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The Relationship Between Executive Functions and Motor Coordination: Longitudinal Impact on Academic Achievement and Language

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Declaration

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Abstract

The reciprocal interactions between the motor and cognitive systems are critical during development. The thesis investigates this relationship by exploring Executive Functions (EFs) in children with typical and atypical motor coordination, and the effect of this association on academic and language outcomes.

Study 1: EFs are higher-order cognitive processes needed for goal-directed behaviour. They involve flexibility of thinking, inhibition of unhelpful responses, strategy development and manipulation of diverse information simultaneously. Children with poor motor skills or Developmental Coordination Disorder (DCD) have demonstrated problems with EFs. However, no studies have explored the development of EFs in DCD longitudinally. Study 1 investigated changes in EFs in children with poor motor skills over two years. Children aged 7-11 years were assessed twice, two years apart, on verbal and nonverbal measures of EFs: executive-loaded working memory; fluency; response inhibition; planning; and cognitive flexibility. Typically developing children (TD: *n*=17) were compared to those with a clinical diagnosis of DCD (*n*=17) and those with identified motor difficulties (MD: *n*=17), but no formal diagnosis.

Developmental gains in EFs were similar between groups, although a gap between children with poor motor skills and TD children on nonverbal EFs persisted. Specifically, children with DCD performed significantly more poorly than TD children on all nonverbal EF tasks and verbal fluency tasks at both time points; and children with MD but no diagnosis showed persistent EF difficulties in nonverbal tasks of working memory and fluency. Both groups demonstrated EF difficulties over two years, which may impact on activities of daily living and academic achievement, in addition to their motor deficit.

Study 2: Academic underachievement has been identified in children with DCD. However, it is unclear whether it extends to all academic domains and whether it is explained by EF abilities, which play an important role in educational attainment and are poorer in DCD. Study 2 examined academic achievement performance in children with and without motor coordination impairments, taking into account the contribution of EF skills. Children with DCD (*n*=17) and children with MD (*n*=32)

were compared to TD children (*n*=41) in measures of reading, spelling and mathematics. Two composite scores of verbal and nonverbal EF respectively were included in the analyses.

There was no evidence of academic difficulties in children with MD. Children with DCD demonstrated poorer mathematical ability compared to their TD peers, but performed as accurately on all other academic tasks. These differences in mathematics in the DCD group were still evident after EF was controlled for in the analyses. Nonverbal EF did not predict performance in any of the academic achievement tasks, whereas verbal EF was a significant predictor of mathematical ability.

Study 3: Motor coordination is fundamentally interrelated with both EF and language, which in turn are related to each other. Recent investigations on the relationship between EF and language have failed to understand the direction and nature of this association, suggesting a third factor may be involved. Study 3 explored the role of motor coordination in the relationship between EF and language. Measures of verbal EF, nonverbal EF, expressive and receptive language were administered to children with DCD (*n*=23), MD (*n*=57) and TD (n=71). A moderation model was tested using Group as the moderating variable, and, next, using motor coordination as a continuous moderating variable (i.e., across groups). Both directions of the association between EF and language were investigated.

The relationship between EF and language was not different between groups in any domains, hence Group was not a significant moderator. When using continuous motor skills data, motor coordination was a significant moderator when EF was the predictor of language outcomes, but not when language was the predictor of EF outcomes. Specifically, the interaction between motor coordination and EF had significant effects on language, as the association between EF and language was positive and significant at low and moderate levels of motor skills, but not at high levels of motor skills.

In conclusion, in this thesis interactions between EF and motor coordination produced complex effects on academic and language outcomes.

CHAPTER 1

1. General Introduction

Movement is the key way in which humans can affect the surrounding world, as it mediates every interaction with the environment. Movement is not merely the execution of a motor response, but is what generates and shapes experiences that are the basis of cognitive development. Therefore, the motor system is very closely intertwined with higher-order cognitive systems, and yet movement and cognition have mostly been studied in isolation. This thesis focuses on the relationship between motor coordination and Executive Functions (EFs), which represent the complex manipulation of cognitive information, and the effect of this relationship on other important developmental outcomes such as language and educational attainment.

The first section of this chapter will introduce motor development and the evidence of its multiple interactions with cognitive development and EF. Different ways of exploring the relationship between motor development and EF will be outlined. One method of studying this interaction is by investigating conditions in which movement is disrupted. Hence, the second section will define Developmental Coordination Disorder (DCD) and discuss its clinical characteristics, terminology and aetiological accounts, including EF and its domains. The focus of this chapter will then shift to discussing the effect of motor coordination, EF and their reciprocal interaction on academic achievement and language outcomes. Finally, the aims and objectives of the studies presented in this thesis will be detailed, illustrating how the investigations proposed are a crucial contribution to the field of developmental psychology, as multiple aspects of child development are linked together rather than studied in isolation.

1.1. The interactive nature of motor and cognitive development

From the first day of their lives, children explore the world around them through their bodies. Learning to reach and grasp, to sit, to manipulate objects, to crawl and walk drives an increasingly complex discovery of the word. The expanding range of motor behaviours developed by the child during the first years of life is essential to the acquisition of sophisticated cognitive abilities, as the development of adequate motor control allows the infant to interact with, and learn from the environment. The idea that action and perception are the roots of cognition was developed by Piaget (1972), whose developmental theory posits that all representational thought arises from perceiving and acting in the world.

This action-based view of cognition has later formed part of the theory of *embodied cognition*, in which the sensorimotor interaction origin of cognitive phenomena is maintained even for higher-lever cognitive abilities (Pezzulo, 2011). Evolutionary processes of the brain are likely to have emerged in order to produce adaptable and complex movement, rather than for the explicit purpose of developing cognition per se (Koziol, Budding, & Chidekel, 2012). Therefore, cognition may be rooted in the development of movement and understanding the nature of this interaction may inform our knowledge of development as a dynamic system.

1.1.1. Development as a dynamic system

An action-oriented perspective of development emphasises the active engagement of the child with the environment rather than the passive responses to stimuli. This is directly linked to the view of motor development itself as being the result of active exploration, as opposed to emerging from neural maturational processes (Thelen, 1995). For example, abilities such as crawling and walking emerge from the dynamic adaptation of initial patterns of movement, such as a tentative first step. Refining initial attempts towards the competent execution of a motor task is only possible through multiple cycles of action and perception, and selection of solutions, that take place in order to reach a goal. Hence, active exploration and modulation towards a goal are an integral part of motor development (Thelen, 1995; Turvey, 1990)

Examples of how motor skills arise from intentional cycles of action and perception are not only demonstrated in early infancy but also in foetuses. Infants as young as a few weeks adapt their arm movements to the presence of a toy many weeks before they develop the ability to reach and grasp (Bhat & Galloway, 2006). Furthermore, the acquisition of early motor skills is driven by active interaction with the environment even before birth. By 22 weeks of gestation self-directed hand movements demonstrated the kinematic patterns of intentional actions, as specific patterns of coordinated movements are modulated towards the end-goal of the action (i.e., either the eye or the mouth; Zoia et al., 2007). When performing kinematic analysis in twin pregnancies, Castiello and colleagues found that by the 14th week of gestation foetuses demonstrate movements specifically directed towards the co-twin, which significantly increased to reach 29% of all movements observed in the 18th week of gestation (Castiello et al., 2010).

Motor behaviours observed in studies such as those above have led to the conceptualisation of movement not as an isolated process, but as *coordination* (Bernstein, 1967) of multiple processes towards a goal. When these are demonstrated in such early stages of development, they are intrinsically intertwined with action monitoring, response selection and inhibition (Thelen, 1995), which are considered to be classical components of higher-order cognitive processes such as EF (Diamond, 2013). This leads to the question of whether there is any dichotomy between motor and cognitive functions, or whether they are part of the same developing system. In the next sections, the evidence that a model integrating the two systems seems to better explain neural, developmental and organisational aspects of human behaviour is reviewed.

1.1.2. Neural overlaps between cognitive and motor functions

From a neural perspective, the motor cortex has been traditionally conceptualised as an area of the brain that simply executes instructions generated elsewhere in the brain. However, this idea of the motor system as a translator of thoughts and sensations into movement has been challenged by a number of studies revealing cognitive and perceptual function in the motor cortex itself (Murata et al., 1997; Rizzolatti et al., 1988). For example, neurons in the premotor cortex do not code for isolated movements but for *motor acts*, which is a term referring to more than one movement coordinated towards a specific goal (Rizzolatti et al., 1988). For example, the same movement executed for different goals (e.g., flexing the index to grasp an object or flexing the index to scratch oneself) activates different neurons, while the same neuron is activated during a motor act (e.g., reaching food) regardless of the part of the body that is used to execute the movement (e.g., left hand, right hand or mouth). Neurons in a specific subarea of the premotor cortex could be classified in different categories such as ‘Grasping neurons’, ‘Reaching neurons’, ‘Holding neurons’, and ‘Tearing neurons’ (Rizzolatti et al., 1988). These categories form a ‘vocabulary’ of motor acts that are independent from the specific movements used in each category.

Furthermore, neurons in the premotor cortex selectively activate depending on the type of motor interaction an object requires (Murata et al., 1997), so that neurons activating during the execution of a movement to grasp an object will also activate just by *seeing* that same object. Hence, visual information is coded based on the motor acts that allow the individual to interact with the environment. These studies on the premotor cortex suggest that the motor system drives an immediate understanding of the surrounding reality, which is pre-conceptual and pre-linguistic. They also reveal how the motor cortex and action are involved in the representation of reality, in concept formation and response selection.

Furthermore, there are overlapping neural structures that co-activate during both motor and cognitive tasks. A review conducted by Diamond (2000) highlighted that the cerebellum, which has long been considered to be devoted to motor control (Ito, 2005), activates during cognitive tasks that require the activation of the prefrontal cortex, which is thought to be largely responsible for executive function (Reitan & Wolfson, 1994). Recent reviews (Stoodley, 2012) and consensus papers (Koziol et al., 2014) recognise that the cerebellum is critical to both movement and cognition. Similarly, the prefrontal cortex is increasingly believed to be sensitive to higher-order cognitive measures but not specific to these measures (Alvarez & Emory, 2006), as it relies on non-frontal brain regions such as the premotor cortex (Dum & Strick, 1991). Again, an integrative approach in which there is a continuum of motor and cognitive processes seem to better explain these functions. For example, the representation of objects, which is traditionally considered symbolic, has been shown to directly depend on the information stored in the sensory and motor areas of the brain that were active during the acquisition of that information (Martin, 2007).

1.1.3. Developmental overlaps between movement and cognition

From a developmental perspective, this interrelationship between cognitive and motor systems is evident in both typical and atypical development, as the following studies illustrate. Spontaneous general movements (Prechtl, Fargel, Weinmann, & Bakker, 1979) are a strong example of how early movement predicts later cognitive development. General movements refer to a set of movement patterns involving all parts of the body that emerge as early as 10 weeks of foetal life (De Vries, Visser, & Prechtl, 1982) and are evident until three to five months of age when intentional goal-directed hand movements develop. When the variety and complexity of general movements are restricted, they are often an early marker of neurological deficit (Prechtl et al., 1997) and can predict minor neurological dysfunction 9-12 years later (Groen, De Blécourt, Postema, & Hadders-Algra, 2005), which in turn is associated with lower cognitive function (Kikkert, de Jong, & Hadders-Algra, 2013). One other early marker of later neurodevelopmental outcomes in the first weeks of life is sucking ability, which, although is a largely reflexive movement, predicts neurodevelopmental outcomes at 18 months more accurately than ultrasound scans (Mizuno & Ueda, 2005). Furthermore, healthy preterm children with better postural control at 6 months of age scored higher 6-18 months later in measures of cognitive development and attention than preterm children with poorer postural control. Problem solving was also predicted by postural control, even when taking into account concurrent motor skills, which supports the predictive nature of early motor skills (Wijnroks & van Veldhoven, 2003). Thus, very early basic movements have been shown to associate with wider outcomes.

In older children too, the role of early gross motor skills in later cognitive development has been highlighted. A study by Piek and colleagues asked parents to complete a developmental screening questionnaire at 11 time points between 4 to 48 months (Piek, Dawson, Smith, & Gasson, 2008). The gross motor trajectory emerging from items measuring the development of posture control, onset of locomotion, crawling, and walking was a significant predictor of cognitive performance at school age. Specifically, when examining the different subscales of a full-scale IQ assessment, processing speed and working memory were predicted by early gross motor trajectories even once SES was controlled for. Although the sample size was relatively small ($N = 33$), the number of time points in which participants were followed up during their early years strengthens the longitudinal predictions and conclusions. Interestingly, fine and gross motor trajectory did not predict later motor skills. Instead, the link was found between early motor development and later cognitive skills, and these results are in line with a review by Campos and colleagues (2000), which examined the evidence for the impact of locomotion on other developmental areas. These authors argue that specific changes in perception, spatial cognition, and social and emotional development are the result of a family of experiences made possible by the onset of locomotion. For example, beginning to walk has a range of consequences for the interaction of the child with the physical and social environment from which developmental progression in cognitive, social and language domains originate. Campos et al. (2000) argue that the age at which motor developmental milestones are reached predicts later cognitive outcomes. Further evidence to support this hypothesis comes from The Northern Finland 1966 Birth Cohort study, in which a representative subsample of 104 adults were assessed on a number of cognitive tasks at 33-35 years of age (Murray et al., 2006). Better performance on EF, specifically cognitive flexibility and working memory, was associated with the age at which participants learned to stand. The effect persisted after maternal educational level, parental social class and gender were taken into account. The finding was not driven by those who were delayed in motor ability, as the same analysis was run excluding all late standers. Results in Murray and colleagues' study suggest that even without involving pathological mechanisms, common underlying neural systems are implicated in infant motor function and adult executive function. Another study on the same population found that these common systems were reflected in adult brain structures, such as increased grey matter density in the premotor cortex and increased white matter density in the frontal lobe in adults with earlier development of motor milestones in infancy (Ridler et al., 2006). Thus, links between motor and cognitive functions seem to be found specifically when higher-level cognitive abilities are measured, as also indicated in a systematic review of studies investigating cognitive and motor skills in 4-16 year old typically developing children (van der Fels et al., 2015).

The evidence outlined above not only supports the idea that both motor and cognitive development have deep roots in cycles of action and perception, but also that there is continuity rather than dualism between structures and functions, as they emerge as part of dynamic systems (Thelen, 1992). Within this framework, developmental processes are the result of complex interactions between multiple systems, rather than being generated from pre-existing genetic programmes or maturational mechanisms. These self-organising dynamic systems generate developmental processes through their own activity within the environment, and the same processes coordinating behaviour in real time represent the multiple sources of changes in development (Smith & Thelen, 2003).

Therefore, given that in typical development relationships between motor and cognitive skills seem particularly strong for higher-level cognitive abilities, it is unsurprising that disruptions in one of the interactive systems could have multiple effects on other systems. In fact, when motor skills are perturbed often cognitive abilities are affected. For example, in a recent study exploring the prevalence of motor difficulties in children with different cognitive levels, 82% of children with mild learning disability (*n* = 61) had significant motor coordination impairments, and only 26% of children with borderline intellectual functioning (*n* = 152) demonstrated typical motor skills (Smits-Engelsman & Hill, 2012). Furthermore, Westendorp and colleagues found that children with learning disability (*n* = 104) demonstrated poorer locomotor and object-control skills than their typically developing age-matched counterparts (*n* = 104; Westendorp, Hartman, Houwen, Smith, & Visscher, 2011).

The significant co-occurrence of motor difficulty and neurodevelopmental disorders provides good evidence of the interactive nature of cognitive and motor functions. Poor motor skills have been identified in children with a range of neurodevelopmental disorders that do not include motor difficulties as part of their core diagnostic criteria. For example, motor difficulties have been identified in children with Autism Spectrum Disorders (ASD) in both the fine and gross motor domains (Lloyd, MacDonald, & Lord, 2013; see Bhat, Landa, & Galloway, 2011 for a review), and even in infants at increased genetic risk of developing ASD (Leonard, Bedford, et al., 2014; Leonard, Elsabbagh, Hill, & al., 2014). Children with Attention Deficit/Hyperactivity Disorder (ADHD; Piek, Pitcher, & Hay, 1999; Pitcher, Piek, & Hay, 2003) as well as children with language impairments (Hill, 2001) are at a significantly higher risk of motor coordination difficulties than their typical peers. Similarly, more than 50% of children with dyslexia and more than 50% of children identified as poor readers by teachers performed below the 5th percentile on a standardised test of motor skills (Iversen, Berg, Ellertsen, & Tønnessen, 2005). Vice versa, children with Developmental Coordination Disorder (DCD), in which impaired motor coordination is the core deficit, often experience difficulties in social-communication and peer interactions (Chen, Tseng, Hu, & Cermak, 2009; Cummins, Piek, & Dyck, 2005; Wagner, Bös, Jascenoka, Jekauc, & Petermann, 2012), demonstrate symptoms of inattention and hyperactivity (Dewey, Kaplan, Crawford, & Wilson, 2002; Kadesjo & Gillberg, 1999), or have significantly poorer reading skills (Tseng, Howe, Chuang, & Hsieh, 2007). As a consequence, co-occurring diagnoses in individuals with DCD are the rule rather than the exception (Kaplan, Wilson, Dewey, & Crawford, 1998).

DCD is a condition in which the acquisition and execution of coordinated motor skills is disrupted and therefore it represents a model case to investigate the overlaps between motor coordination and cognitive functions. The diagnostic criteria, prevalence and characteristics of DCD are described in the next section.

1.2. Developmental Coordination Disorder

DCD is defined on the basis of significant motor coordination impairment in the absence of any physical, neurological or intellectual disability.

1.2.1. Terminology

Historically, children who demonstrated poor motor coordination were described as *motorically deficient* (Dupré, 1925) and for many years the term *clumsy* (Orton, 1937), was widely used (Gubbay, Ellis, Walton, & Court, 1965; Illingworth, 1968; Walton, Ellis, & Court, 1962). *Clumsy child syndrome* (Gubbay, 1975) became the official definition included in the Diagnostic and Statistical Manual of Mental Disorders (3rd ed.; DSM–III; American Psychiatric Association (APA), 1980). Other common terms have included: *sensory integration dysfunction* (Ayres, 1972), *developmental* *dyspraxia* (Cermak, 1985; Denckla, 1984), *perceptuo-motor dysfunction* (Laszlo, Bairstow, Bartrip, & Rolfe, 1988), and *physical awkwardness* (Bouffard & Wall, 1990). In Scandinavia, the term *disorder of attention and motor perception* (DAMP; Gillberg, 1986) was introduced to account for the substantial overlap between problems with motor coordination and attention. In 1992 the International Classification of Diseases and Related Health Problems (10th ed.; ICD-10; World Health Organization (WHO), 1992) designated the condition as *specific developmental disorder of motor function* (SDDMF), which is broadly equivalent to the definition of *developmental coordination disorder* (DCD; Henderson & Barnett, 1998). DCD was first introduced as a label in the fourth revision of the DSM (DSM-IV; APA, 1994) to substitute the term *clumsy child syndrome*. It remains in DSM-5 (APA, 2013).

International consensus meetings favour the use of DCD diagnostic criteria and terminology (Blank, Smits-Engelsman, Polatajko, & Wilson, 2012; Polatajko, Fox, & Missiuna, 1995; Sugden, 2006), thus DCD is the term mostly used worldwide. However, in the UK, the disorder is often referred to as *dyspraxia*, which is at times used interchangeably with DCD (Peters, Barnett, & Henderson, 2001). The term dyspraxia originated from adult neuropsychology in which the definition of *apraxia* described patients with brain damage unable to execute previously learned movements (Polatajko et al., 1995). However, dyspraxia has been used to refer more specifically to disorders of gestures (Dewey, 1995), and although individuals with DCD may experience difficulties with gestures (Hill, Bishop, & Nimmo-Smith, 1998) these are not the defining characteristics of the disorder. While the international scientific community has settled on the term DCD, it is important to note that clinicians, educators and parents are often more familiar with the term dyspraxia, and that confusion with terminology is partly a result of the relatively poor awareness of DCD and its implications, at least in the UK (Kirby, Davies, & Bryant, 2005; Missiuna, Moll, King, King, & Law, 2007; Missiuna, Moll, Law, King, & King, 2006).

1.2.2. Diagnosis, assessment and characteristics of DCD

The most recent edition of the DSM (5th ed., DSM-5; APA, 2013) identifies four criteria for the diagnosis of DCD (see Table 1.1).

Table 1.1. Diagnostic Criteria for DCD (DSM–5; APA, 2013, pg. 74)

A. The acquisition and execution of coordinated motor skills is substantially below that expected given the individual's chronological age and opportunity for skill learning and use. Difficulties are manifested as clumsiness (e.g., dropping or bumping into objects) as well as slowness and inaccuracy of performance of motor skills (e.g., catching an object, using scissors or cutlery, handwriting, riding a bike, or participating in sports).

B. The motor skills deficit in Criterion A significantly and persistently interferes with activities of everyday life appropriate to chronological age (e.g., self-care and self-maintenance) and impacts academic/school productivity, prevocational and vocational activities, leisure, and play.

C. Onset of symptoms is in the early developmental period.

D. The motor skills deficits are not better explained by intellectual disability (intellectual developmental disorder) or visual impairment and are not attributable to a neurological condition affecting movement (e.g., cerebral palsy, muscular dystrophy, degenerative disorder).

As described in Criterion A, individuals with DCD demonstrate lower motor coordination abilities than expected. Norm-referenced tests are therefore used to compare performance on motor tasks with chronological age. The Movement Assessment Battery for Children (2nd ed.; MABC-2; Henderson, Sugden, & Barnett, 2007) and the Bruininks–Oseretsky Test of Motor Proficiency (2nd ed.; BOTMP-2; Bruininks & Bruininks, 2005) are two of the most commonly used motor tests (Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001). Other measures include The McCarron Assessment of Neuromuscular Development (McCarron, 1997), which is used particularly in Australia (e.g., Hoare, 1994; Piek, Barrett, Allen, Jones, & Louise, 2005), and The Test of Gross Motor Development – 2 (TGMD-2; Ulrich, 2000). The DSM-5 however does not specify how much motor coordination should deviate from the norm in order to be identified as an impairment. The European Academy for Childhood Disability's (EACD) most recent guidelines on DCD (Blank et al., 2012), developed on the basis of systematic and meta-analytic research (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013), suggested that the 15th percentile should be used as a cut-off for identifying DCD, as the low sensitivity of current available measures of motor coordination ability may exclude children with moderate impairments. A similar approach is retained in the UK adaptation of these guidelines (Barnett, Sugden, Kirby, & Hill, 2013). Since DCD is a heterogeneous condition (Visser, 2003), domain-specific diagnosis of DCD may be considered when motor difficulties are only evident in one specific area (Blank et al., 2012). In fact, impairments may affect fine motor coordination, gross motor coordination or both and can be expressed in slower, less accurate, and more variable performance (Zwicker, Missiuna, Harris, & Boyd, 2012) in manual dexterity, locomotion, agility, and/or balance tasks (Polatajko & Cantin, 2005; Sugden, Kirby, & Dunford, 2008; Wilson, 2005).

Criterion B is focussed on the impact of motor difficulties on activities of everyday life. Children with DCD may struggle when using objects such as toothbrush, cutlery, scissors, rulers, when taking part in motor activities (e.g., climbing, running, throwing and kicking a ball, etc.) or when learning new motor tasks such as riding a bicycle. Therefore, when at home they may experience difficulties with self-care, such as washing, toileting, eating and dressing (doing up buttons, tying shoelaces, putting clothes on the right way around). In a school environment, they often demonstrate problems with handwriting (poor speed and legibility), copying off the board and drawing, and find it difficult to engage in physical education and school sports (Polatajko & Cantin, 2005; Summers, Larkin, & Dewey, 2008). In order to identify such difficulties, parents and teachers complete questionnaires, such as the MABC Checklist (2nd ed.; MABC-2; Henderson et al., 2007) and the Developmental Coordination Disorder Questionnaire (DCD-Q; Wilson, Kaplan, Crawford, Campbell, & Dewey, 2000).

A detailed history needs to be collected in order to assess Criterion C. Parental and teacher reports should be considered to assess the onset of symptoms, which emerge early in development, although children do not tend to grow out of their motor difficulties (Cousins & Smyth, 2003). An adult with DCD may choose to avoid specific tasks involving motor coordination, yet most activities that are carried out during adult daily life are mediated by movement (e.g., carrying out household chores, cooking and learning how to drive). Since DCD is a lifelong condition, the persistence of motor impairments symptoms continues to affect everyday life in adulthood (Kirby, Sugden, Beveridge, & Edwards, 2008; Tal-Saban, Zarka, Grotto, Ornoy, & Parush, 2012). Finally, a clinical examination is recommended in order to verify that medical or neurological problems cannot explain motor difficulties (Criterion D).

DCD is a condition that affects about 5% of the population (APA, 2013) although prevalence estimates vary between studies depending on the cut-offs used to identify the disorder. In the UK, in a population of children aged 7 to 8 years (N = 6990) who underwent a procedure of diagnosis of DCD, 1.8% of children met criteria for severe DCD and, using broader cut-offs, a further 3.1% were considered as having probable DCD (Lingam, Hunt, Golding, Jongmans, & Emond, 2009). DCD tends to be diagnosed twice as frequently in boys as girls (Kadesjo & Gillberg, 1999).

