Point 2 * NonLinear		0.285	0.292	0.361
		(0.208)	(0.209)	(0.202)
Time Point 1 * Linear		-0.024	0.038	0.111
		(0.288)	(0.292)	(0.301)
Time Point 2 * Linear		-0.333	-0.337	-0.296
		(0.211)	(0.214)	(0.206)

N	972	972	950	867
logLik	-1879.482	-1876.582	-1833.041	-1633.519
AIC	3780.965	3787.164	3708.082	3313.037

Appendix P

Summary table for the results of the mixed models for working memory adjusting for sex, age, ethnicity, deprivation, BMI and SEN as covariates

	Model 1	Model 2	Model 3	Model 4
(Intercept)	1.973***	1.766***	-9.591	-10.472
	(0.264)	(0.410)	(3.725)	(3.907)
Time Point 1	2.084***	1.555***	1.601***	1.386***
	(0.249)	(0.401)	(0.411)	(0.445)
Time Point 2	1.863***	1.452***	1.493***	1.506***
	(0.227)	(0.356)	(0.356)	(0.388)
Exp. NonLinear		0.385	0.186	0.022
		(0.636)	(0.599)	(0.654)
Exp. Linear		0.362	0.542	0.262
		(0.671)	(0.634)	(0.693)
Sex			0.780*	0.645
			(0.363)	(0.393)
Age			1.721**	1.926**
			(0.616	(0.646)
Ethnicity			0.213	0.099
			(0.394)	(0.425)
Deprivation Decile			0.342**	0.381**
			(0.115)	(0.122)
BMI				0.299
				(0.164)
SEN				-1.428*
				(0.618)
Time Point 1 * NonLinear		1.040	0.987	1.241*
		(0.591)	(0.601)	(0.628)
Time Point 2 * NonLinear		1.784***	1.737**	1.605**
		(0.531)	(0.529)	(0.557)
Time Point 1 * Linear		0.666	0.706	0.915
		(0.612)	(0.630)	(0.651)
Time Point 2 * Linear		-0.481	-0.653	-0.694
		(0.539)	(0.542)	(0.566)
N	978	978	955	874
logLik	-2707.449	-2694.848	-2622.796	-2398.222

AIC	5436.897	5423.697	5287.592	4842.444

Appendix Q

Summary table for the results of the mixed models for cognitive flexibility adjusting for sex, age, ethnicity, deprivation, BMI and SEN as covariates

	Model One	Model Two	Model Three	Model Four
(Intercept)	3.315***	3.187***	-0.112	-0.418
	(0.144)	(0.216)	(1.961)	(1.978)
Time Point 1	0.744***	0.512*	0.497*	0.470
	(0.139)	(0.221)	0.224)	(0.245)
Time Point 2	1.300***	1.096***	1.098***	0.987***
	(0.141)	(0.224)	(0.226)	(0.248)
Exp. NonLinear		0.274	0.249	0.231
		(0.332)	(0.314)	(0.335)
Exp. Linear		0.203	0.271	0.112
		(0.343)	(0.326)	(0.348)
Sex			0.894***	0.755***
			(0.192)	(0.199)
Age			0.426	0.528
			(0.324)	(0.327)
Ethnicity			0.070	0.083
			(0.202)	(0.209)
Deprivation Decile			0.124*	0.147*
			(0.061)	(0.062)
BMI				-0.022
				(0.084)
SEN				-1.455***
				(0.313)
Time Point 1 * NonLinear		0.059	0.065	0.100
		(0.331)	(0.333)	(0.352)
Time Point 2 * NonLinear		0.153	0.144	0.190
		(0.338)	(0.339)	(0.358)
Time Point 1 * Linear		0.723*	0.744*	0.863*
		(0.338)	(0.345)	(0.360)
Time Point 2 * Linear		0.533	0.530	0.714
		(0.343)	(0.349)	(0.365)
N	982	982	957	872
logLik	-2054.452	-2052.286	-1990.498	-1791.510

AIC	4130.905	4138.572	4022.996	3629.020