1.2.3. Aetiological research in DCD

Research that has focused on understanding the aetiological mechanisms of DCD encompasses neurological impairment, information processing, neurocognitive and ecological accounts. These are reviewed in turn below.

1.2.3.1. Neurological impairment

The hypothesis that neurological abnormalities may be the underlying cause of the motor and associated deficits in DCD led Kaplan and colleagues to develop a theory of atypical brain development (Kaplan et al., 1998). In this explanation of DCD, problems with general cortical maturation would lead to dysfunction across modalities and would explain the substantial overlap between neurodevelopmental disorders. However, this hypothesis does not account for the specific patterns of symptoms observed in DCD and its exact neurobiological causes, and the theory fails to contribute to directing research and intervention (Wilson et al., 2013).

1.2.3.2. Information processing

A significant amount of research has focused on the information processing account, which is based on the assumption that some disrupted mechanisms in perceptual and motor control underlie DCD. For example, evidence has linked the disorder to poor visuospatial processing (Crawford & Dewey, 2008; Tsai, Wilson, & Wu, 2008; Van Waelvelde, De Weerdt, De Cock, & Smits-Engelsman, 2004), kinaesthetic perception (Coleman, Piek, & Livesey, 2001; Smyth & Mason, 1997), and cross-modal perception (Mon-Williams, Wann, & Pascal, 1999; Schoemaker et al., 2001; Sigmundsson, Ingvaldsen, & Whiting, 1997).

Although this account provides a framework for investigating the disorder, it originates from the idea that action is the result of stages of processing that sequentially take place between stimulus and response: perception, registration and manipulation of sensory information, response selection and programming, and effector (Sage, 1984). As discussed in the first section of this chapter, evidence suggests parallel and interactive processes direct motor and cognitive behaviour within a continuum of cycles between perception and action rather than a hierarchy of separate control mechanisms.

1.2.3.3. Neurocognitive accounts

Cognitive neuroscience is an integrative approach of brain function and behaviour, which investigates the multiple interacting neural networks that support action and cognition (Wilson et al., 2017). Neural structures are inferred through a range of methodologies including neuroimaging (e.g. fMRI) and neurophysiological techniques (e.g. EEG) coupled with neuropsychological measures and experimental investigation of motor control and cognitive behaviour. The leading hypotheses that have emerged from this research on the nature of DCD include the internal modelling deficit, timing and rhythmic coordination problems, and reduced executive control or executive function (Wilson et al., 2013).

The internal modelling deficit hypothesis suggests a disruption in the internal representation of intended movement in DCD. The premise of this hypothesis is that accurate motor control depends on predictive models of motor commands, which generate forward estimates of body positioning in the environment (Shadmehr, Smith,

& Krakauer, 2010). Anticipated movements are compared, through sensory feedback, to the actual body state and online corrections are performed in real time to account for discrepancies between expectations and action (Wolpert, Diedrichsen, & Flanagan, 2011). Evidence for a deficit in generating internal models of action are drawn from paradigms assessing motor imagery, which refers to the process of internal simulation of motor action that involve the same neural processes activated during the actual movement (Jeannerod, 2001) and that were found specifically impaired in children with DCD (Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Williams, Omizzolo, Galea, & Vance, 2013). Further evidence of impaired predictive control in DCD includes poor visual smooth-pursuit tracking, such as difficulties in synchronising eye movement to a target moving along a predictable path (Langaas, Mon-Williams, Wann, Pascal, & Thompson, 1998). When performing visually-guided pointing tasks, requiring a participant to move hands between targets of various sizes, children with DCD demonstrated similar speed-accuracy trade offs (increasing duration of the movement when the target size was reduced) as typically developing children when executing real movements, but not when movements were imagined (Maruff, Wilson, Trebilcock, & Currie, 1999; Williams, Thomas, Maruff, & Wilson, 2008; Wilson, Maruff, Ives, & Currie, 2001). The discrepancies between real and imagined performance suggests a disruption of the ability to predict motor behaviour under different task constraints. The deficit demonstrated by individuals with DCD in motor imagery tasks resembles those of patients with lesions in the posterior parietal cortex (Sirigu et al., 2004). However, this internal modelling account has limited evidence from studies using brain imaging techniques.

Alternatively, the hypothesis that a deficit in the timing of motor responses underlies poor motor performance is supported by evidence of reduced rhythmic coordination under different task constraints. Children with DCD demonstrate more variability of rhythmic coordination patterns (e.g., finger tapping, clap while jumping) when movements are performed under perturbations or when they are required to be synchronised to auditory stimuli (de Castro Ferracioli, Hiraga, & Pellegrini, 2014; Roche, Wilms-Floet, Clark, & Whitall, 2011; Whitall et al., 2008). Motor timing impairments have been linked to some disruption at the level of the cerebellum and its interconnections with the sensory and motor cortices, and there is some evidence of hypoactivation of the parietocerebellar and frontocerebellar networks in DCD while performing a repetitive tracing task (Zwicker, Missiuna, Harris, & Boyd, 2011). However, further research is needed to identify specific corticocerebellar mechanisms that are thought to underlie rhythmic coordination and timing (Wilson et al., 2013).

Finally, executive dysfunction has been highlighted in DCD and investigated as one of the aetiological accounts of DCD. Since this is the focus of this thesis, the next section of this chapter is dedicated to the discussion of the different dimensions of executive function and related investigations conducted in DCD.

1.3. Executive Function

1.3.1. Definition

Executive function (EF) is an umbrella term referring to a collection of high-order cognitive processes that underlie purposeful, goal-directed behaviour (Anderson, 2002; Lezak, 1993), and that regulate, monitor and control thought and action (Espy, 2004; Friedman et al., 2006; Miller & Cohen, 2001). EF encompasses a cluster of cognitive abilities that allows us to engage successfully with formulating plans, manipulating and switching between relevant information, ignoring unhelpful stimuli, and generating alternatives (Stuss, 1992). EF is used for demanding tasks that involve concentration and effort (Diamond, 2013), and for unfamiliar and novel situations requiring new solutions, rather than for well-known, automatised or routine tasks (Shallice, 1990).

Most researchers in this area agree that EF can be subdivided into several sub-skills (Miyake et al., 2000). Definitions of the commonly identified sub-skills are considered below, alongside examples of assessments used in the literature to measure EF subcomponents. Following this, the EF framework and its implications are discussed in light of recent research in the field.

1.3.1.1. Working memory

Working memory refers to the ability to retain and manipulate information for a short period of time in order to direct ongoing or later performance (Alloway, Gathercole, & Pickering, 2006) and to concurrently store and process information (Pennington & Ozonoff, 1996). It can also be referred to as *updating* as it entails replacing old or no longer relevant information with new important information (Friedman et al., 2008). In order to distinguish it from a broader concept of working memory (Baddeley, 2003b), it is referred to, throughout the experimental studies of thesis, as *executive-loaded working memory* (ELWM; Henry, 2012). It represents a process of active manipulation rather than passive storage of data, and involves working with information that is held in mind and is no longer perceptually present (Smith & Jonides, 1999). ELWM is a crucial skill that enables holding and manipulating information in order to solve problems, finding relationship between previous knowledge and new ideas. Examples of tasks measuring ELWM include the 'listening span task' (Leather & Henry, 1994; Siegel & Ryan, 1989). Participants listen to a list of sentences and are asked to decide whether each sentence is true or false. Afterwards, they need to recall the last word of each sentence in order. Other tasks include backward recall of stimuli, such as the ‘backwards digit span’ or ‘backwards colour recall’, where participants need to recall lists of numbers of increasing length, or the colour of series of shapes, in reverse order.

1.3.1.2. Cognitive flexibility

Cognitive Flexibility is the ability to switch flexibly back and forth between tasks or mental sets (Friedman et al., 2008; Miyake et al., 2000). The terms *mental flexibility*, *shifting, set-shifting and switching* are all used to describe this EF skill, which allows changing of strategy and adaptation of behaviour to task demands in a quick and flexible manner (Davidson et al., 2006). It is a crucial skill to switch focus of attention and change perspective, to adjust to changed demands or priorities, to think of alternatives and take advantage of unexpected events or to switch interchangeably between two tasks. One task often used to derive a measure of perseveration is the Wisconsin Card Sorting Task (WCST; Kongs, Thompson, Iverson, & Heaton, 2000). This task requires participants to sort cards based on colour, form and number to one of four key cards. Participants are not told how to categorise the cards, but receive immediate feedback on whether they have sorted the cards correctly. During the task the sorting rule changes without warning (e.g., from colour to form) and participants have to infer the correct sorting strategy based on feedback, shift mental set and start sorting cards following the new rule. The flexible implementation of new strategies to adapt to the changing rules is measured.

1.3.1.3. Inhibition

Inhibition is often conceptualised broadly and may refer to slightly different abilities, as separable inhibition-related processed can be identified (Friedman & Miyake, 2004;

Harnishfeger, 1995; Nigg, 2000). The term *interference control* (also called inhibitory control of attention, or attentional inhibition, or resistance to distractor interference) refers to the ability to suppress irrelevant stimuli that are competing or interfering with the desired response (Nigg, 2000) and is a process that happens at the level of perception (Diamond, 2013). In the classic Stroop task (Stroop, 1935) participants are required to name the ink colour of a colour word, suppressing any conflicting information provided by the automatic reading of the word. *Response inhibition* (also called prepotent response inhibition or behavioural inhibition) is the ability to intentionally suppress dominant, automatic, prepotent responses to successfully complete a task. Two different categories of tasks are used to measure response inhibition. The go/no-go tasks (Cragg & Nation, 2008), and stop-signal tasks (Verbruggen & Logan, 2008) require the participant to press a button when a stimulus appears and to stop the response when a different stimulus appears or when a stop-signal sign is given (usually a auditory signal). These are tasks that require withholding a prepotent response and giving no response at all, and are therefore considered delay tasks (Carlson & Moses, 2001). A different category of tasks measuring response inhibition includes the Luria hand game, where a participant needs to make a fist when shown a finger and vice versa (Luria, 1966), or the Conflicting Motor Response task (Shue & Douglas, 1992) where the child is asked to first copy two different gestures and next is asked to show the other gesture instead of the one presented by the examiner. These are considered conflict tasks, as they require giving an alternative response that conflicts with the natural prepotent response (Carlson & Moses, 2001). A further measure of conflict response inhibition is the Simon task (Simon, 1969) in which two stimuli are presented, one at a time, and a different response is required for each stimulus (press on the right/left for stimulus A/B). The stimuli may be presented on either the congruent or incongruent side to the required response, meaning that during incongruent trials participants must inhibit the natural response to press the button that corresponds with the spatial location of the stimulus.

1.3.1.4. Planning

Planning or problem-solving is the ability to find solutions to guide a response towards a specific result. Efficiency, organisation and strategy are used to plan in advance the sequence of actions required to achieve a goal (Anderson, 2002). Planning is rather complex to assess and some have described it as a ‘higher level’ EF skill, arguing that it reflects the use of several other core EF abilities such as inhibition, switching and working memory (Miyake et al., 2000). A very common task used to measure planning abilities is the tower test (e.g. Tower of London, Tower of Hanoi). Participants are required to use the minimum number of moves to rearrange coloured balls (or discs of different sizes) from an initial starting position on three pegs to a final goal arrangement. However, this task has numerous flaws for testing children including their tendency to move two balls at a time, or to misunderstand questions.

1.3.1.5. Fluency

Fluency defines the ability to generate responses within specific classes of information or around a particular theme. Fluency reflects the flexibility of search processes in long-term memory and the ability to use efficient strategies to access relevant information (Henry, 2012). It is also referred to as *generativity*. Fluency is measured with tests such as the verbal fluency test, which requires the participant to produce as many words as possible starting with a particular letter or as many members of a specific semantic category (e.g. animals).

Therefore, a disruption in EF would be expressed in everyday situations as ineffective planning of tasks, poor organisation of activities, time management problems, difficulties remembering key information whilst carrying out tasks, perseveration and inability to correct errors after feedback, poor self-control and impulsivity, erratic or careless responses, inability to master new tasks and inhibit habits, rigid and inflexible thought processes, difficulties in generating and implementing new strategies.

1.3.2. The unity and diversity of EF

Research investigating whether the aspects of EF discussed above are a set of separable components or a unitary construct is not always consistent. Miyake and colleagues (2000) suggested a conceptual framework that integrates the two perspectives. They identified three core components of EF that are clearly distinguishable but moderately correlated, namely updating, shifting and inhibition. There is substantial evidence supporting this framework of separable and fractionated EFs, but yet related to each other (Anderson, 2002; Garon, Bryson, & Smith, 2008).

There is also research suggesting that this model of dissociable yet interrelated EFs may be suitable for investigating EFs in children. A study conducted by Lehto and colleagues (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003), using confirmatory factor analysis, tested Miyake's three factor model, and this was argued to be the best fit for performance on EF of 8-13 year-old children. Some studies have partially replicated these results by finding evidence for clearly distinguishable constructs of working memory and switching, but not for inhibition (Huizinga, Dolan, & van der Molen, 2006; Van der Sluis, de Jong, & van der Leij, 2007) or conversely, for inhibition and working memory, but not for switching (St Clair-Thompson & Gathercole, 2006).

Contrasting results may be related to the differences in the type of tasks employed and in the age range of samples. In fact, there is some research suggesting that the degree of interrelation and dissociation of EF may change developmentally. For example, EFs may be indistinguishable from each other until 9 years of age (Hughes, Ensor, Wilson, & Graham, 2010; Willoughby, Blair, Wirth, & Greenberg, 2012), or separable yet related by 10 years of age (Duan, Wei, Wang, & Shi, 2010; Wu et al., 2011). This age-dependent trend of EFs' interrelations was also observed in a longitudinal study assessing 135 children at two time points. Brydges and colleagues (Brydges, Fox, Reid, & Anderson, 2014) found evidence for a unitary model at Time 1 when children were 8 years old, but could distinguish between a working memory factor and an inhibition/shifting factor at follow up when children were about 10 years old. Additional evidence for the dissociation of EF constructs is provided by studies looking at the development of EF.

1.3.3. Development of EF

The neural substrates normally responsible for EF control are largely connected to the frontal lobe, which is one of the latest brain areas to reach maturity, as it continues to develop throughout childhood into early adulthood (Hudspeth & Pribram, 1990; Shimamura, 2000; Thatcher, 1991). A protracted development of EF skills is therefore to be expected and clearly observable at a behavioural level, as EF performance does not reach its peak until early adulthood (Friedman et al., 2015; Luciana, Conklin, Hooper, & Yarger, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004). However, evidence suggests that this progression is separable for different EF constructs (Anderson, 2002). Welsh and colleagues (Welsh, Pennington, & Groisser, 1991) compared the performance of 3-12 year-old children (10 participants in each age group) to that of a group of adults, showing how different executive competencies develop at different times. For inhibition and switching, measured by a Matching Familiar Figures task – where subjects are instructed to select among six alternatives the one that exactly matched the standard picture – and a Wisconsin Card Sorting Test respectively, adult levels of maturity were reached by 10 years of age. However, verbal fluency efficiency and complex planning (Tower of Hanoi) continued to develop after the age of 12. Similar results were obtained in a study conducted by Levin and colleagues (Levin et al., 1991) who compared groups of 7-8 year-old and 9-12 year-old children with a group of 13-15 year-old adolescents (total sample of *N*=52 children). Verbal and design fluency, as well as complex planning (Tower of London) and memory strategies were found to be significantly more efficient in adolescents than both groups of younger children, who did not differ. As mentioned above, there may be task related factors which led to this result. Performance on the Wisconsin Card Sorting Test and on a Go-No Go task improved significantly across the two younger groups and was mastered by the age of 12.

A much larger sample of 400 children between 3 and 12 years of age, with 38-41 participants per year group, was assessed on the NEPSY (Korkman, Kirk, & Kemp, 1998) by Klenberg and colleagues (Klenberg, Korkman, & Lahti-Nuuttila, 2001). In this study, performance on inhibition tasks levelled off at 7 years of age, followed by performance on the Tower subtest at age 8, and finally performance on both verbal and design fluency, which continued to develop across age groups up to the 12 year-old children. Another large study (*N*=284) of individuals over a wider age range between 7 and 21 years of age, studied by Huizinga and colleagues (2006), showed that visuospatial and verbal working memory did not fully develop until the age of 12 years; set-shifting continued to develop until 15 years of age; and inhibition followed different patterns depending on the type of task, with earlier maturity for a flanker task and a Stop-signal task and prolonged development for a Stroop task. It may be, therefore, that different aspects of inhibition mature at different ages (Nigg, 2000). In fact, Letho et al. found little evidence in a group of 8-13 year old children for improvement in inhibition as measured by a Matching Familiar Figures task, although working memory (visuo-spatial CANTAB task) and switching (trail making task) developed significantly.

1.3.4. EF and motor coordination

Literature exploring executive functioning in DCD as well as studies investigating the relationships between motor skills and EF have both focused on the three core EF components described earlier. However, rarely has EF performance been compared across verbal and nonverbal domains. Tasks measuring EF often assess the nonverbal domain only and include the manipulation of visuospatial information (Wilson et al., 2013). Besides poor motor skills, children with DCD may have visuospatial processing difficulties (Wilson & McKenzie, 1998) and therefore it is essential to measure EF using tasks with no motor/visuospatial demands. Tasks assessing the verbal domain involve the processing of language-related information. If children with DCD have difficulties in this modality, it might suggest that they have generalised deficits in EF. The assessment of EF across domains is therefore one of the key methodological features of the current thesis.

This section outlines research into EF subcomponents in children with poor motor skills. Throughout this section the phrase ‘children with DCD’ is used for studies that have included participants with a pre-existing clinical diagnosis of DCD. The phrase ‘children with motor difficulties (MD)’ is used for studies in which children were identified through different types of screening as experiencing some level of motor difficulty (although authors in the original studies used a range of different terminologies such as ‘at risk of DCD’ or ‘motor-impaired’). Finally, the phrases children with ‘poor motor skills’, or ‘motor coordination impairments’, or ‘motor deficits’ are all used interchangeably to refer generally to children both with and without a clinical diagnosis of DCD.

1.3.4.1. Working memory

There is some evidence suggesting a deficit in working memory in children with poor motor skills. Alloway (2007) assessed the short-term and working memory skills of a group of 5-11 year-old children with DCD ($N = 55$) using both verbal and visuospatial tasks from a standardised battery developed by the authors. Since there was no control group, performance was compared to standardised scores. Almost half the sample achieved a standard score more than one standard deviation below the mean in the verbal working memory tasks, and more than half of the sample performed at this level in the visuospatial working memory tasks. Performance on visuospatial tasks was worse than on verbal tasks when measuring short-term memory, but not when assessing working memory, where performance was equally poor across domains relative to standardised scores. These results suggested a domain general deficit on working memory across the verbal and nonverbal domains.

Alloway has expanded these original findings in other studies (Alloway, 2007; Alloway & Archibald, 2008), which reported that 6-11 year old children with DCD performed more poorly than expected for their age on standardised tasks of both working memory and short-term memory across verbal and visuospatial domains. When comparing children with DCD to typically developing children, significant difficulties were identified, both for visuospatial and verbal tasks in both memory constructs (Alloway, 2011).

Other studies have suggested a link between motor deficits and working memory difficulties, but have not tested verbal and visuospatial working memory as separate domains. In a study conducted by Michel and colleagues (Michel, Roethlisberger, Neuenschwander, & Roebers, 2011) performance in a Backwards Colour Recall task was not different between two groups of 5 to 7 year-old children with and without MD ($N = 94$), identified through a manual dexterity test. However, manual dexterity correlated with performance in this working memory task in the MD group only ($N = 47$). In contrast, Piek et al. (2004) found no relationship between motor performance and number of correct responses in a working memory task when comparing 28 children with MD and 76 typically developing children between 6 and 12 years of age. Results were replicated in a later study with a group of 18 children diagnosed with DCD, who performed as accurately as a control group (Piek, Dyck, Francis, & Conwell, 2007).

These partially contrasting results may be due to substantial differences in the way participants were selected across studies, as well as the type of tasks employed as measures of working memory. For example, Piek et al. (2004; 2007) used a Trail Making/Memory Updating task which is designed to assess both working memory and inhibition, whereas Michel et al. (2011) used 'pure' measures of working memory including both verbal and visuospatial demands, and Alloway (2007) further differentiated tasks into measuring verbal and visuospatial working memory. Furthermore, different methods have been used for recruitment of participants and inclusion/exclusion criteria in each group. Some research groups used clinical DCD diagnoses, but these diagnoses may have been provided by occupational therapists (e.g., Alloway, 2007; Alloway & Archibald, 2008) or by special education teachers (e.g., Piek et al., 2007). This is problematic as criteria for diagnosing DCD may be assessed differently by clinicians and educators. Even within those studies that included participants with already existing diagnoses of DCD, some administered a standardised assessment of motor skills to corroborate the diagnosis using a cut-off point at the 5th percentile (Piek et al., 2007), whereas others confirmed poor motor skills through parental or teacher questionnaires (Alloway, 2007; Alloway & Archibald, 2008). These are two different methods of corroborating the DCD diagnosis that may not be equally reliable. Other studies instead of using clinical diagnoses have screened a population on standardised measures of motor skills and have afterwards identified children with MD using different cut-off points or different assessment tools. For instance, Michel et al. (2011) administered the manual dexterity subtest of the MABC-2, setting a cut-off point at the 10th percentile, whereas Piek et al. (2004) used the McCarron Assessment of Neuromuscular Development (MAND; (McCarron, 1997) and identified children with MD if they had a standard score of 80 or below (with a mean of 100 and standard deviation of 15). These important issues were addressed in this thesis. Specifically, both children with DCD and MD were included, but the groups were investigated separately, and the recruitment and selection was very carefully managed and documented (see General Methodology Chapter 2 for further details).

1.3.4.2. Cognitive flexibility and planning

Inconsistencies between studies have also been evident when investigating other domains of EF. In one of the studies referred to earlier, Michel and colleagues (2011) administered a cognitive flexibility task, finding no differences in the accuracy of performance between children with and without MD, as measured by the MABC-2 manual dexterity subtest. Other studies measuring switching abilities have administered tasks that required some degree of concurrent planning. Piek et al. (2004) identified no significant relationship between motor ability and a goal neglect task (Duncan, Emslie, Williams, Johnson, & Freer, 1996) measuring the ability to formulate and react to goal-directed plans. However, in a later study using the same measure, a group of children with DCD produced significantly fewer correct trials than a control group (Piek et al., 2007).

Wuang and colleagues (Wuang, Su, & Su, 2011) administered a short form of the Wisconsin Card Sorting Test (Kongs et al., 2000) to a group of 140, 8-9 year-old children with and without MD, with a cut-off point set below the 5th percentile on the MABC-2 total score. The group with MD showed a significant deficit in switching abilities, with higher numbers of perseverative responses and perseverative errors than typical children. Furthermore, in this study, children with MD demonstrated poorer sorting skills, since the total number of correct responses and the number of categories completed were both significantly lower than controls. These difficulties suggest poor problem-solving ability in general in children with poor motor skills.

In another study, planning was measured by a subtest of the Cognitive Assessment System (Naglieri & Das, 1997), and was found to be poorer in a group of 5 year-old children with MD compared to a typical group of the same age (Asonitou, Koutsouki, Kourtessis, & Charitou, 2012). Performance on the planning task significantly discriminated between children with and without MD with a 90.5% accuracy on the original group of 42 participants. Children were classified as having MD if their score on the MABC-2 was below the 15th percentile.

Once again, results across studies are difficult to compare given the differences in the sampling procedures (children with MD or DCD, cut-off points at the 5th or 15th percentile). Whilst some of these measures tap into more than one EF domain at a time, making it difficult to differentiate between specific EF deficits, it may be that the subcomponents of planning and shifting are not entirely separable. The issue of 'task impurity' in EF measures will be addressed in the current thesis in the methodological procedures section.

1.3.4.3. Inhibition

Inhibition has also been investigated in children with DCD or MD. For example, Mandich and colleagues (Mandich, Buckolz, & Polatajko, 2002) assessed 20 children with DCD and 20 typical controls aged 7-12 years on a Simon task. The number of errors for the compatible trials was similar between groups, however during incompatible trials children with DCD demonstrated a significant difficulty: as many as 80% of the children with DCD failed to inhibit incorrect responses, with a frequency that exceeded the 90th percentile error rate value produced by typical children.

Piek et al. (2004) used a Go/No-Go task and found no evidence for a response inhibition deficit in children with MD. Querne and colleagues (2008) also administered a Go/No-Go task and reported that scores for 'correct inhibitions' were similar between children with DCD and control children. Moreover, Michel et al. (2011) reported that analyses of percentage of errors in both the congruent and incongruent conditions revealed no effect of group on a Stroop task (Fruit Stroop), hence children with MD responded as accurately as control children. It is important to note that these studies may be measuring different aspects of inhibition, as some have used Go/No-Go tasks, designed to measure the ability to inhibit an on-going response

(Piek et al., 2004; Querne et al., 2008), or to inhibit an incorrect response (Mandich et al., 2002), while some others assessed interference control (Michel et al., 2011). The current thesis will be specific in the aspect of inhibition it investigates.

1.3.4.4. Studies in typical populations

Only two studies have examined the relationship between motor coordination and executive functioning in typically developing children and adolescents. Rigoli and colleagues (Rigoli, Piek, Kane, & Oosterlaan, 2012) tested a normative sample of 12-16 year-old adolescents ($N = 93$) on measures of movement and executive functioning, controlling for IQ and for ADHD symptomatology. Results suggested that motor coordination was significantly related to visuospatial working memory and not verbal working memory, although the MABC-2 score for the aiming and catching subtest accounted for a significant amount of the variance of both visuospatial and verbal working memory. Non-significant relationships between motor coordination and the switching task were identified. However, there was a significant association between the performance on the balance tasks of the MABC-2 and a composite EF score including inhibition and switching errors. As the inhibition task administered in the study was based on the Stroop paradigm, measuring interference control, authors explained this finding by suggesting that balance may be importantly influenced by interference control abilities. This interpretation is supported by previous research revealing that performance on complex postural tasks was influenced by concurrent cognitive interference tasks, thus providing evidence for a considerable attentional demand on the control of posture that may be involved in balance tasks (Olivier, Cuisinier, Vaugoyeau, Nougier, & Assaiante, 2007; Woollacott & Shumway-Cook, 2002). Although the study by Rigoli et al. (2012) suggests a link between EF and motor coordination, there is no indication of the direction of the relationship.

A further study by Livesey, Keen, Rouse, and White (2006) tested a sample of 36 children between 5 and 6 years old on a Stop-Signal task (Logan & Cowan, 1984) and on the Day/Night Stroop, in which a picture of the sun is presented with the instruction to say ‘night’, or vice versa to say ‘day’ when presented a picture of the moon (Gerstadt, Hong, & Diamond, 1994). Results suggested some degree of relationship between motor skills and interference control, since the MABC-2 score for Manual Dexterity significantly predicted performance on the Day/Night Stroop. However, no significant correlation was found with the Stop-Signal task, suggesting that inhibition of an ongoing response is not affected by motor skills.

The relationship between EF and motor coordination discussed above in typical and atypical populations does not develop in isolation, and has an effect on a number of activities of daily living and on other developmental outcomes. In the next sections the evidence of the impact of this relationship on academic achievement and language is explored.

1.3.5. EF and motor coordination: impact on academic achievement

In this section studies investigating the relationship between academic achievement and EF are discussed separately from studies on the relationship between academic achievement and motor coordination. Next, the few studies that integrated all three domains are reviewed.

1.3.5.1. Executive function and academic achievement

Academic achievement is as crucial aspect of children’s life and well-being. It is plausible to expect that children’s EF will impact on learning processes and engagement in academic tasks. For example, the ability to pay attention to the teacher’s instructions in a noisy classroom, to resist the temptation to give up an effortful task, to learn a new strategy and suppress automatised old strategies, is going to largely rely on the child's inhibition skills. Equally, working memory and cognitive flexibility will contribute to the ability of the child to hold instructions in mind, to manipulate information creatively, find connections between ideas, to generate new solutions and adjust to changes in the demands of tasks. Therefore, learning to read, developing written work, solving mathematical problems, understanding cause and effect in science and other academic skills will be heavily dependent on executive function. Indeed, the evidence of such a relationship is extensive and an overview of this literature is now provided.

In a large representative sample (*N* = 1395) of 5-17 year-old children, Best and colleagues found that performance on EF tasks was related to both reading and mathematical ability. The strength of the correlations varied at different ages, but the developmental pattern of these correlations was remarkably similar for both mathematics and reading, with moderate associations across childhood and adolescence, and spikes at 6 and 8-9 years of age (Best, Miller, & Naglieri, 2011).

Better EFs in the domain of inhibition, working memory, planning and shifting in the preschool years have also been found to significantly predict academic outcomes in reading and mathematics in the first year of school, and this advantage seems to be maintained throughout the first three years of formal schooling (Bull, Espy, & Wiebe, 2008). Therefore, better EFs in preschool provided an advantage to children for their ability to access learning in mathematics and reading. When a large group of teachers (*N* = 3,595) was asked to judge the biggest areas of risk for academic failure at school entry, they placed great emphasis on behaviors that are underpinned by EFs, such as following directions, and working independently and as part of a group (Rimm-

Kaufman, Pianta, & Cox, 2000). The inhibitory control dimension of EF and self-regulation in preschool children appears to be a stronger predictor than intellectual ability of early mathematical and reading abilities (Blair & Razza, 2007), while Monette and colleagues found that working memory contributed uniquely to achievement after pre-academic abilities, affective and family variables were controlled for in the analyses (Monette, Bigras, & Guay, 2011).

EFs continue to predict achievement later in childhood, although some of these relationships seem to be domain-specific (Bull & Scerif, 2001). For example, in a sample of 11 year-old children verbal working memory was related to English, while inhibition and visuospatial working memory were related to English, mathematics and science results on UK national tests of attainment (St Clair-Thompson & Gathercole, 2006). Measures of impulsiveness, self-control and inhibition accounted for more variance than IQ in school attainment in adolescents (Duckworth & Seligman, 2005). Furthermore, lower EFs are consistently found in children with poor academic skills (Brosnan et al., 2002; Sikora, Haley, Edwards, & Butler, 2002).

EFs seem to play a compensatory role in the presence of risk factors for lower achievement. For example, in a large sample of children ($N = 1005$) from low-income families, EFs as early as 48 months moderated the effect of preschool mathematical ability (5 year-old children) on mathematical ability at the end of kindergarten (6 year-old children), so that higher EFs were associated with higher than expected progress on mathematical learning (Blair, McKinnon, & Investigators, 2016). Even when the risk factor is represented by low mathematical skills prior to school entry, EFs significantly moderated the relationship with both mathematics and reading achievement five years later, so that children with high levels of early EFs compensate and catch up with children with higher early mathematical ability (Ribner, Willoughby, Blair, & Investigators, 2017).

These studies indicate that EF is one of the foundations needed for learning to occur (Blair & Diamond, 2008), and this is also reported in children with developmental disorders such as autism (Pellicano et al., 2017) and ADHD (Biederman et al., 2004). Therefore, some of the EF difficulties identified in children with DCD and MD are likely to have an impact on their academic success, beside the negative effect related to their motor coordination impairments. Both of these effects will be discussed in the section below.

1.3.5.2. Academic achievement and motor coordination

There is convincing evidence of the impact of motor coordination on academic outcomes. In a very large sample of more than 12,000 children, motor skills in kindergarten significantly predicted reading and mathematics at the end of the first year of school after controlling for demographic variables and initial academic ability (Son & Meisels, 2006). In this study using growth analysis, the authors concluded that fine motor and eye coordination measures could reliably identify children at risk for academic underachievement. Children with poor gross motor coordination were also found to be at risk of poor attainment (Lopes, Santos, Pereira, & Lopes, 2013). However, fine motor skills seem to be particularly predictive of later achievement (Carlson, Rowe, & Curby, 2013; Dinehart & Manfra, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010). This is not surprising considering that half of the time spent in school is dedicated to activities that require fine motor coordination (Marr, Cermak, Cohn, & Henderson, 2003) and that fine motor skills are involved in recognising and reproducing visual representation of concepts, such as drawing letters, counting the number of objects while manipulating them, or sorting items into groups (Cameron, Cottone, Murrah, & Grissmer, 2016).

Research exploring academic profiles in children with DCD is surprisingly limited considering that a diagnosis of DCD is linked to poorer than expected achievement and the overall risk for school failure (Dewey et al., 2002). The difficulties with motor coordination in DCD are often reflected in poor handwriting, which was reported to be less legible and slower not only in English (Prunty, Barnett, Wilmut, & Plumb, 2013) and French (Jolly & Gentaz, 2013), but also in languages with different writing systems such as Hebrew (Rosenblum & Livneh-Zirinski, 2008) and Chinese (Chang & Yu, 2010; Cheng, Chen, Tsai, Shen, & Cherng, 2011). Poorer handwriting performance has an important effect on the overall quality of written composition, which was found to be significantly poorer than peers and mostly explained by the lower number of words produced per minute and by the higher number of misspelled words (Prunty, Barnett, Wilmut, & Plumb, 2016).

The research into other academic domains has not always been consistent. Although DCD has been associated with poorer reading and spelling (Dewey et al., 2002; Kadesjo & Gillberg, 1999), other studies have found appropriate skills in both these domains (Cheng et al., 2011; Prunty et al., 2016). Problems with mathematical skills seem to be found more consistently in DCD compared to typically developing children (Gomez et al., 2015; Gomez, Piazza, Jobert, Dehaene-Lambertz, & Huron, 2016), although one study suggested these may be delayed rather than deficient (Pieters, Desoete, Van Waelvelde, Vanderswalmen, & Roeyers, 2012). These studies, however, investigated mathematical skills in isolation from other aspects of school achievement. Alloway and colleagues (Alloway, 2007; Alloway & Archibald, 2008;

Alloway & Temple, 2007) did administer a comprehensive standardised assessment of achievement in children with DCD and found low average numeracy and literacy ability (with means for standard scores ranging from 80 to 90, where the population mean is 100 and standard deviation is 15). However, these studies did not compare children to a typically developing group and did not take into account intellectual ability, which was also within the low average range of 80-90 standard scores. Therefore, current understanding of the nature of academic difficulties in children with DCD is poor. No study to date has investigated educational attainment in children with MD, who despite not having a diagnosis may still experience academic difficulties as a result of their poor motor skills.

1.3.5.3. Relationships between motor coordination, executive function, and academic achievement

Although both fine motor ability and EFs were found to correlate to early academic performance (Cameron et al., 2012), there has been very little attempt to address the reciprocal interactions between EF, motor skills and academic outcomes. Nevertheless, a recent study in a typical population of children between 10 and 12 years of age ($N = 236$) found that motor coordination skills had an indirect effect on mathematics, reading and spelling performance via EF abilities in inhibition, working memory and cognitive flexibility (Schmidt et al., 2017). The study indicates that EF might be a mediator of the relationship described above between motor coordination and attainment.

Working memory was found to correlate with academic performance in children with DCD (Alloway & Archibald, 2008b). Moreover, when children with DCD were divided into two groups based on their visuospatial working memory, those with poorer visuospatial working memory performed significantly worse on achievement measures of numeracy and literacy than the high visuospatial working memory group (Alloway, 2011). However, no other study has attempted to clarify *how* poor EFs in DCD (e.g., Wilson et al., 2013) contribute to the academic underachievement in this group. Hence, there is a poor understanding of the reciprocal relationships between EF, motor skills and academic achievement.

In this thesis, a comprehensive approach to the assessment of academic achievement is adopted, in which multiple domains of attainment are investigated in relation to typical and atypical motor development, taking into account the contribution of intellectual ability and investigating the relationship of EF with these factors.

1.3.6. EF and motor coordination: impact on language

1.3.6.1. Executive function and language

The development of language comprehension, the acquisition of vocabulary and expressive language skills require the ability to pay attention, listen and manipulate verbal information, hold information in mind, and find connections and switch between spoken words and the environment. Unsurprisingly, therefore, there is now a substantial body of evidence showing that language and EF skills are related in typical development (Carlson, Davis, & Leach, 2005; Kuhn, Willoughby, Wilbourn, Vernon-Feagans, & Blair, 2014).

This relationship is also evident in children with developmental language disorders and other atypical language pathways, who demonstrate significant EF difficulties, even when completing nonverbal tasks that place no demand on language ability (Botting et al., 2017; Gooch, Hulme, Nash, & Snowling, 2014; Henry, Messer, & Nash, 2012; Im-Bolter, Johnson, & Pascual-Leone, 2006).

However, when investigating links between EF and language, results across studies are inconclusive both in terms of the *direction* and the *nature* of this relationship. Some authors argue the development of EF is facilitated by the acquisition and use of language rules at various levels of complexity (Zelazo, Müller, Frye, & Marcovitch, 2003), that language serves self-regulatory and inhibition abilities (Petersen, Bates, & Staples, 2015), and that correlations between the two domains are seen because the use of language (e.g., inner speech) assists performance in EF tasks (Brace, Morton, & Munakata, 2006). A very recent study exploring this in deaf and hearing children found that language mediated nonverbal EF performance in both groups, but not vice versa (Botting et al., 2017) suggesting again that language skills drive EF performance.

Conversely, studies have shown that working memory may be a precursor for language development (Baddeley, 2003a); inhibition has been argued to be crucial for the ability to select between relevant lexical representations (Mirman & Britt, 2014); and EF may facilitate performance on tasks measuring language (Protopapas, 2014; Ramus & Szenkovits, 2008).

As reflected in these studies, Bishop and colleagues (Bishop, Nation, & Patterson, 2014) identified three possible accounts for the relationship between language and EF: EF affects language; language affects EF; a third factor affects both EF and language. A recent longitudinal study attempted to assess the plausibility of these different models by measuring EF and language skills at three time points (between 4-6 years of age) in typically developing children and in children at risk of language difficulties (Gooch, Thompson, Nash, Snowling, & Hulme, 2016). The study reported weak and non-significant longitudinal effects of early EF on later language skills and vice versa, finding no evidence of causal relationship between the two domains in any direction. However, a strong concurrent association was found at each time point and authors suggested this may be explained by a third factor not measured in the study. Motor coordination may be this third factor, considering its relationship to both EF, discussed in previous sections, and language, discussed below.

1.3.6.2. Motor coordination and language

In the first two years of life both motor skills and communication skills are characterised by great variability, both within a child and between children (Darrah, Hodge, Magill-Evans, & Kembhavi, 2003). However, some relationship between the development of these domains, can be observed despite this variability. A very large population-based sample of mothers (more than 60,000) completed questionnaires on their child's motor and communication skills at one and a half and three years of age (Wang, Lekhal, Aarø, & Schjølberg, 2014). The study revealed a high concurrent correlation between motor and communication skills at one year and a half (.72), which was reduced at three years (.29). Early motor skills positively predicted later communication skills (.38) but not vice versa (-.14). These findings indicate that early motor skills play an important role in the development of communication.

This is not surprising considering that in the first two years of life, the acquisition of increasingly complex motor skills creates opportunities for the child to interact with objects and people in novel ways that facilitate emerging language skills. For example, the onset of independent sitting was found to be a significant predictor of receptive vocabulary at 14 months (Libertus & Violi, 2016). Learning to sit without support frees the hands for both communicative gestures, which in turn open the way to language development (Iverson & Goldin-Meadow, 2005), and for the manipulation and exploration of objects. The development of specific object manipulations in spontaneous play was found to be related to different stages in language development: objects were separated and taken apart during the pre-speech phase; children started to put things together and related objects in novel ways when the first words emerged; constructions started to be more frequent and children used the same objects for different purposes during the vocabulary spurt (Lifter & Bloom, 1989). This parallelism between the development of sophisticated manipulations of objects and language skills was evident in all children, despite great individual differences in rate of language acquisition. The study suggested that specific ways of manipulating objects were a prerequisite and facilitated the emergence of language, by allowing the child to notice and make inferences about the characteristics and different uses of the objects, thus associating a meaning to objects, which in turn is crucial for word learning (Iverson, 2010).

Achieving motor milestones such as crawling and walking also exposes the child to a range of opportunities to relate to people and the environment in a novel way. For example, when children become able to walk away from the mother, they start to communicate with her from a distance, and are therefore facilitated in their responsiveness to referential gestures and social referencing (Campos et al., 2000). Indeed, early gesture has been reported a number of times as being key to later language development (e.g., Iverson & Goldin-Meadow, 2005; Rowe & Goldin-Meadow, 2009) and also relies on adequate motor coordination skills (Iverson & Braddock, 2011).

Despite the research linking motor skill and communication in infancy, evidence in typical development of the relationship between motor skills and language in *later* childhood is scarce. However, some work has explored the use of gesture in communication tasks in school age children (e.g., McNeil, Alibali, & Evans, 2000), and neurophysiological links between language and motor functions were found in adults (see Willems & Hagoort, 2007 for a review).

Research into children with atypical development of language found that parent-reported motor skills in the first year of life were a precursor of problems with language acquisition at 6 years of age (Viholainen et al., 2006). It is unclear whether the concurrent relationship becomes weaker with time, although children with language impairments often experience significant motor difficulties regardless of age (Cheng, Chen, Tsai, Chen, & Cherng, 2009; Hill, 2001; Iverson & Braddock, 2011; Vukovic, Vukovic, & Stojanovik, 2010; Webster, Majnemer, Platt, & Shevell, 2005).

1.3.6.3. Relationships between motor coordination, executive function and language

No study to date has concurrently explored the mutual interactions between EF, language and motor coordination, although as reviewed above children with language disorders have demonstrated difficulties in both motor skills (Hill, 2001) and executive function (Henry et al., 2012).

One study exploring EF and language in a large epidemiological sample of young children did include measures of early communicative gestures, but these were only assessed in terms of their communicative aspects despite having an important motor component (Kuhn et al., 2014). Nevertheless, the study revealed that individual differences in communicative gestures at 15 months predicted language at 2 and 3 years, which in turn predicted EF at 4 years of age.

Therefore, models that explicitly test the moderation or mediation effect of EF and/or motor coordination on language and vice versa, are needed in order to contribute to the understanding of existing results as well elucidating some of the unresolved issues of the nature and direction of these relationships. Such a model was included in the current research, which is outlined in detail in the next section.

1.4. The Current Study

The ability to effectively control behaviour through flexible thinking, working memory, inhibition of unhelpful responses or self-regulation, planning and problem-solving, is a fundamental skill in human behaviour.

The crucial role of EF in all aspects of life is well documented in the literature. EF has been reported to be a stronger predictor for school readiness than IQ (Blair & Razza, 2007) and continues to predict academic achievement later throughout childhood (Gathercole, Pickering, Knight, & Stegmann, 2004). In adulthood, EF predicts general success in life including career (Prince et al., 2007), relationships (Eakin et al., 2004), and mental and physical health (Dunn, 2010; Kusche, Cook, & Greenberg, 1993). A general construct of self-control, which is directly related to inhibition (Eslinger, Flaherty-Craig, & Benton, 2004), has been shown in a cohort of 1000 children, to predict a range of adult outcomes 30 years later. These included physical health, substance dependence, personal finances, and criminal offending, even when intelligence and social class were taken into account, and when comparing sibling-pairs, which shared the same family background (Moffitt et al., 2011).

The development of EF is intertwined with the development of intellectual abilities (Friedman et al., 2006), socio-emotional control (Tottenham, Hare, & Casey, 2011), language (Gooch et al., 2016) and motor function (Diamond, 2000; Paz, Wise,

& Vaadia, 2004; Rosenbaum, Carlson, & Gilmore, 2001). However, the nature of these interrelations is poorly understood and far more progress needs to be made (Diamond, 2007).

This thesis is focused on the relationship between executive and motor function and aims to contribute to the understanding of this complex dynamic, including its wider impact on academic achievement and language. This will be achieved by including cross-sectional and longitudinal data on typical and atypical motor development, and by exploring different aspects of EF, academic and language abilities.

Specifically, investigating EF abilities in children with DCD may shed light on the mechanisms that determine this interaction. Although the research discussed above revealed an association between motor and EF skills and identified EF deficits in children with motor impairments (Wilson et al., 2013; Wilson et al., 2017) results are not always consistent, as studies have often investigated isolated EF constructs.

Findings are difficult to compare across studies partly because of substantial disparities in methodologies, with some studies including participants with clinical diagnosis of DCD and other investigating children at risk of DCD or experiencing motor difficulties (MD). It is unclear to date what is the overlap of EF profiles between these two groups of children (i.e., children identified through clinical diagnosis or screening for poor motor skills). Therefore, this study includes children with motor impairments both with a diagnosis of DCD and those with MD but without a formal diagnosis.

Furthermore, although changes in EF with age can be identified during the school years (Best et al., 2011; Romine & Reynolds, 2005) it is unclear how EF difficulties evolve in children with DCD, as no study to date has investigated this topic longitudinally. *Study 1* aims to provide a longitudinal analysis of the EF profiles of children with motor coordination impairments, through the assessment of a comprehensive range of EF domains in children with DCD and in children identified as having MD but without a diagnosis.

Since children with DCD are at risk of educational underachievement, and given the significant contribution of EF to school success, it is also important to explore the influence that specific EF abilities have on academic achievement in children with poor motor skills. Although in typical development EF seems to mediate the relationship between motor coordination and academic outcomes (Schmidt et al., 2017), research addressing how the interaction between motor deficits and EF affects educational success is very limited and has focused on working memory only (Alloway, 2007). *Study 2* of this thesis therefore aims to understand academic achievement in children with poor motor skills, with and without a diagnosis of DCD, and to explore how EF abilities contribute to academic success.

Finally, although language outcomes have been related to both EF (Bishop et al., 2014) and motor skills (Iverson, 2010), no study to date has investigated the reciprocal interactions of these domains. Specifically, studies exploring the relationship between EF and language have suggested a third factor may be involved (Gooch et al., 2016) but no attempt has been made to test the hypothesis motor coordination may be contributing to this relationship. Thus, *Study 3* aims to explore the role of motor skills and motor coordination impairments in determining the relationship between EF and language in both directions (i.e., when EF is the predictor of language outcomes, and when language is the predictor of EF outcomes), with a focus on examining the effect of the interaction between EF and motor coordination on language.

Specific research questions and hypotheses are reported in the relevant chapter for each study. Before describing these three studies in detail (Chapter 3-5), the general methodology adopted in this thesis will be reported in the next chapter.

CHAPTER 2

2. General Methodology

This chapter illustrates the design of the research project as a whole, including recruitment of participants, the inclusion and exclusion criteria, and all standardised and experimental measures employed throughout the project. The chapter also describes the rationale motivating the choices of materials and procedures. Each of the three studies included in the research project was conducted on subgroups of the overall sample. Therefore, further details of specific methods, including participants' background characteristics, are outlined in the method section of each study. Ethical approval for this current project was obtained from the Language and Communication Science Proportionate Review Board at City, University of London (Appendix A).

2.1. Design

The current project is a follow-up and extension of a previous study (Bernardi, Leonard, Hill, & Henry, 2016; Leonard, Bernardi, Hill, & Henry, 2015), which investigated executive function (EF) in children with a diagnosis of Developmental Coordination Disorder (DCD), in children with Motor Difficulties (MD), and in typically developing (TD) children ($N = 91$). In order to be included in the sample and assigned to one of these three groups, participants completed a range of screening tasks, including one motor screening test and multiple cognitive screening tests such as intellectual ability, language, and reading tests (see Materials, section 2.3, for more details). Children with MD demonstrated an impairment of motor skills in the motor screening test, although they did not have a formal diagnosis of DCD. Next, included children completed an experimental battery of EF tasks. In this previous study, the author of the present thesis acted as the research assistant, thus collecting all data for both the original study and the PhD project.

Three studies were conducted for the current thesis, which will be outlined briefly in this section in order to clarify the overall design of the project. Study 1 (Chapter 3) investigated EF in children with DCD and MD longitudinally. In Study 1, a subsample of children who participated in the original project (Time 1) was re-recruited and followed up two years later (Time 2), and was administered identical screening and experimental measures (final sample Study 1: *N* = 51). Study 2 (Chapter 4) assessed academic achievement in children with DCD and MD and examined the contribution of EF to academic outcomes. The sample for Study 2 comprised two subsamples: the same children tested in Study 1, along with newly recruited participants. For the subsample from Study 1, Study 2 analysed their EF at Time 1 (collected as part of the original project) and their academic achievement at Time 2 (collected as part of the PhD project). The new participants were administered the motor and cognitive screening measures, and those who met inclusion criteria (*n* = 60) completed the EF battery of tasks used in the original project. This became Time 1 for the newly-recruited subsample. Two years later, those children who were available to continue their participation were followed-up. Those who, after repeating the motor and cognitive screening tests, satisfied inclusion criteria (*n* = 39) then completed the academic achievement measures. This became Time 2 for the newly-recruited subsample. The final sample for Study 2 comprised data from all children who provided academic achievement measures at Time 2, (*n*=51 from Study 1, *n*=39 from new recruits; Total Sample *N*=90). In order to investigate the relationships between motor, language and EF skills, Study 3 (Chapter 5) analysed the data from Time 1 of all children included in both the original project and the PhD project (*N* = 151).

Table 2.1. Summary details of the final numbers of participants and assessments administered at both time points in each study.

	Original Project[*]	**PhD Project**		
		1st wave of data collection	*2nd wave of data collection*	**Total number of participants**
Time 1	*n* = 91 - Screening measures - EF battery	*n* = 60 - Screening measures - EF battery	n.a.	*n* =151 [Study 3]
Time 2		*n* = 51 [Study 1] - Screening measures - EF battery - Academic assessment	*n* = 39 - Screening measures - Academic assessment	*n* = 90 [Study 2]

Note. Study 1 title: A two-year follow-up study of executive functions in children with developmental coordination disorder and motor difficulties; Study 2 Title: Academic achievement in children with developmental coordination disorder and motor difficulties: the role of executive functions; Study 3 Title: An exploratory analysis of the role of motor coordination in the relationship between executive function and language abilities. Screening measures included both cognitive and motor tasks at both time points. EF = Executive Function. [*](Leonard et al., 2015).

The structure of the PhD project is summarised in Table 2.1. At Time 1, all children completed motor and cognitive screening measures and the EF battery of tasks. At Time 2, all children were re-assessed on the motor and cognitive screening measures. From the original study sample of 91 children, 56 were available for the follow-up and 51 were included after re-screening; at Time 2 these children re-completed the EF battery and the academic achievement tasks. Similarly, from the newly-recruited PhD sample of 60 children, 48 were available for the follow-up and 39 were included after re-screening. At Time 2 these children completed the academic achievement tasks. Specific reasons why participants were excluded or not available for follow-up are reported in the relevant section of each study, alongside the exact number of participants per group. Further details concerning participant characteristics and recruitment are provided below in Section 2.2.

2.2. Participants and Procedures

2.2.1. Recruitment

Participants in the study were recruited in the research project using two main recruitment pathways.

The majority of participants were recruited through two collaborating primary schools in South-East London. After liaising with headteachers, teachers and teaching assistants, the researcher visited each class in Year 3 to Year 6 (21 different classes in total, five or six per year group). The researcher briefly presented the study to the children before distributing to each of them the information sheet and consent form (Appendix B). This procedure ensured that children had a basic understanding of the project prior to requesting permission form their parents to participate. Children whose parents returned a signed consent form, subsequently received parental questionnaires (see Materials, section 2.3) to complete and return to teachers or the school office in a sealed envelope. Only children who returned all questionnaires took part in the screening phase of the project.

Each child was taken out of their classroom individually, at a time that had been previously agreed with the class teacher. Before any assessment took place, participants were introduced carefully to the study, it was explained to them what a research project is, the topic that was being investigated and its rationale, what their contribution would entail and any questions were answered at this point. It was made very clear to children that their participation was voluntary and that they could withdraw from the study at any time without giving explanations. Assent needed to be obtained before testing could begin (Appendix C). All assessments took place in a quiet room in one-to-one sessions that lasted between 45 minutes and one hour each. The number of sessions conducted in school per each child at each time point (Time 1 and Time 2) varied between one to six, depending on whether children were included after initial screening or not (see inclusion criteria, Section 2.2.2, below).

Some of the children recruited in the current study had already taken part in the original study (Leonard et al., 2015), of which this PhD project is a follow-up and extension. The children who were followed up from the original study completed all assessments that formed their Time 2 data set, and were not tested again two years later. At the same time, newly recruited children, who did not take part in the original study, completed their Time 1 testing (identical to the original study). These newly recruited children were followed-up two years later when their Time 2 data set was collected.

Many of the children who participated in the original study had left their primary school when recruitment for the current PhD project took place. Therefore, both schools agreed to contact parents of children who left on behalf of the research team and sent the information sheet by post. Parents who contacted us and agreed to take part in the follow-up were invited to arrange a visit at the university or at their home. For the newly recruited children, those who were in Year 5 and 6 were asked to return a form with their contact details (Appendix D), so that their parents could be contacted after children left primary school. Two years later these parents were approached by phone, email or post and invited to participate in the follow-up phase of the study arranging a visit at their home or at the university.

The second method of recruitment aimed at recruiting children with a diagnosis of Developmental Coordination Disorder (DCD). All of these children had already participated in the original study, and their parents were contacted by phone or email and invited to take part in this follow-up project. Originally, these children were recruited through the Dyspraxia Foundation by placing an advert on their website and Facebook page inviting parents of children aged 7-11 years with a diagnosis of DCD/Dyspraxia to contact the research team for more information. Suitable candidates (see Section 2.2.2, for inclusion and exclusion criteria) were seen at the university or at their house. These children were recruited in areas around London and Leeds.

Children in any group who were seen at the research lab completed the assessment on the same day over one session of about 6 hours, including lunch and regular breaks. Home visits had a similar structure but were sometimes carried out over two to three sessions of 1.5 – 2 hours.

Task order was varied between children depending on their individual needs (i.e., any fatigue, loss of attention, motivation etc.). This also ensured results in the study were not affected systematically by order effects. All tasks were presented as games, rather than tests, to increase engagement and make the sessions enjoyable and rewarding for the children. Children were encouraged and praised throughout the assessments, were offered to choose stickers after each session and received a certificate at the end of their involvement in the study. Testing sessions were thus child-led and took as much time as the child required to complete the tasks to the best of his/her abilities.

2.2.2. Inclusion and exclusion criteria

Children with a diagnosis of Developmental Coordination Disorder (DCD) were originally recruited through the Dyspraxia Foundation as illustrated above. Parents who contacted the research team to volunteer for the study were emailed the information sheet, any queries were answered at this point and the inclusion and exclusion criteria were explained to them. Specifically, children had to be at least 7 years old and could not be older than 11 years and 11 months. Furthermore, children with any medical condition such as joint hypermobility syndrome, or with a diagnosis of any other neurodevelopmental disorder, such as Attention Deficit/Hyperactivity Disorder (ADHD) or Autism Spectrum Disorder (ASD), were not invited to take part. When parents of included children were approached for the follow-up phase at Time 2, any child who in the meantime received any diagnosis other than DCD was excluded from the sample.

The DCD diagnosis had been received prior to recruitment from clinical professionals (such as paediatricians, psychiatrists or educational psychologists) and was corroborated at both time points by the research team following the DSM-5 (APA, 2013) criteria (see Chapter 1, Section 1.1.2). Specifically, children had to demonstrate significant motor difficulties (Criterion A) by performing at or below the 16th percentile on a standardised test of motor skills (Movement Assessment Battery for Children, 2nd Edition; MABC-2 (Henderson, Sugden, & Barnett, 2007); see Materials, section 2.3, for details). This cut-off was chosen following the latest consensus statement on DCD, which suggested the 15th percentile should be used for identifying DCD (Blank et al., 2012). The MABC-2 allows for children to be assigned a percentile score of 9 or 16, but not 15, thus the closest percentile score of 16 was used. The impact of poor motor skills on activities of daily living (Criterion B) was assessed through the

MABC-2 checklist, given the evidence of its reliable use for this purpose (Shoemaker et al. 2012). All children in the DCD group had to score below the 5th percentile on this checklist in order to demonstrate poor performance on a range of activities of daily living. Parents had to confirm that the onset of symptoms was early in development (Criterion C). Furthermore, the cognitive screening phase included an assessment of verbal and nonverbal IQ to ensure that all children scoring below the cut-off for intellectual disability could be excluded from the sample (Criterion D). Finally, as mentioned above, any medical conditions resulted in the child being excluded from the sample (Criterion D). One child recruited through collaborating schools in the original study sample had a diagnosis of Dyspraxia and was included in the DCD group only after the diagnosis was corroborated.

Children recruited through schools for the TD and MD groups were also excluded if parents reported any diagnosis of any neurodevelopmental disorders or medical condition. All of these children completed the motor screening phase using the MABC-2 Test and Checklist. Participants were allocated to the typically-developing (TD) group if they performed at or above the 25th percentile on the MABC-2 test and did not demonstrate any significant impact of poor motor skills on daily activities (MABC-2 checklist above the 15th percentile). Children who performed at or below the 16th percentile on the MABC-2 were assigned to the motor difficulties (MD) group regardless of their score on the MABC-2 checklist. These identical motor screening criteria were applied to the subgroups of children who took part in the follow-up phase of the project, as screening was repeated. Any child who at Time 1 belonged to the TD group and at Time 2 performed at or below the 16th percentile on the MABC-2, thus demonstrating some degree of motor difficulty, was excluded from the follow-up phase. Similarly, participants who at Time 1 were allocated to the MD group and at Time 2 performed at or above the 25th percentile, were excluded from the follow-up phase of the study as evidence for their motor difficulties could no longer be identified. Further details of the specific numbers of children in each group who were excluded at Time 1 and at Time 2 are reported in the method section of each study.

Table 2.2. Summary of the inclusion and exclusion criteria for each group at each time point.

Inclusion Measure	**TD group**	**MD group**	**DCD group**
Movement Assessment Battery for Children (MABC-2) and Checklist	MABC-2 Total score ≥ 25th %, Checklist >15th %	MABC-2 Total score ≤ 16th %	MABC-2 Total score ≤ 16th %, Checklist < 5th %
British Abilities Scales (BAS3)	Standard score ≥ 70	Standard score ≥ 70	Standard score ≥ 70
Clinical Evaluation of Language Fundamental (CELF-4-UK)	Scaled score ≥ 4 on either Formulated Sentences or Word Classes-Receptive subtests	Scaled score ≥ 4 on either Formulated Sentences or Word Classes-Receptive subtests	Scaled score ≥ 4 on either Formulated Sentences or Word Classes-Receptive subtests
Test of Word Reading Efficiency (TOWRE)	Standard score ≥ 70	Standard score ≥ 70	Standard score ≥ 70
Parent reports of clinical diagnosis	No clinical diagnosis	No clinical diagnosis	Diagnosis of DCD only

Cognitive screening measures were also administered to all children at both time points (excluding reading at Time 2). Regardless of the group they belonged to, participants were excluded from the study if at any time point they performed more than two standard deviations below the mean on the overall score on measures of intellectual ability (British Abilities Scales 3rd Edition; BAS3; Elliot & Smith, 2011; $M = 100$, $SD = 15$), on *both* subtests of the language assessment (Clinical Evaluation of Language Fundamentals 4th Edition; CELF-4-UK; Semel, Wiig, & Secord, 2006; M

= 10, *SD* = 3), or at Time 1 on the total standard score of the reading assessment (Test of Word Reading Efficiency; TOWRE; Torgensen, Wagner, & Rashotte, 1999; *M* = 100, *SD* = 15). Inclusion and exclusion criteria for each group at each time point are summarised in Table 2.2.

2.3. Materials

2.3.1. Parental questionnaires

Parents of participating children were asked to complete two questionnaires collecting background information regarding their children and families. Parents completed the questionnaires independently and returned them directly to the researcher or to their child's school. These questionnaires are detailed in turn below.

2.3.1.1. Motor skills

The Movement Assessment Battery for Children Checklist, 2nd Edition (Henderson, Sugden, & Barnett, 2007) was used to assess performance on a range of motor behaviours that can be observed in everyday activities. The checklist includes 30 statements requiring parents to judge their child's level of motor competence in tasks involving movement in a static and/or predictable environment such as the classroom (e.g., "Uses scissors to cut paper"), and in a dynamic and/or unpredictable environment such as the playground (e.g., "Catches a ball using a two-handed catch). Parents respond to the statements deciding how their child deals with the tasks on a scale from "Very well" to "Not close" (scoring 0–3 points). These rating are summed to calculate a total score, which is mapped on three percentile bands, with scores below the 15th percentile representing a risk of motor difficulties and scores below the 5th percentile being indicative of motor difficulties affecting daily living.

The checklist is an appropriate measure for assessing Criterion B of the DCD diagnosis (Schoemaker, Niemeijer, Flapper, & Smits-Engelsman, 2012). Therefore, as illustrated in the Participants section, children in the TD group scored above the 15th percentile in this checklist, while children in the DCD group scored below the 5th percentile. For the MD group the checklist did not function as a tool for inclusion or exclusion from the sample, because this group was not intended to meet criteria for a diagnosis of DCD but to represent children who demonstrate some level of motor difficulties. The MABC-2 test was therefore considered sufficient in order to assess motor difficulties and include children in the MD group. The MABC-2 checklist meets general standards for validity and reliability (Schoemaker et al., 2012), although test-retest reliability has only been tested in the previous edition of the M-ABC checklist (r = .089; Henderson & Sugden, 1992), the content of which is highly overlapping with the more recent version.

2.3.1.2. Behaviour

The Strengths and Difficulties Questionnaire (Goodman, 1997) was used as a behavioural screening questionnaire assessing five dimensions, namely conduct problems, emotional symptoms, hyperactivity, peer relationships, and pro-social behaviour. The SDQ measures 25 psychological attributes, some of which can be thought of as strengths (e.g., “Think things out before acting”), and others can be thought of as difficulties (e.g., “Easily distracted, concentration wonders”). Parents rated each item as ‘Not True’, ‘Somewhat True” or “Certainly True”, which were converted to scores of 0 to 2 for negative items, and 2 to 0 for positive aspects.

The raw score for the five items assessing hyperactivity, inattention and impulsivity were summed and used in the analyses of the original project (Leonard et al., 2015) in order to control for subclinical symptoms of inattention/hyperactivity that could affect EF performance. Scores on the SDQ were not used in any of the main analyses for the three studies in the current project, although an exploratory analysis that included the SDQ hyperactivity and inattention scores was conducted for Study 1 (see Chapter 3, Results section). Validity and reliability are satisfactory, with reliability coefficients ranging between .57 and .72 depending on the scale considered, and a reliability of .72 for the Hyperactivity-Inattention scale (Goodman, 2001).

2.3.2. Screening tasks

2.3.2.1. Motor skills

The Movement Assessment Battery for Children (MABC-2; Henderson et al., 2007) is a test of motor performance composed of eight subtests, which are grouped into three domains: three Manual Dexterity tasks, two Aiming & Catching tasks, and three Balance tasks (one task for static balance and two tasks for dynamic balance). The tasks vary for the three different age bands: Age Band 1 (3-6 years); Age Band 2 (7-10 years); Age Band 3 (11-16 years). The tasks for relevant age bands are described in turn below.

For 7-10 year-old children, the Manual Dexterity tasks consist in picking up pegs from a box and inserting them into a board, threading a lace through the holes of a board, and drawing a trail through a maze of two thin lines; 11-16 year-old children have to turn pegs upside-down and re-insert them in the board, construct a triangle using nuts and bolts, and draw a trail through a more complicated maze. The Aiming & Catching tasks require children to: throw a ball at the wall and catch it with two hands (Age Band 2) or one hand (Age Band 3); aim at a target on the floor with a bean bag (Age Band 2) or aim at a target on the wall with a ball (Age Band 3). For the

Balance tasks children are required to: balance on a board with one leg (Age Band 2) or with two legs one in front of the other (Age Band 3); walk hill-to-toe forward (Age Band 2) or backwards (Age Band 3) along a straight line; stand on one leg and hop forward on five mats positioned on the floor in a straight line (Age Band 2) or in a zig-zag row (Age Band 3).

All tasks need to be performed in a strictly specified way. For example, children are asked not to rest materials on their body while completing the manual dexterity tasks. Before each task a demonstration is given by the examiner and children have some practice attempts. Most tasks allow for multiple attempts and best performed trials are used for final scores. This ensures that participants' real motor skills are captured and that any difficulty understanding or remembering instructions does not interfere with final performance. For children who took part in the follow-up phase of the project, the MABC-2 was administered at both time points in order to assess whether typical or atypical motor skills were stable across the two time points. Children who did not demonstrate stability across time were excluded from the relevant studies (see Method section of each study chapter).

Each of the eight subtest raw scores is transformed into a standard score (M = 10, SD = 3). The eight-item standard scores are summed to form a Total Test Score (range 8-152), which in turn can be transformed into a standard score (M = 10, SD = 3) and a percentile score. There is good evidence of the validity and reliability of the MABC-2 test, with test-retest reliability reported as .080 for the Total Test Score (Henderson et al., 2007).

2.3.2.2. *Intellectual abilities*

The British Abilities Scales 3rd Edition (BAS3; Elliot & Smith, 2011) was used to calculate IQ scores. Verbal reasoning was measured through the Word Definition subtest, which involved explaining the meaning of individual words (e.g., “doubt”), whereas the Verbal Similarities subtest required the child to explain how three things were similar (e.g., “fur, scales, feathers”). The Matrices subtest was used to assess nonverbal reasoning and required children to choose one diagram amongst six options in order to correctly complete a matrix. For each subscale, raw scores were converted to a standard (*T*) score and were prorated to obtain a General Conceptual Ability Score (GCA; *M*=100, *SD*=15), as indicated in the BAS-3 manual. Before converting *T*-scores into the GCA score, the Matrices *T*-score was doubled to ensure that the weight of verbal abilities in the final GCA score was equal to that of nonverbal abilities.

Participants with a GCA score below 70 were excluded from the sample, as IQ scores of more than two standard deviations below the mean are in the intellectual disability range (APA, 2013). The BAS3 was administered at both time points for children who were followed up in the project, hence ensuring children maintained adequate intellectual ability at Time 2. The BAS3 is a valid and reliable test overall, and test-retest reliability is reported as .73 for the Matrices subtest, as .86 for the Word Definition subtest and .79 for the Verbal Similarities subtest (Elliot & Smith, 2011).

2.3.2.3. *Language*

The Clinical Evaluation of Language Fundamentals 4th Edition (CELF-4-UK; Semel et al., 2006) is a widely used assessment of language abilities. Expressive language was measured with the Formulated Sentences subtest, requiring the child to formulate semantically and grammatically correct sentences about visual stimuli using given words (and some given phrases for 8 year-olds or older children) of increasing complexity (e.g., “although”, “as soon as”). In the Word Classes-Receptive subtest the child had to identify functional or conceptual relationship between words by selecting two out of four images (7 year-olds) or four orally presented words (8 year-olds or older children; e.g., “noon, sunset, dusk, yesterday”). Standard scores (*M* =10; *SD* = 3) on each subscale were used as measures of expressive and receptive language respectively.

Children who scored more than two standard deviations below the mean on *both* subtests were excluded from the sample. Participants in the follow-up phase had to continue meeting these criteria in order to be included in the study. The CELF-4-UK Examiner’s Manual presents extensive evidence of validity, and reliability for relevant ages ranged from .74 to .79 for the Formulated Sentences subtest, and from .83 to .91 for the Word Classes- Receptive subtest (Semel, Wiig, & Secord, 2006).

2.3.2.4. Reading

The Test of Word Reading Efficiency (TOWRE; Torgensen et al., 1999) included a Sight Word Efficiency subtest and a Phonemic Decoding Efficiency subtest. The child is given 45 seconds to read as many items as possible in a list of 104 words and 63 non-words respectively. The total number of words and non-words read correctly within the the time limit was calculated and converted into a standard score. The final total standard score (*M* = 100; *SD* = 15) was used as a measure of reading ability.

Participants with scores more than two standard deviations from the mean (i.e., total standard score below 70) were excluded from the sample. This measure was only administered at Time 1, because at Time 2 word and pseudo-word reading was part of the academic achievement assessment (see section 2.3.4). There is satisfactory evidence for the validity and reliability of the TOWRE, and test-retest reliability ranged from .82 to .97 for children 6 to 9 years old (Torgensen et al., 1999).

2.3.3. Executive Functioning Tasks

The following EF domains were measured: executive-loaded working memory; fluency; response inhibition; planning; and cognitive flexibility. For each of these five domains a verbal and a nonverbal task were administered. The two tasks in each domain were parallel and analogous where possible, with the verbal tasks requiring the manipulation of verbal information and nonverbal tasks involving visuo-spatial or motor demands. Each EF task is described below.

2.3.3.1. Executive-loaded working memory (ELWM)

The Listening Recall task from the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001) was used to assess the ability to concurrently process and store verbal information. Participants heard a list of sentences, had to decide whether sentences were true or false, and later recall the last word of each sentence in the correct order. The task was presented to participants in blocks of six trials. Initially, each trial included one sentence only, and the number of sentences per trial increased in each subsequent block. Participants who successfully completed four out of six trials were administered the next highest block. Participants had to hold in memory the last word of each sentence (storing) while judging whether the sentence was true (processing), and at the end of the trial, children were asked to recall the last words of each sentence in order. Administration was stopped when three out of six trials in a block were incorrect. The total number of correct trials was used as a measure of *verbal ELWM*, which is a more reliable measure than span (Ferguson, Bowey, & Tilley, 2002). Test–retest reliability varied between .38 and .83 depending on age ranges (Pickering & Gathercole, 2001).

The Odd-One-Out test (Henry, 2001) was used to assess the ability to manipulate and concurrently store visuospatial information. The experimenter presented a card (20 x 5cm) with three similar nonsense visual items and participants were asked to point to the 'odd-one-out' (processing). Children had to store the spatial location of the odd-one-out (left, middle or right) and later recall and point to that location on an empty grid of identical dimensions as the card. Blocks of three trials were administered and participants progressed to the next block when a minimum of two out of three trials were completed correctly. The initial block included only one card before recalling the spatial location, with an increasing number of cards per trials in each subsequent block. Total number of correct trials was used as a measure of *nonverbal ELWM*. Reliability of .80 is reported for the span version of the Odd-One-Out test (Henry, 2001).

2.3.3.2. Fluency

The Verbal Fluency subtest of the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001) was used to measure the ability of the child to generate verbal responses. Letter Fluency (Condition 1) consisted of producing as many words as possible starting with the letters 'F', 'A' and 'S'. Category Fluency (Condition 2) required participants to generate words that belonged to the categories of 'animals' and 'boys' names'. Category Switching (Condition 3) involved switching between names of 'fruit' and names of 'furniture'. The child was given one minute per each letter and per each category to produce as many words as possible. The sum of correct answers without repetitions in the two categories (Condition 2) was used as a measure of *verbal fluency* in the study. This raw score was preferred to the total score including all conditions, because Category Fluency was considered to be the simplest task out of the three conditions. In fact, the Letter Fluency task (Condition 1) requires some level of phonological ability and may recruit different brain regions than category fluency (Schwartz, Baldo, Graves, & Brugger, 2003), while switching between categories (Condition 3) explicitly overlaps with the domain of cognitive flexibility. Category Fluency has a test–retest reliability of .70 (Delis et al., 2001).

The Design Fluency test (D-KEFS) was administered to assess the ability to generate fluent nonverbal responses. Participants were presented with sets of identically placed dots and had to connect the dots using four straight lines, none of which could be drawn in isolation from the other lines (i.e., each line had to be connected to at least one other line at a dot). The child was given one minute to draw as many different designs as possible. In Condition 1 children had to generate designs in boxes containing arrays of filled dots only. In Condition 2, each box contained sets of both filled and empty dots, and participants had to connect empty dots only. In Condition 3, children had to switch between empty dots and filled dots when drawing each design. The sum of correct designs generated for Condition 1 (filled dots) and Condition 2 (only empty dots), was used as a measure of *nonverbal fluency*. Condition 3 raw scores were not included because this task requires switching ability that could potentially confound the measurement of fluency. Reliability was reported as .66 for filled dots and .43 for empty dots (Delis et al., 2001).

2.3.3.3. Inhibition

The ‘Verbal Inhibition, Motor Inhibition’ test (Henry et al., 2012) was used to assess the ability of inhibiting verbal and motor responses. The test requires participants to learn a copy response in an initial set of trials, and then inhibit that response to produce an alternative one.

In the verbal inhibition test the child initially copied the experimenter who alternated in a pseudo-random order between the words ‘car’ and ‘doll’ for a set of 20 trials (Copy 1 task). In the next set of 20 trials the child had to inhibit the copying response by responding with the opposite word (Inhibit 1 task; i.e., the correct response for ‘car’ was ‘doll’ and vice versa). The next two sets of 20 trials were administered using an identical format and the same words (Copy 2 task and Inhibit 2 task), hence Part A of the verbal task was formed of four sets of 20 trials. In Part B, an identical sequence of four sets of 20 trials was repeated using two new stimulus words (‘drum’ and ‘bus’).

The nonverbal inhibition test had the same structure as the verbal task but used hand gestures instead of words as stimuli, which consisted in either a pointed finger or a fist for Part A of the motor task, and either a flat horizontal hand or a flat vertical hand for Part B of the motor task. Children had to copy the hand action randomly produced by the experimenter during Copy tasks. During Inhibit tasks, the examiner presented one of the two gestures but the child had to respond with the other gesture instead (e.g., a pointed finger was the correct response when the hand gesture was a fist and vice versa).

For both the verbal and motor task, two practice trials were administered before Copy 1 task and Inhibit 1 task, to ensure that children fully understood instructions. Performance was timed in each set of Copy/Inhibit trials, and children were instructed to respond quickly but to prioritise accuracy over speed.

The total number of errors overall in the verbal test was used as a measure of *verbal inhibition*, while total number of errors overall in the motor test was used to measure *nonverbal inhibition*. The number of errors included any type of incorrect response given during both the Copy or the Inhibit tasks. This is due to the fact that during the Copy tasks the experimenter alternates randomly between two words or two gestures, thus the child is required to inhibit the alternative response. Using total error scores as the final measure of response inhibition is consistent with the original study from which this test is adopted, reporting Cronbach's alpha of .727 for the total error scores from parts A and B in the verbal task and .915 for total error scores from parts A and B in the motor task (Henry et al., 2012).

2.3.3.4. Planning

The Sorting Test (D-KEFS) was used to measure organisational and problem-solving abilities. The child is asked to sort six cards that resemble puzzle pieces into two groups, three cards in each group, in as many different ways as possible. Cards can be grouped into two categories based on verbal-semantic information from the words written on the cards (verbal sorts; e.g., animals vs. transports; things that fly vs. things that move on the ground), or based on visuo-spatial features of the cards (perceptual sorts; e.g., blue cards vs. yellow cards; straight edges vs. curved edges). The total number of correct verbal sorts was used as the measure for *verbal planning*, and there were three possible verbal sorting categories per card set (i.e., maximum score of six). The total number of correct perceptual sorts represented the measure for *nonverbal planning*, with five possible perceptual sorts per card set (i.e., maximum score of ten). Test–retest reliability is reported as .49 (Delis et al., 2001).

2.3.3.5. Cognitive Flexibility/Switching

The Trail-Making test (D-KEFS) was used to assess the ability to switch between verbal stimuli (letters and numbers). The test includes one visual cancellation task and four connecting circles tasks all presented on an A3 piece of paper. The primary EF task, the Number-Letter Switching task (Condition 4), required the child to connect letters and numbers in an alternating sequence, switching between the two (A to 1; 1 to B; B to 2; 2 to C etc.; the last connection was 16 to P). The child was encouraged to complete the task as quickly as possible, although there was no time limit. Key component processes necessary to perform this switching task were also measured in order to assess whether EF performance was affected by difficulties with underlying component skills. In the Visual Scanning task (Condition 1) children were presented with a visual array of 54 numbers between 1 and 9 and were required to find and mark all the number 3s as quickly as possible. In the Motor Speed task (Condition 2) children had to draw a trail over a dotted line, which symmetrically followed the same maze as the Number-Letter Switching task, connecting empty dots, thus removing any verbal processing from the task. The Visual Scanning task and the Motor Speed task ensured that cognitive flexibility could be measured without confounds of visual search and motor speed. This was particularly important in the current study considering that children with motor impairments were participating. Two further component tasks were included. An array of number and letters were presented to participants, who had to connect just the numbers on the Number Sequencing task (Condition 2; numbers between 1 and 16) or just the letters on the Letter Sequencing task (Condition 3; letters between A and P).

The sum of the total time taken for Number Sequencing and Letter Sequencing was subtracted from the total time taken for the Number-Letter Switching task in order to calculate the ‘switching cost’, which was used as the measure for *verbal cognitive flexibility*. This measure controlled for differences in the speed of processing sequences of numbers and letters. Test–retest reliabilities for measures contributing to ‘switching cost’ are reported as follows: number sequencing (.77), letter sequencing (.57) and letter/number switching (.20; Delis et al., 2001).

The Intra-Extra Dimensional (IED) Set Shift test (Cambridge Neuropsychological Test Automated Battery; Cambridge Cognition, 2006) was used to measure visuo-spatial switching abilities. The task was completed on a tablet and children had to respond by tapping on the touchscreen. To begin with, two tasks assessing processing speed were administered. The Motor Screening task required participants to touch as quickly as possible the centre of a series of crosses appearing one after the other in different positions on the screen. In the Big Circle, Little Circle task, a big and a small circle were presented next to each other in the centre of the screen and children had to quickly touch the little circle in the first set of trials, and later choose the big circle only on the next set of trials. These tasks ensured that children were able to respond to visual stimuli adequately and that they familiarised with the touchscreen. Next, the main IED Set Shift task was administered. Initially, two *simple stimuli* that consisted in colour-filled shapes appeared on the computer screen, and participants were instructed to touch one of the two to learn from positive or negative feedback the rule to give correct responses. After six consecutive correct responses new rules and/or stimuli were introduced, and at each stage the child had to learn the new rule by trial and error. The ‘intradimensional shift’ consisted of seven stages, in which the colour-filled shapes were the only relevant stimuli to obtain correct responses. At some of these stages, *complex stimuli* were formed by white lines appearing adjacent to or overlaying the colour-filled shapes, which however remained the only relevant stimuli. During the stages of 'extradimensional shift' the white lines became (without warning) the only relevant stimuli to obtain positive feedback, and therefore required the child to switch the attention from the colour-filled shapes to the white lines.

The total number of errors was used as a measure of *nonverbal cognitive flexibility*. Test–retest reliability for total errors in this task is reported as .40 (Cambridge Cognition, 2006).

2.3.4. Academic achievement tasks

The Wechsler Individual Achievement Test, 2nd UK Edition (WIAT-II UK; Wechsler, 2005) is a comprehensive and widely used measure of achievement in children and adolescents and was used to assess three areas of educational attainment: reading, spelling and mathematics. The subtests to measure these three areas are illustrated below.

2.3.4.1. Reading

The Word Reading subtest required participants to read aloud from a list of words of increasing complexity. The Pseudoword Decoding subtest assessed phonetic decoding skills. For this test, children were asked to read aloud a list of nonsense words, which represent phonetic structures of the English language (sample items are administered). There was no time limit to complete either of the tests and children were encouraged to be accurate rather than quick. For both tests, self-corrections were counted as correct responses, and administration was interrupted after seven consecutive errors. Word accuracy was scored and the total number of correct responses was converted to a standard score. The maximum total raw score was 55 for Pseudoword Decoding and 131 for Word Reading. Since these two tests measured different components of reading, the standard scores were kept as separate measures of reading throughout the analyses of data. Reliability of relevant ages is reported as .95 to .97 for Word Reading and as .96 to .98 for Pseudoword Decoding (Wechsler, 2005).

2.3.4.2. Spelling

In the Spelling test, words were dictated to the child, who was encouraged to listen carefully to each word and sentence associated with it, and to clearly write the word on a response booklet. After pronouncing each word, the examiner included a sentence containing the target word because this provided context clues for homonyms and supported the child to spell the word correctly. The test was discontinued after six consecutive incorrect items. The total number of correctly spelled words was recorded (maximum total raw score was 53 points) and transformed into a standard score. If handwriting was illegible, children were asked to re-write the word or spell orally, as this meant that spelling ability could be measured without the confound of poor handwriting. Age-based reliability coefficients for this task ranged between .94 and .96 (Wechsler, 2005).

2.3.4.3. Mathematics

The Numerical Operations test consisted of solving written calculations or equations involving addition, subtraction, multiplication and division. Children were presented with a response booklet containing boxes with increasingly difficult operations. In each box some space was provided to work out the correct response, which had to be recorded anywhere in the box. Children were given all the time they required to solve as many problems as they could, and were interrupted after six consecutive errors. When children declared to be finished and fewer than six consecutive responses were incorrect, the examiner encouraged participants to attempt to solve as many items as necessary to reach the target for the discontinuation rule. The total number of correct responses was recorded (maximum total raw score is 54) and converted into a standard score, which was used as the measure of mathematical ability in the study. When written numbers were illegible or ambiguous, participants were asked to read the response aloud. Reliability for this task is reported as .93 to .95 for the ages relevant to the current study.

2.4. Statistical Analyses

All analyses were conducted using IBM SPSS Statistics version 23. The type of analysis depended on the research questions raised in each study. To summarise, Study 1 included hierarchical multiple regressions and multivariate analysis of variance (MANOVA); Study 2 included hierarchical multiple regressions and Chi Square tests; Study 3 included moderation analyses using multiple regressions with interactions. All details about the specific methods of analysis are reported in the relevant sections of each study.

2.5. Methodology Rationale

In this section the rationale motivating the methodological procedures adopted for the current study are discussed.

The strict inclusion criteria ensured that all children with additional diagnoses other than DCD were excluded. In the case of medical conditions and intellectual ability, the exclusion was necessarily linked to the DSM-5 diagnostic criteria. Other neurodevelopmental disorders such as ASD and ADHD were also criteria for exclusions since the associated symptoms may have a specific impact on EF abilities (Happé, Booth, Charlton, & Hughes, 2006). Possible conditions affecting EF performance include developmental language impairment (Henry et al., 2012) and dyslexia (Booth, Boyle, & Kelly, 2010; Reiter, Tucha, & Lange, 2005). Therefore, further criteria for exclusion were a marked impairment on language and reading performance, for which all children in this study were screened. Reading and language impairments are often identified in the literature in children performing below -1.25 standard deviations in measures of language (Tomblin, Records, & Zhang, 1996), and 1.5 standard deviations below the mean in measures of reading achievement (Peterson & Pennington, 2012). The current study set the cut-off for exclusion from the study to 2 standard deviations below the mean on the reading screening task, and/or in *both* the language assessment subtests, and/or in the IQ test, so that cut-offs harmonised between study tests. This ensured that language, reading and intellectual abilities of participants were sufficient to access the EF and academic tasks administered, but allowed for a broader range of abilities to be investigated in the sample, including participants with low skills but within 97.7% of the population. The main purpose of the study was to identify children with motor impairments, and stricter inclusion criteria could have interfered with capturing all kinds of motor difficulties including those associated with low ability in other domains. Although it may be argued that typically developing children with language, reading or IQ scores below one standard deviation from the mean are not strictly ‘typical’, excluding those children from the TD group only would have increased group differences with the DCD and MD groups, thus affecting group differences in EF and academic performance.

Another issue to be considered is that a DCD sample excluding children with overlapping conditions may not be representative of a clinical population of children with DCD, considering that neurodevelopmental disorders often co-occur (Hulme & Snowling, 2009; Williams & Lind, 2013). However, the aim of this thesis was to identify the EF, language and academic strengths and difficulties associated specifically with diagnosed and undiagnosed motor coordination impairments. This is a necessary first step to better understand individuals with DCD and isolate the cognitive profiles that characterise them. Implications of this method are further discussed in Chapter 6.

The investigation conducted in the three studies of this thesis was focussed on children with motor coordination impairments, but not restricted to those with an existing diagnosis of DCD. Considering the poor awareness of DCD amongst teachers and clinicians (Kirby et al., 2005), it may happen that some children with DCD are not identified. Therefore, the current study included children without a diagnosis who nevertheless demonstrated significant motor difficulties (MD group). As illustrated in Chapter 1, many studies on DCD have recruited participants from school samples, rather than from clinical populations, and results across studies obtained from individuals with research diagnoses may not be comparable with those from individuals with clinical diagnoses. In the current study we included both the DCD group and the MD group in order to establish whether profiles of children with a DCD diagnosis are similar to profiles of individuals who have not been identified.

The study assessed a wide range of EFs across five different domains. These included not only working memory, inhibition and cognitive flexibility, which are identified as ‘core’ EF skills (Miyake et al., 2000), but also planning and fluency. There are both theoretical and experimental reasons for including these two additional domains. As discussed in Chapter 1, the three-factor model found in adults is not as strong when applied to children, although some evidence exists (Lehto et al., 2003). A study by Levin et al. (1996) found evidence for a five-factor structure of EF (including a *planning* factor and a *conceptual/productivity* factor on which fluency loaded) in children between 5 and 16 years of age. Therefore, it may be that although in adults planning and fluency load on the three core EFs, in children this three-factor structure develops with age. Indeed, there is evidence of the dissociable nature of fluency and planning in studies showing that verbal and design fluency, as well as planning, are significantly more efficient in adolescents than younger children (Levin et al., 1991) and that verbal fluency efficiency and planning continue to develop after the age of 12 (Welsh et al., 1991), while these age-related differences are not as evident for other EF constructs. Furthermore, the three-factor structure may be compromised in clinical populations. In fact, planning and fluency are measures that have been used in previous experimental research on neurodevelopmental disorders (Pennington & Ozonoff, 1996). Some further experimental reasons for including fluency and planning are the fact that fluency was not measured in children with DCD before our original cross-sectional study (Leonard et al., 2015) and that planning has been found to be a weakness in children with DCD (Asonitou et al., 2012). Finally, the experimental EF battery was adopted from a previous study investigating EF in children with language impairments (Henry et al., 2012).

The EF battery included a verbal and a related and parallel nonverbal measure for each of the five domains. This procedure ensured that confounding factors could be taken into account. For example, children with DCD not only have impaired motor skills, but often demonstrate poor visuo-spatial ability (Wilson & McKenzie, 1998). Therefore, EF tasks that require a certain degree of motor control (e.g. pressing a button or drawing) or the processing of visuo-spatial information (e.g., distinguish between shapes on a screen) may be problematic for this population because of the task demands rather than because of their EF skills. Comparing performance on both nonverbal and verbal versions of each EF task is particularly relevant to assess children with a motor deficit (Study 1), as it will add evidence on their EF control when it involves a motor or visuo-spatial demand *vs* when it does not. Similarly, measuring EF in tasks that do not require the explicit use of verbal information is crucial to explore the relationship of EF and language (Study 3).

The task impurity problem (Miyake et al., 2000) is particularly relevant when measuring EF. The EF tests administered in the current study were as simple as possible, to avoid using complex assessments of EF which may tap into multiple EF constructs or other cognitive skills (e.g. Tower of London; Miyake et al., 2000). Any part of the assessments that involved multiple EF domains was excluded (e.g, switching between fruit and furniture in the Verbal Fluency task). Finally, component skills were controlled for where possible (e.g., calculating the switching cost in the cognitive flexibility task rather than using the total completion time).

Finally, the choices of the EF measures were motivated by all of the above reasons and were considered the best available tests satisfying the need of simple, age-appropriate, domain specific tasks, that could isolate either verbal or nonverbal demands. However, some of the EF measures administered have relatively low reliability estimates. Since EF abilities are most engaged in novel and unfamiliar situations, repeating the task in order to measure reliability will inevitably reduce its novelty, hence reducing effective assessment of EF. Furthermore, the same EF task may be completed using different strategies at different time of measurements. As a consequence, low reliability may be an inherent characteristic of EF measures (Miyake et al., 2000). Nevertheless, as outlined in both the introduction and method sections, all these tasks have been used in previous research and tests are well established in the

EF literature. The discussion of findings will consider this issue when interpreting results that may be affected by measures with low reliability.

The next three chapters will illustrate in turn the three main studies resulting from the PhD project. Throughout these chapters the following terminology is adopted: the phrase ‘children with DCD’ refers to children with a clinical diagnosis of DCD; the phrase ‘children with MD’ refers to the group of children recruited in the current project with motor difficulties identified through screening but without a DCD diagnosis; the phrases children with ‘poor motor skills’ or ‘motor coordination impairments’ or ‘motor deficits’ refer generally to children *both* with and without a diagnosis (i.e., both the MD and DCD groups). Each of the three following chapters will outline briefly the literature supporting the research questions and hypotheses, the specific methods adopted, results and discussion of findings.

CHAPTER 3

3. Study 1 – A two-year follow-up study of executive functions in children with motor difficulties and Developmental Coordination Disorder

3.1. Introduction

The crucial role played by Executive Function (EF) in everyday situations and life outcomes has been extensively documented (Diamond, 2013; Moffitt et al., 2011). As outlined in Chapter 1, difficulties in EF have been identified in both children with poor motor skills (Wilson et al., 2017), and adults with DCD, who consistently report EF symptoms as a key area of concern (Kirby et al., 2008; Purcell, Scott-Roberts, & Kirby, 2015; Tal-Saban, Ornoy, & Parush, 2014). However, research is largely cross-sectional. In typical populations EFs have protracted development into early adulthood (Friedman et al., 2015; Luciana et al., 2005; Luna et al., 2004). Therefore, it may be misleading to infer developmental trajectories from comparing cross-sectional studies assessing EF in individuals with DCD at different ages, as the recruitment and assessment methods differ across studies. Thus, it is crucial to investigate EF longitudinally in the same individuals with poor motor skills.

To date, two studies have assessed EF longitudinally in early childhood: in a group of 5-6 year-old children with poor manual dexterity skills (Michel et al., 2011); and in a group of 4-6 year-old children screened for motor coordination impairments at two time points (Michel, Molitor, & Schneider, 2016). In both studies, children were followed up one year later, and those with persistent motor impairments demonstrated performance gains with age in EF tasks. However, poorer EFs were identified at both time points when the children with motor difficulties were compared to samples of children with average or above average motor coordination scores, matched for age, gender and intellectual ability. These two studies had a relatively short (one year) gap between the two measurement points and only focused on early childhood.

Given the EF deficits in children with poor motor skills, it is important to understand whether EFs reach typical levels of maturity at any point during development or whether the deficit persists into adulthood. Indeed, it is in later childhood that the development of EFs starts differentiating between separate constructs. Specifically, inhibition seems to reach adult levels between 8-12 years (Huizinga et al., 2006; Welsh et al., 1991), while working memory continues to develop into adolescence and even early adulthood (Huizinga et al., 2006; Levin et al., 1991). A longitudinal perspective reflecting developmental change in later childhood is essential to better understand the nature of EF difficulties in children with motor impairments.

The current study provides this perspective. As outlined in Chapter 2 (Section 2.1), it is a follow-up of previous research conducted by Leonard and colleagues (2015). They recruited children between 7-11 years of age by screening for movement difficulties as well as through clinical diagnoses of DCD. These two groups of children with poor motor skills, namely a DCD group and a motor difficulty (MD) group, were compared separately to a group of typically developing (TD) children. A comprehensive EF assessment battery was administered including parallel verbal and non-verbal measures in five EF domains. Specifically, the battery included measures of executive-loaded working memory, response inhibition, and cognitive flexibility. Although these three domains are identified as ‘core’ EF skills (Miyake et al., 2001), this three-factor model is not as strong when applied to children, for whom a broader set of five factors may be more appropriate (Levin et al., 1996). Therefore, measures of planning and fluency, which have previously been used in populations with neurodevelopmental disorders (Henry et al., 2012; Pennington & Ozonoff, 1996) were also included in the battery.

The authors reported that both the MD and DCD groups performed significantly more poorly than TD children on *nonverbal* tests of ELWM, inhibition and fluency. There were no reported differences in performance on switching tasks, but the MD group scored significantly below TD children on the task measuring nonverbal planning abilities. Critically, no differences in performance were found on any *verbal* EF tasks.

Two years later these children were followed up in the current study using the same EF assessment battery, to provide a longitudinal perspective on EF in children with poor motor skills (DCD and MD). Two main research questions were put forward: (RQ1) Do children with poor motor skills show persistent EF difficulties at each time point compared to TD children? (RQ2) Do children with poor motor skills demonstrate gains in EF? If so, how do these EF gains compare to those of TD children?

Based on the original study findings, it was expected that children with DCD and MD would demonstrate difficulties in nonverbal EF tasks compared to TD children, and that these difficulties would be evident at both time points. It was predicted that at least some gains in EF performance would be apparent for both groups, but that these may vary between EF domains, as well as between verbal versus nonverbal task types.

3.2. Method

3.2.1. Participants

As outlined in Chapter 2 (Section 2.2), parents of children who participated in the original study (Leonard et al., 2015) were approached. Informed consent was obtained from 56 parents and their children (61.5 % of the original sample) to take part in this follow-up study.

At Time 1 the MABC-2 (Henderson et al., 2007) was used to differentiate children with and without motor coordination difficulties (scores at or above the 25th percentile for TD children, at or below the 16th percentile for MD/DCD children) as well as to corroborate the diagnosis of children in the DCD group. The BAS3 (Elliot & Smith, 2011) was administered to assess intellectual abilities (*M*=100; *SD*=15; see Chapter 2, Section 2.3.2 for further details). Any child scoring more than two standard deviations below the mean on this task (IQ < 70) was excluded from the sample (see Chapter 2, Section 2.2.2 for exclusion criteria).

At Time 2 children were assigned initially to their original groups: TD (*n*=20), DCD (*n*=19) and MD (*n*=17). However, to confirm group membership and suitability for the study, participants were re-assessed on motor and cognitive ability using the MABC-2 and the BAS3 respectively. Two of the children in the DCD group performed 2SDs below the mean on the BAS3 at Time 2, and were consequently excluded from the sample. One TD child performed on the 16th percentile of the MABC-2 and two more TD children performed on the 9th percentile. All three of these children demonstrated some degree of motor difficulty at Time 2 and therefore could no longer be included in the TD group. All children in the DCD or MD group showed persistent motor difficulties across time (MABC-2 scores below 16th percentile at Time 2). The final sample after these five exclusions included 51 children, 17 in each group. Background characteristics of age, motor and intellectual ability scores are presented in Table 3.1, together with results of one-way ANOVAs comparing the groups on these measures. The following group differences emerged: Children with DCD were significantly older than TD children at Time 1 (*p*=.037) and children with MD at both time points (*p*s<.001); TD children obtained significantly higher intellectual ability scores than the MD group at Time 2 (*p*=.015); as expected, TD children had higher motor ability than the DCD and MD groups at both time points (*p*s<.001).

Table 3.1. Means, standard deviations (in parentheses) and ranges of age and scores on motor and intellectual ability tasks in typically-developing children (TD), children screened for motor difficulties (MD) and children with a diagnosis of DCD. One-way ANOVA Welch adjusted F values, degrees of freedom (in parenthesis) and effect sizes are reported for age, intellectual ability scores and motor skills.

Measure	**TD Group** (*n*=17;11 girls)	**MD group** (*n*=17; 9 girls)	**DCD group** (*n*=17; 4 girls)	**ANOVA** *Welch adjusted*
	Mean (SD) *Range*	Mean (SD) *Range*	Mean (SD) *Range*	*F* (df) η_p^2
Time1 – Chronological Age (Months)	109.14 (10.92) *90.33-128*	100.76 (7.37) *93.22-124.22*	118.82 (13.96) *97-143*	*11.91* (2,29.89)*** .320
Time2 – Chronological Age (Months)	135.01 (11.60) *116.22-157*	126.13 (6.91) *118-148*	144.18 (14.48) *121-169*	*11.97* (2,29.03)*** .306
Time1 – BAS3 General Conceptual Ability	108.47 (12.46) *92-138*	96.82 (17.02) *71-125*	98.88 (12.81) *78-119*	*3.50* (2,31.51)* .122
Time2 – BAS3 General Conceptual Ability	117.29 (17.42) *89-153*	99.47 (22.57) *70-136*	104.41 (12.08) *79-127*	*4.21* (2,30.04)* .158
Time1 – MABC-2 Percentile	58.82 (20.13) *25-95*	3.76 (2.68) *0.5-9*	5.71 (5.74) *0.1-16*	*61.08* (2,25.29)*** .823
Time2 – MABC-2 Percentile	51.06 (21) *25-84*	5.35 (4.01) *1-16*	2.22 (2.58) *0.1-9*	*46.32* (2,27.11)*** .774

Note. MABC-2 = Movement Assessment Battery for Children; BAS3 = British Abilities Scales.
*$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$

3.2.2. Measures

A comprehensive EF assessment battery was administered, including a verbal and a nonverbal measure for each of the following EFs: executive-loaded working memory, fluency, response inhibition, planning and cognitive flexibility (see Table 3.2 for summary details). These measures were identical to those administered at Time 1 and are fully reported in Chapter 2 (Section 2.3.3).

3.2.1. Procedures

All children were assessed individually in a quiet room and sufficient breaks were given between tasks to maintain motivation. Task order was varied to suit the child's needs and offer maximum variety. Children who were seen at the research lab or in their home completed the assessment on the same day or over two to three sessions of 1.5 – 2 hours. Children who were tested in their school (66% at Time 1 and 48% at Time 2) completed five or six sessions of 45 minutes – one hour each.

Table 3.2. Description of tasks administered to assess Executive Functions.

EF Measured	Domain	Task	Description	Outcome Variable
Executive-Loaded Working Memory	Verbal	Listening Recall (WMTB-C; Gathercole et al., 2001)	Participants recall the last word of a sentence after making a judgement as to whether the sentence was true or false, with the number of sentences increasing as the task continues.	Total correct trials
	Nonverbal	Odd-One-Out (Henry, 2001)	A nonverbal equivalent of the above task, in which participants recall the spatial location of a nonsense shape after making a judgement as to which of the shapes was the 'odd one out'.	Total correct trials
Fluency	Verbal	Verbal Fluency (D-KEFS; Delis et al., 2001)	Participants generate as many words as possible belonging to two different specific categories, within one minute.	Total correct responses
	Nonverbal	Design Fluency (D-KEFS; Delis et al., 2001)	Participants generate as many designs as possible, according to a series of particular criteria, within one minute.	Total correct responses
Inhibition	Verbal	VIMI – verbal (Henry et al., 2012)	Participants copy a word said by the experimenter, or provide another word (i.e., inhibit the copying response), depending on instructions.	Total errors
	Nonverbal	VIMI – motor (Henry et al., 2012)	Participants copy an action demonstrated by the experimenter, or provide another action (i.e., inhibit the copying response), depending on instructions.	Total errors
Planning	Verbal	Sorting (D-KEFS; Delis et al., 2001)	Participants sort two sets of six cards into two groups of three in as many ways as possible based on verbal features	Total correct verbal sorts
	Nonverbal	Sorting (D-KEFS; Delis et al., 2001)	Participants sort two sets of six cards into two groups of three in as many ways as possible based on perceptual features	Total correct perceptual sorts
Switching	Verbal	Trail Making Test (D-KEFS; Delis et al., 2001)	Participants have to draw a line between numbers and letters in sequence, switching between the two (e.g., 1-A-2-B, etc.)	Completion time switching cost
	Nonverbal	Intra/Extra Dimensional Shift (CANTAB; Cambridge Cognition, 2006)	Participants learn a rule through initial trial and error in relation to a shape and then have to switch to a different rule to continue achieving 'correct' answers.	Total errors

3.2.1. Statistical analysis

In order to identify initial group differences on background measures one-way ANOVAs were conducted for each variable at each time point.

Hierarchical multiple regressions were then conducted to explore any differences in EF performance between groups at both time points (RQ1). Since participants in this follow-up were a subgroup of the original sample (Leonard et al., 2015), regressions were conducted at both Time 1 and Time 2 in order to compare the same subgroup of participants across time. The multiple regression approach was taken so that the group differences in age and IQ (reported in Table 3.1) could be controlled at Step 1 of each regression, before examining whether there were group differences in EF performance at Step 2 using two dummy-coded Group variables. The reference group was always TD children, hence the two comparisons were TD vs. MD and TD vs. DCD. Regression models analysing EF performance at Time 1 included IQ scores obtained at Time 1 and similarly, for EF performance at Time 2 the corresponding IQ scores at Time 2 were entered. Since the 10 EF tasks were, in some cases, administered at different times, the exact age at which each child completed a specific task was entered as a predictor of the regression model investigating that particular EF ability. For example, for the regression model investigating verbal fluency at Time 1 the age of each participant at the time they completed the verbal fluency task at Time 1 was entered as a predictor. Bonferroni corrections were applied to the final models of all regressions ($p \leq .005$).

Next, a repeated measures MANOVA was used to test for differences in EF performance between the two time points and identify whether the group variable had an impact on these differences over time (RQ2). Group was entered as the between-subjects factor (3 levels) and Time as the within-subjects factor (2 levels), and all EF measures were entered as dependent variables.

Finally, in order to detect any improvement in EF performance over time within each group, three separate repeated measures MANOVAs were conducted for TD, MD and DCD children respectively. Time was entered as within subject factor (2 levels).

3.3. Results

The means, standard deviations and ranges of scores for each of the 10 EF measures at both time points are presented in Table 3.3.

Table 3.3.Descriptive statistics for each EF measure at both time points.

			TD (*n*=17)	**MD** (*n*=17)	**DCD** (*n*=17)
EF Domain	**EF measure**		Mean; *SD* (Range)	Mean; *SD* (Range)	Mean; *SD* (Range)
Working Memory *Verbal*	WMTBC Listening Recall *Total Correct*	Time 1	14.24; *3.05* (8-21)	11.12; *3.86* (6-19)	13.88; *3.14* (10-23)
		Time 2	17.53; *4.99* (12-27)	14.35; *3.92* (8-24)	16.24; *4.09* (12-29)
Working Memory *Nonverbal*	Odd-One-Out *Total Correct*	Time 1	11.53; *3.20* (6-17)	6.88; *3.44* (3-14)	7.82; *3.19* (4-15)
		Time 2	13.18; *2.94* (7-18)	8.76; *3.31* (3-17)	9.88; *3.94* (4-16)
Fluency *Verbal*	D-KEFS Verbal Fluency *Total Correct*	Time 1	30.65;*8.08* (15-44)	26.24; *5.98* (16-39)	24.50; *7.79*[a] (3-38)
		Time 2	38.06; *9.46* (17-52)	30.41; *7.94* (18-51)	28.82; *8.83* (12-48)
Fluency *Nonverbal*	D-KEFS Design Fluency *Total Correct*	Time 1	14.76; *4.25* (7-22)	10.35; *4.44* (1-20)	12.12; *3.71* (5-21)
		Time 2	19.65; *5.56* (10-28)	14.24; *3.56* (10-22)	15.12; *4.48* (9-23)

Response Inhibition *Verbal*	VIMI Verbal *Total Errors*	Time 1	9.47; *6.50* (0-23)	12.35; *6.65* (5-29)	16.53; *9.96* (4-36)
		Time 2	8.53; *5.99* (0-24)	12.82; *6.52* (5-28)	14.82; *6.55* (6-27)
Response Inhibition *Nonverbal*	VIMI Motor *Total Errors*	Time 1	28.94; *14.17* (3-51)	43.53; *12.39* (21-61)	48.82; *16.62* (21-74)
		Time 2	26.71; *11.12* (8-48)	40.53; *13.85* (11-64)	43.71; *15.83* (14-71)
Planning *Verbal*	D-KEFS Verbal Sorting *Total Correct*	Time 1	2.24; *.97* (1-4)	2.00; *1.06* (0-3)	2.65; *1.06* (1-4)
		Time 2	2.65; *1.06* (1-4)	2.41; *1.0* (1-4)	2.35; *1.17* (0-4)
Planning *Nonverbal*	D-KEFS Perceptual Sorting *Total Correct*	Time 1	7.12; *1.65* (3-9)	4.41; *2.45* (0-7)	4.47; *2.24* (0-8)
		Time 2	7.47; *1.18* (6-10)	4.88; *2.74* (0-9)	6.06; *1.39* (3-9)
Cognitive Flexibility *Verbal*	D-KEFS Trail Making *Switching cost (sec.)*	Time 1	34.65; *41.16* (-8 – 162)	86.60; *87.09*[b] (-31 – 244)	24.81; *47.75*[c] (-101 – 102)
		Time 2	16.35; 33.*94* (-16 – 128)	22.88; *32.14* (-25 – 84)	9.18; *40.77* (-41 – 121)
Cognitive Flexibility *Nonverbal*	CANTAB IEDS *Total Errors*	Time 1	20.29; *12.90* (8-42)	29.53; *14.92* (8-56)	29.53; *11.59* (8-51)
		Time 2	16.94; *8.98* (7-35)	24.82; *10.76* (9-38)	23.35; *12.61* (9-54)

Note. EF=Executive Function; WMBTC=Working Memory Test Battery for Children; D-KEFS=Delis-Kaplan Executive Function System; VIMI=Verbal Inhibition, Motor Inhibition; CANTAB=Cambridge Neuropsychological Test Automated Battery; IEDS=Intra-/Extra-Dimensional Shift.

[a]1 Missing data point; [b]2 missing data points; [c]1 missing data point.

3.3.1. RQ1: Do children with poor motor skills show persistent EF difficulties at each time point compared to TD children?

Hierarchical multiple regressions analyses exploring group differences at each time point are discussed separately for each EF construct.

3.3.1.1. Executive-Loaded Working Memory

The details of Step 2 of each regression analysis on Executive-Loaded Working Memory (ELWM) are reported in Table 3.4.

The final regression models for *verbal* ELWM were significant at both Time 1 $F(4, 46) = 10.47, p < .001$, and Time 2, $F(4, 46) = 8.24, p < .001$, accounting for 47% and 43% of the variance respectively[1]. Age and IQ were significant predictors of verbal ELWM performance at both time points. However, the entry of the dummy-coded group variables at Step 2 made no contribution to the model, indicating no group differences.

The final regression models for *nonverbal* ELWM were significant at both Time 1 $F(4, 46) = 7.90, p < .001$, and Time 2, $F(4, 46) = 6.36, p < .001$, accounting for 41% and 36% of the variance respectively. Age was a significant predictor at Time 1 only and IQ was a significant predictor at Time 2 only. In terms of group differences, the MD group performed significantly more poorly than the TD group at both Time 1 ($p = .005$) and Time 2 ($p = .036$). Similarly, there was a significant difference between the DCD and TD groups, with better performance in the TD group, at Time 1 ($p < .001$) and Time 2 ($p = .024$).

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[1] Note that percentages correspond to R^2 values, which may differ from *adjusted* R^2 values reported in each table.

Table 3.4. Summary details of step 2 of the hierarchical multiple regression analyses predicting performance in the executive-loaded working memory measures.

Executive-Loaded Working Memory		***Details of Step 2 for each regression***						
		Final Model F(df) Adj. R^2		*Age*	*IQ*	*TD Vs. MD*	*TD Vs. DCD*	ΔR^2 Step 2
Verbal	Time 1	*10.47*(4,46) **.43***** *p*<.001	β	.48***	.37**	-.13	-.11	.01 *p=.56*
			Unst.β	*.13*	*.09*	*-.99*	*-.83*	
			SE	*(.04)*	*(.03)*	*(1.01)*	*(1.05)*	
				p=.001	*p=.002*	*p=.33*	*p=.43*	
	Time 2	*8.24*(4,46) **.37***** *p*<.001	β	.57***	.42***	.02	-.19	.03 *p=.31*
			Unst.β	*.19*	*.10*	*.218*	*-1.81*	
			SE	*(.05)*	*(.03)*	*(1.40)*	*(1.33)*	
				p<.001	*p=.001*	*p=.87*	*p=.18*	
Nonverbal	Time 1	*7.90*(4,46) **.36***** *p*<.001	β	.38**	.13	-.42**	-.57***	.22*** *p*=.001
			Unst.β	*.11*	*.03*	*-3.37*	*-4.51*	
			SE	*(.04)*	*(.03)*	*(1.14)*	*(1.18)*	
				p=.010	*p=.30*	*p=.005*	*p<.001*	
	Time 2	*6.36*(4,46) **.30***** *p*<.001	β	.16	.36**	-.34*	-.35*	.10* *p*=.035
			Unst.β	*.05*	*.07*	*-2.74*	*-2.81*	
			SE	*(.04)*	*(.03)*	*(1.27)*	*(1.21)*	
				p=.27	*p*=.009	*p*=.036	*p*=.024	

Note. For each regression the final model F values, degrees of freedom in parentheses, and adjusted R^2 are presented, along with the change in R^2 in Step 2 of the model. Standardized beta values, *unstandardized coefficients*, and *standard errors* (in parentheses) are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .005$) are indicated in boldface.

$^*p \leq .05$; $^{**}p \leq .01$; $^{***}p \leq .001$; $^{\dagger}p \leq .06$ non-significant trend.

3.3.1.2. Fluency

The details of Step 2 for each regression analysis on Fluency are reported in Table 3.5.

The final regression models for *verbal* fluency were significant at both Time 1 $F(4, 45) = 6.25$, $p < .001$, and Time 2, $F(4, 46) = 6.81$, p < .001, accounting for 33% and 35% of the variance respectively. Age was a significant predictor at both time points, whereas IQ was not significant. No differences between the MD and TD groups were identified. However, the DCD group produced significantly fewer verbal responses than the TD group at both time points (*p*s = .001). Note that one child in the

DCD group did not provide valid verbal fluency scores at Time 1 (this was due to a parent interfering with the assessment of verbal fluency, i.e. suggesting strategies to complete the task). Therefore, as a result of listwise deletion of cases with missing values, the relevant regression analysis was conducted with 50 participants only.

Table 3.5. Summary details of step 2 of the hierarchical multiple regression analyses predicting performance in the fluency measures.

		Details of Step 2 for each regression						
Fluency		Final Model *F*(df) Adj. R^2		*Age*	*IQ*	*TD Vs. MD*	*TD Vs. DCD*	ΔR^2 Step 2
Verbal	Time 1	*5.49*(4,45)	β	$.56^{***}$	.11	-.08	$-.55^{***}$	
		.27***	*Unst.β*	*.31*	*.06*	*-1.24*	*-8.97*	$.20^{**}$
		p=.001	*SE*	*(.09)*	*(.07)*	*(2.45)*	*(2.55)*	*p*=.003
				p=.001	*p*=.412	*p*=.615	*p*=.001	
	Time 2	*6.09*(4,46)	β	$.45^{**}$	.22	-.14	$-.54^{***}$	
		.29***	*Unst.β*	*.31*	*.11*	*-2.85*	*-10.72*	$.19^{**}$
		p=.001	*SE*	*(.10)*	*(.07)*	*(3.16)*	*(2.99)*	*p*=.003
				p=.003	*p*=.094	*p*=.371	*p*=.001	
Nonverbal	Time 1	*4.04*(4,46)	β	.29	.16	$-.33^{*}$	$-.34^{*}$	
		$.20^{**}$	*Unst.β*	*.10*	.05	*-3.04*	*-3.20*	$.10^{\dagger}$
		p=.007	*SE*	*(.05)*	*(.04)*	*(1.49)*	*(1.55)*	*p*=.058
				p=.085	*p*=.401	*p*=.047	*p*=.044	
	Time 2	*5.28*(4,46)	β	$.36^{*}$	.12	$-.34^{*}$	$-.50^{**}$	
		.26***	*Unst.β*	*.14*	.03	*-3.63*	*-5.39*	$.17^{**}$
		p=.001	*SE*	*(.06)*	*(.04)*	*(1.74)*	*(1.65)*	*p*=.006
				p=.018	*p*=.380	*p*=.042	*p*=.002	

Note. For each regression the final model *F* values, degrees of freedom in parentheses, and adjusted R^2 are presented, along with the change in R^2 in Step 2 of the model. Standardized beta values, *unstandardized coefficients*, and *standard errors* (in parentheses) are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .005$) are indicated in boldface. One missing data point for verbal fluency measures at Time 1 (DCD group).

$^{*}p \leq .05$; $^{**}p \leq .01$; $^{***}p \leq .001$; $^{\dagger}p \leq .06$ non-significant trend.

The final regression models for *nonverbal* fluency were significant at Time 1 *F*(4, 46) = 4.04, *p* = .007, and Time 2, *F*(4, 46) = 5.28, *p* = .001, accounting for 26% and 32% of the variance respectively. After applying a Bonferroni correction ($p \leq .005$)

the final regression model at Time 1 becomes a non-significant trend, yet significant predictors will still be interpreted. Age was a significant predictor at Time 2 only and IQ was not significant at either time point. The MD group performed significantly more poorly than the TD group at both Time 1 (p = .047) and Time 2 (p = .042). Similarly, there was a significant difference between the DCD and TD groups at Time 1 (p = .044) and Time 2 (p = .002), with higher scores in the TD group.

3.3.1.3. Response Inhibition

The details of Step 2 of the regression analyses on Response Inhibition are reported in Table 3.6.

The final regression model for *verbal* response inhibition was not significant at Time 1 (p = .175). It was also not significant at Time 2 (p =.029) after a Bonferroni correction was applied ($p \leq .005$). Although there was a significant effect of group, between TD and DCD groups, at Time 1 (p = .024) and at Time 2 (p = .008), this needs to be interpreted in light of an overall non-significant regression model.

The final regression models for *nonverbal* response inhibition were significant at Time 1, $F(4, 46) = 4.60$, p = .003, and Time 2, $F(4, 46) = 4.86$, p = .002, accounting for 29% and 30% of the variance respectively. Neither age nor IQ were significant predictors at any time point. There was a significant group difference between the MD and TD groups at Time 1 (p = .032), that was not evident at Time 2 (p = .079). The DCD group performed significantly more poorly than the TD group at both Time 1 (p = .001) and Time 2 ($p < .001$).

Table 3.6. Summary details of step 2 of the hierarchical multiple regression analyses predicting performance in the response inhibition measures.

Response Inhibition		***Details of Step 2 for each regression***						
		Final Model F(df) Adj. R^2		*Age*	*IQ*	*TD Vs. MD*	*TD Vs. DCD*	ΔR^2 Step 2
Verbal	Time 1	*1.66*(4,46)	β	-.02	-.01	.16	$.41^{*}$	
		.05	*Unst.β*	*-.01*	*-.01*	*2.72*	*7.15*	.10
		p=.175	*SE*	*(.11)*	*(.08)*	*(3.01)*	*(3.06)*	*p*=.076
				p=.898	*p*=.965	*p*=.370	*p*=.024	
	Time 2	*2.96*(4,46)	β	-.22	-.16	.16	$.46^{**}$	
		$.14^{*}$	*Unst.β*	*-.11*	*-.06*	*2.24*	*6.54*	$.14^{*}$
		p=.029	*SE*	*(.08)*	*(.05)*	*(2.48)*	*(2.34)*	*p*=.027
				p=.165	*p*=.265	*p*=.373	*p*=.008	
Nonverbal	Time 1	*4.60*(4,46)	β	-.14	-.08	$.35^{*}$	$.59^{***}$	
		$.22^{**}$	*Unst.β*	*-.18*	*-.09*	*12.04*	*20.59*	$.22^{**}$
		p=.003	*SE*	*(.19)*	*(.15)*	*(5.46)*	*(5.56)*	*p*=.002
				p=.365	*p*=.547	*p*=.032	*p*=.001	
	Time 2	*4.86*(4,46)	β	$-.29^{\dagger}$	-.09	.29	$.59^{***}$	
		$.24^{**}$	*Unst.β*	*-.34*	*-.07*	*9.52*	*19.05*	$.22^{**}$
		p=.002	*SE*	*(.17)*	*(.11)*	*(5.30)*	*(5.01)*	*p*=.002
				p=.055	*p*=.515	*p*=.079	*p*<.001	

Note. For each regression the final model F values, degrees of freedom in parentheses, and adjusted R^2 are presented, along with the change in R^2 in Step 2 of the model. Standardized beta values, *unstandardized coefficients*, and *standard errors* (in parentheses) are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .005$) are indicated in boldface.

$^{*}p \leq .05$; $^{**}p \leq .01$; $^{***}p \leq .001$; $^{\dagger}p \leq .06$ non-significant trend.

3.3.1.4. *Planning*

Details of Step 2 of the regression analyses on Planning are reported in Table 3.7.

The final regression models for *verbal* planning were not significant either at Time 1 ($p = .104$) or at Time 2 ($p = .525$). None of the predictors was significant at any time point.

The final regression models for *nonverbal* planning were significant at both Time 1 $F(4, 46) = 7.79$, $p < .001$, and Time 2, $F(4, 46) = 13.84$, $p < .001$, accounting for 40% and 55% of the variance respectively. Age was a significant predictor at Time

2 only (p = .001), whereas IQ was significant at Time 1 (p = .005) and Time 2 (p < .001). There was a significant group difference between the MD and TD groups at Time 1 (p = .017), that was not evident at Time 2 (p = .094). The DCD group performed significantly more poorly than the TD group at Time 1 (p = .005) but not at Time 2 (p = .051), although their performance remained relatively poor at this time point.

Table 3.7. Summary details of step 2 of the hierarchical multiple regression analyses predicting performance in the planning measures.

			Details of Step 2 for each regression					
Planning		Final Model F(df) Adj. R^2		*Age*	*IQ*	*TD Vs. MD*	*TD Vs. DCD*	ΔR^2 Step 2
Verbal	Time 1	*2.04*(4,46)	β	.22	.21	.04	.18	
		.08	*Unst.β*	*.02*	*.02*	*.08*	*.39*	.02
		p=.104	*SE*	*(.01)*	*(.01)*	*(.38)*	*(.39)*	p=.596
				p=.194	p=.150	p=.824	p=.321	
	Time 2	*.82*(4,46)	β	-.21	-.18	.25	.12	
		-.02	*Unst.β*	*-.02*	*-.01*	*-.56*	*-.27*	.04
		p=.525	*SE*	*(.01)*	*(.01)*	*(.42)*	*(.42)*	p=.414
				p=.221	p=.267	p=.189	p=.498	
Nonverbal	Time 1	*7.79*(4,46)	β	.11	$.37^{**}$	$-.36^{*}$	$-.44^{**}$	
		$\mathbf{.35}^{***}$	*Unst.β*	*.02*	.06	*-1.84*	*-2.27*	$.14^{**}$
		p<.001	*SE*	*(.03)*	*(.02)*	*(.74)*	*(.76)*	p=.007
				p=.441	p=.005	p=.017	p=.005	
	Time 2	*13.84*(4,46)	β	$.34^{**}$	$.54^{***}$	-.23	$-.25^{\dagger}$	
		$\mathbf{.51}^{***}$	*Unst.β*	*.06*	.06	*-1.02*	*-1.13*	.05
		p<.001	*SE*	*(.02)*	*(.01)*	*(.59)*	*(.56)*	p=.094
				p=.006	p<001.	p=.094	p=.051	

Note. For each regression the final model F values, degrees of freedom in parentheses, and adjusted R^2 are presented, along with the change in R^2 in Step 2 of the model. Standardized beta values, *unstandardized coefficients*, and *standard errors* (in parentheses) are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .005$) are indicated in boldface.

$*p \leq .05$; $** \ p \leq .01$; $*** \ p \leq .001$; $^{\dagger} p \leq .06$ non-significant trend.

3.3.1.5. Cognitive Flexibility

Details of Step 2 of the regression analyses on cognitive flexibility are reported in Table 3.8.

Table 3.8. Summary details of step 2 of the hierarchical multiple regression analyses predicting performance in the cognitive flexibility measures.

Cognitive Flexibility		Final Model F(df) Adj. R^2	***Details of Step 2 for each regression***	*Age*	*IQ*	*TD Vs. MD*	*TD Vs. DCD*	ΔR^2 Step 2
Verbal	Time 1	*4.15*(4,43)	β	-.18	-.29*	.22	-.08	
		.22**	*Unst.β*	*-.90*	-1.32	*31.02*	*-11.59*	.05
		p=.006	*SE*	*(.77)*	*(.62)*	*(22.25)*	*(22.52)*	p=.216
				p=.249	p=.039	p=.170	p=.610	
	Time 2	1.48(4,46)	β	-.27	-.24	-.10	-.09	
		.04	*Unst.β*	*-.71*	-.44	*-7.66*	*-6.40*	.01
		p=.223	*SE*	*(.44)*	*(.28)*	*(13.69)*	*(13.03)*	p=.822
				p=.115	p=.123	p=.579	p=.625	
Nonverbal	Time 1	*8.84*(4,46)	β	-.45**	-.40**	.03	.34*	
		.39***	*Unst.β*	*-.47*	*-.37*	*.83*	*9.85*	.08*
		p<.001	*SE*	*(.14)*	*(.11)*	*(4.02)*	*(4.09)*	p=.048
				p=.002	p=.002	p=.836	p=.020	
	Time 2	*7.10*(4,46)	β	-.63***	-.17	.06	.42**	
		.33***	*Unst.β*	*-.53*	*-.10*	*1.49*	*9.85*	.12*
		p<.001	*SE*	*(.12)*	*(.06)*	*(3.61)*	*(3.43)*	p=.016
				p<.001	p=.194	p=.682	p=.006	

Note. For each regression the final model F values, degrees of freedom in parentheses, and adjusted R^2 are presented, along with the change in R^2 in Step 2 of the model. Standardized beta values, *unstandardized coefficients*, and *standard errors* (in parentheses) are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .005$) are indicated in boldface; 3 missing data points for verbal cognitive flexibility measures at Time 1 (2 MD, 1 DCD).

*$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$; $^{\dagger}p \leq .06$ non-significant trend.

The final regression models for *verbal* switching were as follows: a significant trend at Time 1 $F(4, 43) = 4.15$, $p = .006$, and non-significant at Time 2. At Time 1 IQ was a significant predictor ($p = .039$). None of the other predictors were significant at any time points and no differences were identified between groups. Note that one child in the DCD group and two children in the MD group did not provide valid verbal fluency scores at Time 1 (this was due to children being unable to complete the task). Therefore, as a result of listwise deletion of cases with missing values, the relevant regression analysis was conducted with 48 participants only.

The final regression models for *nonverbal* switching were significant at both Time 1 $F(4, 46) = 8.84$, $p < .001$, and Time 2, $F(4, 46) = 7.10$, $p < .001$, accounting for 43% and 38% of the variance respectively. Age was a significant predictor at Time 1 ($p = .002$) and at Time 2 ($p < .001$), whereas IQ was significant at Time 1 only ($p = .002$). There were no significant group differences between the MD and TD groups at any time points. The DCD group performed significantly more poorly that the TD group at Time 1 ($p = .020$) and Time 2 ($p = .006$).

3.3.1.6. Summary and additional analyses

In summary, children with DCD obtained poorer scores than TD children on all nonverbal EF tasks, as well as verbal fluency, at both time points. Children with MD at Time 1 performed more poorly than TD children in all nonverbal EF domains except switching; however, at Time 2, nonverbal planning and nonverbal inhibition differences were no longer evident and only nonverbal ELWM and nonverbal fluency differences persisted.

Given the disparities between MD and DCD groups emerging from the analyses above, additional regression analyses were conducted to directly compare children with DCD and MD across the 10 EF measures and identify significant group differences. Identical procedures as per the analysis above were adopted. A multiple regression approach was taken so that the group differences in age and IQ (reported in Table 3.1) could be controlled at Step 1, and at Step 2 two dummy-coded Group variables were entered. However, for this analysis the reference group was the DCD group. The MD and DCD groups differed significantly in two EF areas: (1) *verbal fluency* at both time points (Final model Time 1, $F(4,45)=5.49$, Adj. $R^2=.27$, $p=.001$, DCD vs. MD: $B=7.72$, $SE\ B=2.80$, $p=.008$; Final model Time 2, $F(4,46)=6.09$, Adj. $R^2=.29$, $p=.001$, DCD vs. MD: $B=7.87$, $SE\ B=3.35$, $p=.023$); and (2) *nonverbal switching* at both time points (Final model Time 1, $F(4,46)=9.36$, Adj. $R^2=.40$, $p<.001$, DCD vs. MD: $B=-9.60$, $SE\ B=4.37$, $p=.033$; Final model Time 2, $F(4,46)=7.10$, Adj. $R^2=.33$, $p<.001$, DCD vs. MD: $B=-8.36$, $SE\ B=3.81$, $p=.033$. Therefore, the DCD group performed significantly more poorly that the MD group on measures of verbal fluency and switching at both time points.

3.3.2. RQ2: Do children with poor motor skills demonstrate gains in EF? If so, how do these EF gains compare to those of TD children

A repeated measures MANOVA addressed the second research question investigating whether children with poor motor skills demonstrate gains in EFs and how these gains compare to those of TD children. A significant effect of Time $F(1,45)=12.11$, $p<.001$, $\eta_p^2=.771$ was identified. Univariate tests indicated the effect of Time was significant for verbal ELWM $F(1,45)=32.42$, $p<.001$, $\eta_p^2=.419$, nonverbal ELWM $F(1,45)=11.25$, $p=.002$, $\eta_p^2=.200$, verbal fluency $F(1,45)=20.21$, $p<.001$, $\eta_p^2=.310$, nonverbal fluency $F(1,45)=34.10$, $p<.001$, $\eta_p^2=.431$, nonverbal planning $F(1,45)=6.76$, $p=.013$, $\eta_p^2=.131$, verbal switching $F(1,45)=13.12$, $p=.001$, $\eta_p^2=.226$, and nonverbal switching $F(1,45)=5.10$, $p=.029$, $\eta_p^2=.102$. All these EF measures improved from Time 1 to Time 2, with participants increasing the number of correct responses or reducing the number of errors in each task. The effect of time was non-significant for verbal inhibition $F(1,45)=.30$, $p=.59$, $\eta_p^2=.007$, nonverbal inhibition $F(1,45)=1.37$, $p=.25$, $\eta_p^2=.030$, and verbal planning $F(1,45)=.70$, $p=.79$, $\eta_p^2=.002$.

There was also a main effect of Group *F*(1,45)=3.17, *p*<.001, η_p^2=.462. However, these group differences have been assessed through the previous regressions and will not be discussed further. The most relevant result for the second research question was the outcome of the interaction between Time and Group, which was non-significant *F*(1,45)=.94, *p*=.54, η_p^2=.202. Thus, EF performance changed in a similar way over time in each group.

Separate repeated measures MANOVAs were conducted within each group to identify potential differences in the pattern of improvement of DCD, MD and TD children. These different patterns may not have been revealed in the previous MANOVA (no time*group interaction) because of the significant group differences in age and IQ identified in the analysis of background variables. A significant effect of Time was identified overall for the TD group *F*(1,16)=7.89, *p*=.006, η_p^2=.771. The effect of Time was non-significant for both the MD group *F*(1,14)=.86, *p*=.115, η_p^2=.202, and the DCD group *F*(1,15)=.81, *p*=.133, η_p^2=.201. However, differences between EF constructs were identified in the univariate analyses reported in Table 3.9, which can summarised as follows: TD children improved significantly in verbal ELWM, verbal and nonverbal fluency and verbal switching; children with MD improved significantly in verbal ELWM, nonverbal fluency and verbal switching; children with DCD improved significantly in verbal and nonverbal ELWM, verbal and nonverbal fluency and nonverbal planning.

Table 3.9. Details of repeated measures MANOVAs conducted within each group and time point for each EF measure.

EF Domain		**TD**	**MD**	**DCD**
		F(df) η_p^2	F(df) η_p^2	F(df) η_p^2
Working Memory	*Verbal*	9.18(1,16) *.365* $p = .008^{**}$	22.50(1,14) *.657* $p < .001^{***}$	9.07(1,15) *.377* $p = .009^{**}$
	Nonverbal	3.97(1,16) *.199* $p = .064^{\dagger}$	2.77 (1,14) *.175* $p = .118$	4.89 (1,15) *.246* $p = .043^{*}$
Fluency	*Verbal*	9.91(1,16) *.606* $p = .006^{**}$	10.40(1,14) *.394* $p = .134$	10.05(1,15) *.401* $p = .003^{**}$
	Nonverbal	27.27 (1,16) *.630* $p < .001^{***}$	10.85 (1,14) *.404* $p = .012^{*}$	5.36 (1,15) *.263* $p = .035^{*}$
Response Inhibition	*Verbal*	.64 (1,16) *.038* $p = .436$	.06 (1,14) *.004* $p = .807$	.46 (1,15) *.031* $p = .500$
	Nonverbal	.74 (1,16) *.044* $p = .403$	.49 (1,14) *.030* $p = .495$	.84 (1,15) *.053* $p = .374$
Planning	*Verbal*	1.15 (1,16) *.067* $p = .300$	1.00 (1,14) *.059* $p = .332$	1.22 (1,15) *.075* $p = .287$
	Nonverbal	.44 (1,16) *.026* $p = .519$	1.03 (1,14) *.061* $p = .324$	15.00 (1,15) *.500* $p = .002^{**}$
Cognitive Flexibility	*Verbal*	7.41 (1,16) *.031* $p = .015^{*}$	1.12 (1,14) *.243* $p = .011^{*}$	.001 (1,15) *.001* $p = .978$
	Nonverbal	1.06 (1,16) *.062* $p = .519$	2.80 (1,14) *.149* $p = .114$	3.27 (1,15) *.179* $p = .090$

Note. *F* statistic, (degrees of freedom), *effect sizes* and significance level; 1 missing data point for the DCD group; 2 missing data points for the MD group.
$^{*}p \le .05$. $^{**}p \le .01$. $^{***}p \le .001$. $^{\dagger}p \le .06$ non-significant trend.

3.4. Discussion

The current study followed up 7-11 year-olds two years later, investigating EF difficulties in children with a diagnosis of DCD and in children with equivalent motor difficulties (MD group), without a diagnosis. It is the first study of its kind to use a longitudinal approach to explore EFs in a population of children with poor motor skills in middle childhood. In line with predictions, children with MD and DCD showed persistent EF difficulties at both time points, largely associated with nonverbal domains of EF. In particular, children with a diagnosis of DCD performed significantly more poorly than TD children at both time points on *all* nonverbal measures of EF, and also verbal fluency. Children in the MD group, without a DCD diagnosis, also demonstrated poorer performance at Time 1 on nonverbal EF tasks (all nonverbal EF tasks except switching). However, at Time 2 only nonverbal fluency and nonverbal ELWM difficulties persisted in this group.

In accordance with predictions, significant improvements over time across all three groups were detected in many EF tasks: verbal and nonverbal ELWM, fluency and switching; and nonverbal planning. Critically, the interaction between time and group was non-significant across the EF domains. Therefore, no overall differences between groups were identified in the pattern of developmental change in EF over a period of two years.

Each EF domain is discussed separately below to examine these results in detail.

3.4.1. Executive-Loaded Working Memory (ELWM)

Performance in the Listening Recall task (Pickering & Gathercole, 2001), measuring *verbal ELWM*, was not different between groups at any time point. Verbal ELWM also improved significantly in all groups from Time 1 to Time 2. However, on the odd-one-out task (Henry et al., 2012), measuring *nonverbal ELWM*, both the MD and DCD groups performed significantly more poorly than TD children at both time points. Further, the improvement across time on the nonverbal ELWM task was less marked: TD children demonstrated a non-significant trend for improvement, DCD children showed a marginal improvement, and MD children demonstrated no differences between Time 1 and Time 2.

Importantly, the group differences in performance between the MD and TD children, as well as those between DCD and TD children, on *nonverbal ELWM* were evident at both Time 1 and Time 2. These differences in performance are consistent with the findings of the original study (Leonard et al., 2015). Several previous studies (Alloway, 2007, 2011; Alloway & Archibald, 2008) have also identified a visuospatial ELWM deficit, however they additionally detected a verbal ELWM deficit that was not evident in the current study at either time point. Yet, the difficulties reported by Alloway and colleagues in the visuospatial domain seemed to be more significant than the verbal ones, and could better discriminate between children with DCD and children with other clinical diagnoses or control children. Therefore, there is a reasonably consistent picture that nonverbal ELWM difficulties are of particular importance for children with DCD and MD.

Previous research in typically developing populations shows that an improvement in ELWM is to be expected in the age range considered here (Huizinga et al., 2006). Studies have consistently found that WM has a protracted development during childhood into early adolescence in both the verbal and visuospatial domains (Brocki & Bohlin, 2004; Luciana et al., 2005). In fact, in the current study, a significant gain in verbal ELWM performance was identified across all three groups. However, in the nonverbal ELWM task, the gain from Time 1 to Time 2 failed to reach significance for the TD group. This relative lack of progression may be due to a ceiling effect in the Odd-One-Out task, as a proportion of TD children (42%) reached the last stage of the task, where participants need to identify the odd-one-out on 6 sets of abstract figures and then recall their position on a blank grid. These children may have been able to continue on to higher level of performance if the task had allowed it. A further interesting note can be made regarding the Odd-One-Out task. Although participants had to remember the location of shapes, many children adopted a verbal strategy for this visuospatial task. In fact, they memorised the location of the odd-one-out as a word ('right', 'left' or 'middle') and used inner speech to rehearse the correct sequence of words (rather than visually rehearsing the correct sequence of locations). Although children had to process visuospatial information, the storing of that information became a verbal task. It is not surprising that children switched to verbal strategies when possible, considering that after the age of 8 years (participants were 7-11 year old at Time 1 and 9-14 at Time 2) nonverbal stimuli are likely to be manipulated in working memory using a verbal approach (Palmer, 2000) as this is more efficient than a nonverbal one (Fenner, Heathcote, & Jerrams-Smith, 2000). Nevertheless, children with DCD or MD seemed not to be as efficient as TD children, even if using a verbal storing strategy. In fact, although DCD children demonstrated marginal improvements in ELWM, both groups with poor motor skills performed more poorly than TD children at both time points.

3.4.2. Fluency

Regression analyses highlighted that on the *design fluency* task, children with MD and DCD performed significantly more poorly than TD children at both time points. This was consistent with the original cross-sectional analyses (Leonard et al., 2015), and both sets of findings contribute novel results to the literature, as no previous studies have assessed nonverbal fluency in a population of children with poor motor skills. To complete the task, children were required to draw lines between dots, which inevitably involves motor skills. Therefore, lower performance than TD children is to be expected in this task. However, accuracy and quality of drawings did not affect scores. For instance, following the D-KEFS manual guidelines, shaky or wavy lines and most curved lines were accepted and scored as correct, together with unintended inaccuracies that the examinee attempted to self-correct. These procedures ensured that the motor demand of the task was reduced to a minimum. It may be argued that the speed at which children with MD and DCD draw lines between dots was the reason for poorer performance on this timed task (children have to produce as many different designs as possible in one minute). However, there were no differences in the original sample (Bernardi et al., 2016) when comparing performance of MD and DCD children to that of TD children on a motor speed task, in which children have to draw a trail and connect dots over a dashed line. Therefore, children with MD and DCD seemed to have poorer design fluency ability than TD children over and above what might be expected based on their motor skills.

There was no difference between the TD and MD groups in *verbal fluency* performance. Instead, a rather surprising result was that children with DCD performed significantly more poorly than TD children on the verbal fluency task at both Time 1 and 2. This finding is in contrast with results obtained on the original sample (Leonard et al., 2015). There were differences in the composition of the samples, with fewer participants in the current longitudinal study, so that could have affected the findings. One possibility is that language and/or reading abilities had an influence on the verbal fluency performance of children with DCD. This is unlikely to explain results as no differences in such skills were detected at Time 1 between TD and DCD groups. However, since the regression analyses conducted on the original sample included reading skills as a predictor, a further exploratory regression analysis on verbal fluency was conducted on current data at both time points, which included TOWRE reading scores as an additional control variable in Step 1. The regression models were significant at both time points[2]. Importantly, performance in the DCD group remained significantly poorer than that of TD children on the verbal fluency task at both Time 1 and Time 2. These results suggest that group differences in reading cannot fully explain poorer performance in the verbal fluency task in children with DCD, who seemed to demonstrate a domain general deficit on fluency tasks. In contrast, fluency difficulties in the MD group were specific to the nonverbal domain.

Poorer verbal fluency in the DCD group compared to both the MD and TD groups may reflect reduced ability to self-generate subcategories of related items and switch between them once exhausted, as has been suggested for children with specific language impairment (Henry, Messer & Nash, 2015). These authors also reported a significant relationship between inhibition scores and verbal fluency errors. Since inhibition mechanisms may mediate the ability to suppress repeated or irrelevant items in the given semantic category, inaccurate error monitoring may explain poorer performance in children with DCD in this task. In fact, verbal inhibition difficulties (compared to TD children) seemed to be specific to the DCD group – not the MD group – when measuring total time of completion of verbal inhibition tasks in the original sample (Bernardi et al., 2016). Evidence of some verbal inhibition difficulties

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[2] The regression models were significant at Time 1, $F(5, 44) = 6.52$, $p < .001$ (Step 2 Adjusted $R^2 = .36$, $\Delta R^2 =.12$, $p = .017$), and Time 2, $F(5, 45) = 5.36$, $p = .001$(Step 2 Adjusted $R^2 = .30$, $\Delta R^2 =.24$, $p = .001$), and accounted for 43% and 37% of the variance respectively. Significant group differences between DCD and TD were detected at Time 1(B = -12.11, SE B = 4.15, $p = .006$) and Time 2 (B = -23.84, SE B = 5.76, $p < .001$).

in the DCD group emerging from the current study are discussed in the next section on response inhibition.

Finally, a significant improvement in performance on both the verbal and design fluency tasks was identified across all three groups. There was an exception for children with MD, who did not improve on verbal fluency. The result is consistent with previous research providing evidence for a protracted development of both verbal and nonverbal fluency until 12 years of age (Klenberg et al., 2001) or even until early adolescence (Levin et al., 1991; Welsh et al., 1991).

3.4.3. Response Inhibition

The regression analyses for performance on the verbal response inhibition task were non-significant at both time points after Bonferroni correction was applied. However, at Time 2 a non-significant trend was identified in both the final regression model, and the DCD vs. TD group comparison. Although this finding cannot be considered a statistically significant result, it suggests that children with DCD may still be experiencing some degree of difficulty with the inhibition of verbal responses in comparison to their TD peers. The VIMI verbal task is the first response inhibition test without motor demands to be used in a population of children with DCD, hence no previous literature is available to help interpret this result. However, an analysis on the original sample revealed that children with DCD took *longer* to inhibit a verbal response than TD children, despite being as accurate (Bernardi et al., 2016) This suggests that further research may be needed to examine whether children with DCD may be unable to inhibit verbal responses as efficiently as their peers.

The ability to inhibit motor responses was significantly reduced in children with DCD and MD compared to TD children at Time 1. Previous research in children with DCD found no evidence for inhibition deficits in a Go/No-Go task (Piek et al., 2004; Querne et al., 2008). However, in a Simon task, children with DCD demonstrated significant difficulties (Mandich et al., 2002). Demands on the Simon task are closer to those on the VIMI motor test, since both require giving an alternative response that conflicts with a more natural, prepotent response. Therefore, results at Time 1 seem to be consistent with previous research. At Time 2, however, motor inhibition difficulties persisted only in the DCD group, and were no longer evident in the MD group. This result was somewhat unexpected, as no improvement was detected in the MD group between the two measurement points.

The analysis of the total number of errors produced in the VIMI task revealed that no group improved between measurement times in any of the tasks. In a group of children of a similar age range as the current study, Lehto et al. (2003) found no developmental progression in inhibition. The current findings are in line with substantial research suggesting early development of inhibition, which seems to reach adult maturity by 10-11 years of age (Brocki & Bohlin, 2004; Huizinga et al., 2006; Levin et al., 1991; Welsh et al., 1991).

3.4.4. Planning

Children with DCD or MD did not differ from TD children on the number of verbal sorts they identified in the sorting task. None of the groups demonstrated any type of improvement from Time 1 to Time 2 in the number of verbal sorts. It is important to note that the task administered may not be ideal to detect progression in the verbal domain of problem-solving. In fact, the space for improvement was limited by the structure of the task, which allowed 6 possible verbal sorts in total (3 per each card set). On the other hand, there were 10 possible perceptual strategies to sort the cards correctly, which offered a larger window for improvement in nonverbal planning. Yet, TD and MD children did not show any progression across time in the perceptual sorting task either. Instead, the DCD group demonstrated significantly better performance at follow-up. This result was further supported by the regression analysis, which showed a significant group difference (DCD vs. TD) at Time 1 but only a trend towards a group difference at Time 2 (and a non-significant change in R^2 at Step 2, after Group comparisons dummy variables had been entered into the regression model). Differences between the MD and TD groups identified at Time 1 were also not evident at Time 2. Hence, both MD and DCD children seemed to compensate to a certain degree for any difficulties in the ability to identify effective nonverbal features to sort cards into groups.

Furthermore, although research examining planning in children with DCD has reported significant difficulties compared to typically developing children (Asonitou et al., 2012; Wuang et al., 2011), both of these studies used populations of somewhat young children (5 years old and 8-9 years old, respectively). It may be that children with MD or DCD are affected by a delayed maturation of nonverbal planning, but that this EF construct does reach complete maturation eventually.

3.4.5. Cognitive Flexibility

No group differences were identified in verbal cognitive flexibility. The switching cost to complete a trail making task was similar between MD/DCD and TD children. The MD group performed as accurately as the TD children at both time points. However, the DCD group demonstrated poorer performance than TD children at Time 1 and Time 2. These results are consistent with previous research highlighting significant differences in performance on cognitive flexibility tasks between DCD and control children (Piek et al., 2007; Wuang et al., 2011), but non-significant differences when comparing groups with poor motor skills (but no formal diagnosis) and groups with typical motor skills (Michel et al., 2011; Piek et al., 2004).

Although no developmental progression was highlighted for DCD children between the two time points, the TD and MD groups improved significantly. This result may be due to the fact that children with DCD were significantly older than the other two groups. Since evidence suggests cognitive flexibility develops up until 13 years of age (Davidson et al., 2006; Huizinga et al., 2006; Lehto et al., 2003), the TD and MD groups may have had a wider window for developing verbal switching abilities.

3.5. Conclusions

This is the first study assessing a wide range of EFs longitudinally in a population of 7-11 year-old children with poor motor skills, who were followed-up two years later. It represents an important contribution towards a better understanding of the challenges experienced by individuals with poor motor skills, considering the major impact that EF difficulties, and their interaction with motor problems, may have on daily living and academic achievement. The results reflect the complexity of EF and its intricate relationship with motor coordination. In fact, the EF profiles of children in each group were different for separate EF constructs at each time point.

Our hypothesis of linear growth alongside consistently reduced function in the nonverbal domain of EF in children with poor motor skills, was partly verified. As predicted, children with MD and DCD demonstrated some EF deficits at both time points and predominantly in the *nonverbal* domain, while developmental improvements were identified in seven out of ten of the EF constructs. More specifically, in the MD group, nonverbal fluency and nonverbal ELWM deficits persisted after two years, while nonverbal inhibition and nonverbal planning difficulties were no longer evident at the second time point. For children with DCD, the EF profiles did not change across time points, as all nonverbal EFs remained significantly poorer than those for TD children over time. Additionally, children with DCD performed significantly more poorly than TD children in verbal fluency at both time points. However, we did not identify any differences between groups in the rate of developmental change, supporting the hypothesis of linear EF growth for those with and without motor difficulties.

Results suggest that where a gap in EF performance is identified in children with DCD and MD compared to TD children, this tends to persist with development. This finding is consistent with longitudinal studies in younger populations of children with poor motor skills (Michel et al., 2011; Michel et al., 2016), as well as with evidence of stability of individual differences in EFs across development in the typical population (Miyake & Friedman, 2012).

The persistent EF difficulties demonstrated by children with DCD and MD are likely to impact on academic achievement and activities of daily living in addition to their motor impairment. Neither group caught up with their TD peers, yet they did not fall further behind. Nevertheless, EF difficulties may have a growing impact on everyday life and academic achievement given that the executive load of the environment is likely to increase with age while support decreases. For instance, transition to secondary school entails higher academic expectations but reduced guidance. Being a slow and less competent writer, as well as being less able to organise and plan tasks efficiently may have a cumulative negative impact on access to learning and achievement, and therefore on general well-being.

Although the pattern of growth in EF abilities was not different between groups, some of the difficulties encountered by children with MD at Time 1 were not evident at Time 2 (nonverbal inhibition and nonverbal planning). Therefore, it is important to clarify with further longitudinal research whether specific EF domains reach typical levels of ability at a later stage during development, or whether impairments persist into adulthood.

Findings also suggested that children with MD, without a diagnosis, did not show difficulties in as many EF domains as children with DCD (i.e., nonverbal switching and verbal fluency were poorer relative to TD children only for those with DCD, whose scores were also poorer relative to the MD group). These group differences cannot be attributed to an intermediate level of motor skills impairment in the MD group, as they were no different on motor skills to the DCD group. Therefore, somewhat better EFs may represent a protective factor (Johnson, 2012) in children with MD, reducing the risk of meeting the criteria for a clinical diagnosis of DCD. Experiencing EF difficulties might mean that motor impairments are more visible and that children with DCD are, therefore, more likely to achieve referral and diagnosis. It may also be that when motor skills are poor, better EFs play a compensatory role in everyday tasks. For example, when handwriting is difficult and effortful because of poor motor skills, those children with better inhibition will have better ability to stay on task and effectively complete homework than those with poor inhibitory control. Yet, the increasing demands of the environment could mean that EF difficulties, even if not pervasive in children with MD, could become evident later in adolescence and adulthood. In fact, Purcell and colleagues (2016) reported that in a sample of adults, who later were diagnosed with DCD, EF problems were a major area for concern and the most common reason for seeking an assessment.

An important feature of the findings was that children with poor motor skills did worse than TD children largely on nonverbal EF tasks. This suggests that EF difficulties in children with DCD and MD are linked to their core motor and/or visuspatial impairments rather than to more domain general cognitive processing problems. In fact, all nonverbal EF tasks used in the current study had a motor or visuo-spatial demand, which are both documented weaknesses of children with DCD (Wilson et al., 2012). Even though EF difficulties were largely limited to the nonverbal domain, these may nonetheless impact on many activities of daily living as real life circumstances require the ability to master verbal and nonverbal domains of EF simultaneously and adaptably. In order for children with MD and DCD to best demonstrate their capabilities and reach their potential, it may be helpful to reduce the nonverbal executive load of everyday and school-related tasks, and to use verbal information where possible, given their relatively good verbal EF performance.

It is important, however, to consider that, given the heterogeneous cognitive profiles of children with DCD (Sumner, Pratt, & Hill, 2016) it is important to consider individual differences in EF performance. Although children MD and DCD as a group had poorer EF performance than TD children, it will be important to consider in future work whether all individual children in these groups have poor EF. In a study conducted on 23 adults with DCD, although 52.4% reported EF problems, another 23.8% stated EF as being a strength (Kirby et al., 2008). Hence, there may be a subgroup of individuals with DCD/MD who have EF problems and others who do not.

Understanding where individual differences are to be expected or whether specific EF problems are characteristic of DCD will allow the development of more targeted interventions to improve life outcomes for children with motor coordination impairments.

In conclusion, children with poor motor skills, both with and without a DCD diagnosis, demonstrated a range of EF difficulties that persisted across two years. EF problems largely affected nonverbal domains and were less pervasive in children with MD without a diagnosis of DCD. Both the MD and DCD groups showed significant gains in EFs over middle childhood that matched those of the TD group, indicating that EF progression over time was at the level expected.

CHAPTER 4

4. Study 2 – Academic achievement in children with motor difficulties and Developmental Coordination Disorder: the role of executive function

4.1. Introduction

DCD is defined on the basis of a motor coordination impairment that impacts school productivity (APA, 2013). Therefore, academic underachievement may be expected in children with DCD as this is part of their diagnosis. However, as outlined in Chapter 1, very few studies have investigated the specific difficulties encountered in school by children with DCD. No study to date has explored academic performance in children with MD, who despite not having a diagnosis may still experience problems at school as a result of their poor motor skills. The current study addresses this gap in the literature by investigating educational attainment in a range of academic domains in both children with DCD and MD.

Handwriting is a crucial skill for academic success and productivity, and there is convincing evidence reporting that it is specifically affected in individuals with DCD because of the motor coordination demand it entails. Children with DCD are significantly slower than peers when executing a range of handwriting tasks across languages (Chang & Yu, 2010; Prunty et al., 2013; Rosenblum & Livneh-Zirinski, 2008). The quality of production of written text is affected in this group, and poorer performance than typically developing (TD) peers is mostly explained by the reduced amount of text produced and the higher number of misspelled words (Prunty et al., 2016). When spelling ability was measured in isolation – not as part of a broader free writing task – it has been found to be adequate in children with DCD. This finding suggests that when cognitive demands are increased, such as on a written composition task, the cognitive resources available for composition quality may be reduced in DCD (Prunty et al., 2016). The literature has explored this quite comprehensively and is consistent in reporting the handwriting difficulties of children with DCD. Hence, the current study did not focus on handwriting ability.

Studies investigating other aspects of educational attainment have sometimes reported contradictory results. In particular, spelling and reading were found to be problematic in children with DCD in some studies (Dewey et al., 2002; Kadesjo & Gillberg, 1999), but others found appropriate ability in both reading (Cheng et al., 2011) and spelling (Prunty et al., 2016). Some of these differences may be related to the fact that only one of these studies (Prunty et al., 2016) has excluded children with a diagnosis of Dyslexia. The current study addressed this issue by screening all children using a reading measure and excluding those with obvious reading impairments.

Studies assessing literacy and numeracy comprehensively found performance in DCD was below the age-expected level on standardised tasks of achievement (Alloway, 2007; Alloway & Archibald, 2008; Alloway & Temple, 2007). However, these studies did not compare children to a control group. Moreover, the DCD group means ranged between standard scores of 80 to 90 (in tasks with a mean of 100 and a standard deviation of 15) on *both* academic tasks and on tasks measuring intellectual ability. It is not clear from these studies whether numeracy and literacy performance was specifically affected in DCD, or indicative of generally low intellectual functioning. In the current study children were compared to both a TD group and the population norm, and intellectual ability was taken into account in the analyses.

One study based on school reports of 43 children with DCD found that 88% of the group had school failure in mathematics (Vaivre-Douret et al., 2011). Numerical abilities underlying mathematical achievement, such as number fact retrieval and procedural calculation, have been found to be delayed (rather than deficient) in children with DCD compared to their TD peers (Pieters et al., 2012). Other research suggests that children with DCD can perform as accurately as peers when solving simple addition sums, but that they require longer periods of time to do so (Gomez et al., 2015). These studies, however, have focused on numerical abilities only, rather than general achievement in mathematics and other domains. Therefore, it is poorly understood whether academic difficulties extend to all areas of educational attainment. For this reason, the current study included multiple measures of academic skills.

Academic underachievement in children with DCD may be explained by the EF difficulties identified in this group (Study 1; Leonard et al., 2015), considering that EF is a significant predictor of academic outcomes (Best et al., 2011; St Clair-Thompson & Gathercole, 2006). In a group of children with DCD numeracy and literacy scores were found to correlate to working memory performance (Alloway & Archibald, 2008). However, as outlined in Chapter 1, the contribution of EF to academic achievement is not limited to working memory but extends to a wide range of EF domains. The role of different domains of EF, other than working memory, in determining the educational attainment of children with DCD has not been studied to date. The current study included a comprehensive battery of EF assessments in the investigation of academic achievement in children with DCD.

In summary, the study aims to address these gaps in the literature and improve previous research by investigating academic achievement in children with DCD and MD, and by analysing the contribution of EFs to academic outcomes.

Specifically, the following research questions are investigated: RQ1) Do children with MD/DCD perform within expected ranges for academic ability when compared to the population norm? RQ2) Are there group differences in academic achievement between children with MD/DCD and TD children when intellectual ability is taken into account? RQ3) Are there group differences in academic achievement between children with MD/DCD and TD children when EF is additionally taken into account?

Based on the literature reviewed above, it was predicted that children with DCD would demonstrate academic difficulties, both when compared to the population norm and when compared to the TD group, and that these difficulties may be explained by their EF skills. For children with MD it was tentatively predicted that performance would be within the average range when compared to the population norm, as their lack of a diagnosis may suggest they do not have obvious problems with academic achievement. However, it was expected that differences would be identified compared to TD children because of their poor motor skills, and that these differences may be explained by their EF ability.

4.2. Method

As outlined in the Chapter 2, the current study is a follow-up from the original project (Leonard et al., 2015). However, specific participants' background characteristics and procedures are reported below.

4.2.1. Participants

As introduced in the Chapter 2, the sample for Study 2 comprised two subsamples: the same children tested in Study 1, along with newly recruited participants.

For the subsample from Study 1, all details about re-recruitment and background characteristics of participants are reported in Chapter 3. To summarise, the sample was based on children from the original study (Leonard et al., 2015) who were available and continued to meet study criteria. It consisted of a total of 51 children: 17 in the DCD group (11 males; mean age at Time 2: 12.0 years, SD: 1.2 years, range: 10.1 – 14.1); 17 children in the TD group (6 males; mean age at Time 2: 11.3 years, SD: 1.0 years, range: 9.7 – 13.1); and 17 children in the MD group (8 males; mean age at Time 2: 10.5 years, SD: 0.6 years, range: 9.8 – 12.3).

For the newly recruited sample, additional TD and MD participants were recruited through schools (see Chapter 2, Section 2.2.1, for further details). Parents of children who consented to participate received parental questionnaires to complete. Children whose parents had returned the questionnaires were screened on cognitive and motor measures using identical inclusion and exclusion criteria as for the original project (see Chapter 2, Section 2.2.2). A total of 60 children were recruited in this phase: 33 children in the TD group, 27 children in the MD group. These participants were assessed on the experimental EF battery (Time 1). Two years later, 50 of these newly recruited children were reachable and approached for the follow-up phase of the study. A total of 48 children were available for testing at Time 2 (25 in the TD group and 23 in the MD group). On the motor assessment, one child in the TD group scored below the 16th percentile, while eight children in the MD group scored above the 16th percentile. These children no longer met study criteria and were excluded from the sample. Therefore, at follow-up (Time 2), a total of 24 TD children (8 males; mean age at Time 2: 11.1 years, SD: 1.2 years, range: 10.1 – 14.1) and 15 children with MD (10 males; mean age at Time 2: 10.9 years, SD: 1.2 years, range: 10.1 – 14.1) completed the academic achievement assessment. Children recruited in both waves were then collapsed together to form the final sample for the current study (*N*=90). Specifically, there were 41 children in the TD group, 32 children in the MD group and 17 in the DCD group. These careful screening procedures ensured that children in the final sample satisfied inclusion criteria for their group at both time points (i.e. children in the MD group continued to experience motor difficulties across two years, and children in the TD group did not experience any type of motor difficulty at any point). Table 4.1 reports background characteristics for each group at Time 1, together with group comparisons on these measures.

Table 4.1. Means, standard deviations (in parentheses) and ranges of key study variables (age and scores on motor and intellectual ability tasks) in typically-developing children (TD), children screened for motor difficulties (MD) and children with a diagnosis of DCD. One-way ANOVA Welch adjusted *F*-values, degrees of freedom (in parentheses) and effect sizes are reported for age, intellectual ability and motor skills.

Measure	**TD Group** (*n*=41;25 girls)	**MD group** (*n*=32; 14 girls)	**DCD group** (*n*=17; 4 girls)	**ANOVA** *Welch adjusted*
	Mean (SD) *Range*	Mean (SD) *Range*	Mean (SD) *Range*	*F*(df) η_p^2
Chronological Age (Months)	9.09 (.95) *7.5-11.8*	8.65 (.73) *7.6-10.9*	9.91 (1.15) *8.1-11.9*	*8.71* (2,39.78)*** .320
MABC-2 Percentile	58.22 (21.99) *25-95*	4.44 (2.77) *0.5-9*	5.71 (5.74) *0.1-16*	*117.97*(2,35.85)*** .823
BAS3 General Conceptual Ability	106.59 (11.54) *92-138*	97.84 (15.94) *71-125*	98.88 (12.81) *78-119*	*4.46* (2,41.54)* .122

Note. MABC-2 = Movement Assessment Battery for Children; BAS3 = British Abilities Scales. TD > DCD = MD for MABC-2; DCD > TD = MD for age; TD > MD for BAS3.

$^{*}p \leq .05$; $^{**} p \leq .01$; $^{***} p \leq .001$.

As expected, given criteria for inclusion in the three groups, TD children had higher motor ability than the DCD and MD groups (*p*s < .001). However, the groups were not exactly matched on age and IQ. Specifically, children with DCD were significantly older than TD children (*p* = .012) and children with MD (*p* <. 001); TD children obtained significantly higher intellectual ability scores than the MD group (*p* = .027). This may be an issue when investigating group differences and interpreting academic achievement scores, as higher performance can be expected from older children and from children with higher levels of intellectual functioning. Therefore, standard scores were used as the outcome variables for all academic tasks, so that performance was adjusted for age. Furthermore, IQ was included as a predictor in all the analyses conducted when investigating group differences in academic achievement, so that group differences in intellectual ability could be taken into account.

4.2.2. Measures and Procedures

For children with DCD (who all took part in the original study), a one-day 'Time 2' visit was arranged at the university or at their house. For newly recruited children, at Time 1 all children with MD and TD completed the assessments over several sessions in a quiet room at their school. However, at Time 2, some of these children had left primary school and were, therefore, seen at their house or at the university for one session. All other children were tested at Time 2 again at their school over several sessions.

All screening measures, including assessments of motor skills, intellectual ability, language and reading, were administered at both time points. At Time 1, children completed all 10 experimental EF tasks, and at Time 2 their academic achievement was measured. A detailed description of all of these measures is included in Chapter 2 (Section 2.3). However, Table 4.2 also summarises the assessments administered at each time point.

Table 4.2. Description of tasks administered to assess background skills, executive functions and academic achievement.

Phase	Skills measured	Domain	Task	Outcome Variable
Screening: Time 1 & Time 2	Motor Coordination	Manual Dexterity; Aiming & Catching; Balance	MABC-2	Percentile Score
	Intellectual Ability	Nonverbal Reasoning	Matrices (BAS3)	General Conceptual Ability Score
		Verbal Reasoning	Word Definition and Verbal Similarities (BAS3)	
	Language	Expressive	Formulated Sentences (CELF)	Standard Score
		Receptive	Word Classes (CELF)	
	Reading	Word and Nonword Reading	TOWRE	Total Standard Score
EF Assessment: Time 1	Executive-Loaded Working Memory	Verbal	Listening Recall (WMTB-C)	Total correct trials
		Nonverbal	Odd-One-Out (Henry, 2001)	Total correct trials
	Fluency	Verbal	Verbal Fluency (D-KEFS)	Total correct responses
		Nonverbal	Design Fluency (D-KEFS)	Total correct responses
	Inhibition	Verbal	VIMI – verbal	Total errors
		Nonverbal	VIMI – motor	Total errors
	Planning	Verbal	Sorting (D-KEFS)	Total correct verbal sorts
		Nonverbal	Sorting (D-KEFS)	Total correct perceptual sorts
	Switching	Verbal	Trail Making Test (D-KEFS)	Completion time switching cost
		Nonverbal	Intra/Extra Dimensional Shift (CANTAB)	Total errors
Academic Achievement Assessment: Time 2	Literacy	Reading	Word Reading (WIAT-II UK)	Total Standard Score
			Pseudoword Decoding (WIAT-II UK)	Total Standard Score
		Spelling	Spelling WIAT-II UK	Total Standard Score
	Numeracy	Mathematics	Numerical Operations WIAT-II UK	Total Standard Score

4.2.3. Statistical Analysis

Groups were compared on background characteristics (age, intellectual ability, motor skills) using one-way ANOVAs – please refer to Table 4.1 for details - and these variables were controlled where appropriate (see below for details).

The first research question (RQ1 – Do children with MD/DCD perform within expected ranges for academic ability when compared to the population norm?) was addressed by comparing the number of children scoring below the cut-offs of 1SD and 2SDs from the mean to the expected frequencies in each group. For example, the expected number of children scoring less than 1 SD below the mean in the MD group ($n = 32$) on each task was 5, which corresponds to the 16% of the sample. These expected frequencies were compared to the observed frequencies using a one sample chi-square test for each academic achievement task, in each group. The distribution of children scoring below or above -1SD, and below or above -2SD from the mean in each group, was compared to the distribution of the population norm. When the observed frequencies were zero, the test was not performed. Bonferroni corrections were applied to the Pearson χ^2 value ($p \leq .0125$).

The second research question (RQ2 – Are there group differences in academic achievement between children with MD/DCD and TD children when intellectual ability is taken into account?) was explored using multiple regression analyses. A regression model was run to predict scores on each academic task – with standard scores as the outcome variables for all regressions. There was one regression for each of the four academic achievement outcome measures. Using a regression procedure meant that the initial group differences in IQ (reported in Table 4.1) could be taken into account at Step 1 of each regression. Age was not included in the model, despite the fact that the groups also differed on age (see Table 4.1); this was because the standard scores were already adjusted for age in each academic outcome. Two dummy-coded Group variables were entered in Step 2, using TD children as the reference group, so that the two comparisons were TD vs. MD and TD vs. DCD. Bonferroni corrections were applied to final models ($p \leq .0125$).

To account for the contribution of EF to group differences in academic success (RQ3 – Are there group differences in academic achievement between children with MD/DCD and TD children when EF is additionally taken into account?) a series of multiple regressions were again conducted, initially entering IQ at Step 1 and dummy-coded Group variables at Step 2 (as for RQ2). However, in order to test the role of EF, a Step 3 was added to each model, in which a composite score of Verbal EF and a composite score of Nonverbal EF were entered. These composite scores were calculated by transforming the raw scores obtained in the ten EF measures into z-scores. The mean and standard deviation of raw scores of the TD group in each of these tasks were used to calculate the z-scores to ensure that the reference mean and standard deviation could be as close as possible to that of a typical population. The obtained z-scores were then reversed for measures that used number of errors or time as the outcome variables, so that higher z-scores would correspond to better performance across all measures. Z-scores obtained from verbal EF measures were then summed to form a Verbal EF composite score, and the sum of nonverbal EF z-scores constituted the Nonverbal EF composite score. The rationale for creating EF composite scores separately for verbal and nonverbal domains is firstly a result of power constraints. Our sample of 90 participants was not large enough to include all ten EF measures separately. Secondly, verbal and nonverbal EF may contribute differently to reading and numeracy performance (Cragg, Keeble, Richardson, Roome,

& Gilmore, 2017; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013). Third, EF difficulties in children with DCD and MD mostly affect the nonverbal domain (see Leonard et al., 2015, and Chapter 3), and so may explain more variance in academic success in children with DCD/MD than verbal EFs.

4.3. Results

The means (standard deviations) and ranges of scores for each of the academic achievement task are reported in Table 4.3 for the TD, MD and DCD groups.

Table 4.3. Descriptive statistics for each academic achievement measure.

Measure	**TD Group** (*n*=41) M (SD) *Range*	**MD Group** (*n*=32) M (SD) *Range*	**DCD group** (*n*=17) M (SD) *Range*
Word Reading	110.59 (9.35) *90-128*	104.10 (13.51) *73-125*	106.00 (8.70) *88-120*
Pseudoword Reading	106.51 (7.28) *88-117*	101.23 (11.10) *77-117*	102.29 (9.37) *77-112*
Spelling	108.90 (13.60) *79-132*	102.03 (17.18) *73-139*	98.88.15 (15.83) *78-126*
Numerical Operations	122.34 (17.10) *89-151*	109.96 (20.25) *75-158*	88.15 (15.23) *65-114*

Note. TD = typically-developing; MD = motor difficulties; DCD = developmental coordination disorder. For each task the mean (M), standard deviation in parentheses (SD), and *ranges* of scores are reported.

4.3.1. RQ1) Do children with MD/DCD perform within expected ranges for academic ability when compared to the population norm?

Inspection of the descriptive statistics of standard scores for each academic measure ($M = 100$, SD = 15) reported in Table 4.5, illustrates that the group means of children with DCD and MD are close to the population mean of 100 for most academic tasks, except for the numerical operations test in which the DCD group had a much lower group mean of 88. However, the ranges of scores for those in the DCD and MD groups included at least some children with lower levels of performance on some academic tasks.

In the TD group, none of the participants scored at or below -2SD from the mean (SS ≤ 70) in any of the academic tasks. On the spelling task, 5 TD children (12.2% of the TD group) scored at or below -1SD from the mean (SS ≤ 85). On the remaining three tasks, the whole TD group performed above the -1SD from the mean cut-off.

In the MD group, none of the participants scored at or below -2SD from the mean (SS ≤ 70) in any of the academic tasks. On the word reading task, 3 MD children (9.7% of the MD group) scored at or below -1SD from the mean (SS ≤ 85); on the pseudoword reading task, 4 children (12.9% of the MD group) scored at or below -1SD from the mean; on the spelling task, 7 children (22.6% of the MD group) scored at or below -1SD from the mean; and on the numerical operations task, 3 children (9.7% of the MD group) scored at or below -1SD from the mean.

In the DCD group, 3 children (17.6% of the DCD group) scored below -2SD from the mean (SS ≤ 70) on the numerical operations task. No children with DCD, however, scored below this -2SD cut-off on the other academic tasks. On the numerical operations task, a further 6 children scored below -1SD from the mean, which meant that a total of 9 children scored at or below a SS of 85 on this task (52.9% of the DCD group). On the pseudoword reading task, 1 child (5.9% of the DCD group) scored at or below -1SD from the mean; on the spelling task, 6 children (35.3% of the DCD group) scored at or below -1SD from the mean.

These distributions of frequencies were compared to those expected in the population norm and results of one sample chi-square tests for the total number of children who scored below -1SD from the mean in each group are reported in Table 4.4.

Table 4.4. Results for one sample chi-square tests comparing the number of children scoring at or below one SD from the mean to the frequencies in the general population in each academic task. No tests were carried out when frequencies were zero.

Measure	**TD Group** (*N*=41) $n \leq$ -1 SD χ^2 (df)	**MD Group** (*N*=32) $n \leq$ -1 SD χ^2 (df)	**DCD group** (*N*=17) $n \leq$ -1 SD χ^2 (df)
Word Reading	$n = 0$	$n = 3$ 1.05 (1) $p = .307$	$n = 0$
Pseudoword Reading	$n = 0$	$n = 4$ .29 (1) $p = .589$	$n = 1$ 1.29 (1) $p = .255$
Spelling	$n = 5$ .44 (1) $p = .506$	$n = 7$ .82 (1) $p = .365$	$n = 6$ 4.71^{*}(1) $p = .030$
Numerical Operations	$n = 0$	$n = 3$ 1.05 (1) $p = .307$	$\mathbf{n = 9}$ $\mathbf{17.26^{***}}$**(1)** $\mathbf{p < .001}$

Note. TD = typically-developing; MD = motor difficulties; DCD = developmental coordination disorder. For each task the number of children scoring less than 1 SD below the mean ($n \leq$ -1SD) is reported alongside the critical Pearson χ^2 value and the degrees of freedom (in parentheses). Significant Pearson χ^2 values after Bonferroni corrections ($p \leq .0125$) are indicated in boldface; *$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$

The percentages of children scoring at or below -1SD from the mean were not significantly different from those expected in a normal population on any academic tasks for the TD and MD groups. However, children with DCD were significantly more likely than expected to score at or below -1SD from the mean in the numerical operation task, as 52.9% of the children scored at or below a standard score of 85. The number of DCD children scoring below this cut-off in the spelling task became non-significant after Bonferroni correction was applied. Finally, no differences between the DCD group and a normal population were found in either of the reading tasks.

4.3.2. RQ2) Are there group differences in academic achievement between children with MD/DCD and TD children when intellectual ability is taken into account?

The four final regression models for each of the academic achievement measures were significant and details of Step 2 for each of these regression are reported in Table 4.5.

Table 4.5. Summary details of final models and Step 2 of the hierarchical multiple regression analyses predicting academic performance.

			Details of Step 2 for each regression			
Academic Task	*Final Model F(df) Adj. R^2*		*IQ*	*TD Vs. MD*	*TD Vs. DCD*	*ΔR^2 Step 2*
Word Reading	*12.74*(3,85)	β	.51***	-.12	-.05	
	.29***	*Unst.β*	.41	*-2.95*	*-1.45*	.01
	***p*<.001**	*SE*	*(.08)*	*(2.34)*	*(2.34)*	*p=.48*
			p<.001	*p=.22*	*p=.60*	
Pseudoword Reading	*5.70*(3,85)	β	.33**	-.17	-.11	
	.14***	*Unst.β*	.22	*-3.34*	*-2.54*	.03
	***p*=.001**	*SE*	*(.07)*	*(2.16)*	*(2.57)*	*p=.28*
			p=.002	*p=.13*	*p=.32*	
Spelling	*6.05*(3,85)	β	.34***	-.11	-.18	
	.15***	*Unst.β*	.38	*-.3.45*	*-7.07*	.03
	***p*=.001**	*SE*	*(.12)*	*(3.61)*	*(4.29)*	*p=.25*
			p=.001	*p=.34*	*p=.10*	
Numerical Operations	*33.81*(3,85)	β	.48***	-.13	-.51***	
	.53***	*Unst.β*	.74	*-.5.74*	*-28.27*	**.23*****
	***p*<.001**	*SE*	*(.12)*	*(3.72)*	*(4.41)*	***p<.001***
			p<.001	*p=.13*	*p<.001*	

Note. For each regression the final model *F* values, degrees of freedom in parentheses, and adjusted R^2 are presented, along with the change in R^2 in Step 2 of the model. Standardized beta values, *unstandardized coefficients*, and *standard errors* (in parentheses) are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .0125$) are indicated in boldface; *$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$; $^{\dagger}p \leq .06$ non-significant trend.

The final regression model for *word reading* was significant $F(3, 85) = 12.74$, $p<.001$, and accounted for 31% of the variance. IQ was a significant predictor

(p<.001), however no differences between groups at Step 2 were identified on the word reading measure.

The final regression model for *pseudoword reading* was significant $F(3, 85) = 5.70$, p=.001, and accounted for 17% of the variance. IQ was a significant predictor (p=.002), and no differences between groups at Step 2 were identified on the pseudoword reading measure.

The final regression model for *spelling* was significant $F(3, 85) = 6.05$, p=.001, and accounted for 18% of the variance. IQ was a significant predictor (p=.001), however no differences between groups at Step 2 were identified on the spelling measure.

The final regression model for *numerical operations* was significant $F(3, 85) = 33.81$, p<.001, and accounted for 54% of the variance. On entry of the dummy-coded group variables at Step 2, there was a significant change in R-squared (p<.001) confirming that there were group differences on this measure. Inspection of the beta-values showed that that there were no differences between children with MD and TD on the numerical operations measure. However, children with DCD performed significantly below TD children (p<.001). IQ was also a significant predictor (p<.001) of numerical operations.

To summarise, children with MD performed as expected for their age and intellectual ability and were no different to their TD peers on any measure of academic achievement. Children with DCD also performed at the TD group level on reading and spelling measures, however their numeracy scores were significantly lower than those of TD children.

4.3.3. RQ3) Are there group differences in academic achievement between children with MD/DCD and TD children when EF is additionally taken into account?

Descriptive statistics for composite scores for verbal and nonverbal EF tasks in each group are reported in Table 4.6, alongside the raw scores for each EF measure from which the z-scores were calculated.

Table 4.6. Descriptive statistics for each EF measure.

EF Domain	**EF measure**	**TD** (*n*=41) Mean; *SD* (Range)	**MD** (*n*=32) Mean; *SD* (Range)	**DCD** (*n*=17) Mean; *SD* (Range)
Verbal EF Composite Score	Sum of z-scores	-.0001; *3.05* (-7.47 – 7.37)	-2.77; *3.89* (-11.19 – 2.69)	-1.73; *3.29* (-7.53 – 5.75)
Nonverbal EF Composite Score	Sum of z-scores	-.76; *2.92* (-6.35 – 6.08)	-3.24; *3.07* (-7.56 – 2.55)	-3.52; *3.27* (-7.97 – 5.46)
Working Memory *Verbal*	WMTBC Listening Recall *Total Correct*	14.24; *3.05* (8-24)	11.12; *3.86* (6-19)	13.88; *3.14* (10-23)
Working Memory *Nonverbal*	Odd-One-Out *Total Correct*	11.53; *3.20* (6-17)	6.88; *3.44* (3-14)	7.82; *3.19* (4-15)
Fluency *Verbal*	D-KEFS Verbal Fluency *Total Correct*	30.65;*8.08* (15-44)	26.24; *5.98* (16-39)	24.50; *7.79*[a] (3-38)
Fluency *Nonverbal*	D-KEFS Design Fluency *Total Correct*	14.76; *4.25* (7-22)	10.35; *4.44* (1-20)	12.12; *3.71* (5-21)
Response Inhibition *Verbal*	VIMI Verbal *Total Errors*	9.47; *6.50* (0-23)	12.35; *6.65* (5-29)	16.53; *9.96* (4-36)
Response Inhibition *Nonverbal*	VIMI Motor *Total Errors*	28.94; *14.17* (3-51)	43.53; *12.39* (21-61)	48.82; *16.62* (21-74)
Planning *Verbal*	D-KEFS Verbal Sorting *Total Correct*	2.24; *.97* (1-4)	2.00; *1.06* (0-3)	2.65; *1.06* (1-4)
Planning *Nonverbal*	D-KEFS Perceptual Sorting *Total Correct*	7.12; *1.65* (3-9)	4.41; *2.45* (0-7)	4.47; *2.24* (0-8)
Cognitive Flexibility *Verbal*	D-KEFS Trail Making *Switching cost (sec.)*	34.65; *41.16* (-8 – 162)	86.60; *87.09*[b] (-31 – 244)	24.81; *47.75*[c] (-101 – 102)
Cognitive Flexibility *Nonverbal*	CANTAB IEDS *Total Errors*	20.29; *12.90* (8-42)	29.53; *14.92* (8-56)	29.53; *11.59* (8-51)

Note. EF=Executive Function; WMBTC=Working Memory Test Battery for Children; D-KEFS=Delis-Kaplan Executive Function System; VIMI=Verbal Inhibition, Motor Inhibition; CANTAB=Cambridge Neuropsychological Test Automated Battery; IEDS=Intra-/Extra-Dimensional Shift.

[a]1 Missing data point; [b]2 missing data points; [c]1 missing data point.

Three of the four final regression models for the academic achievement measures (including verbal and nonverbal composite EFs as predictors) were significant after Bonferroni corrections (*p*<.0125). Table 4.7 summarises the details of Step 3 for each of these regression analyses. All regressions included IQ (Step 1), dummy-coded Group variables (Step 2), and verbal/nonverbal EF composite scores (Step 3) as predictors.

Table 4.7. Summary details of Step 2 of the hierarchical multiple regression analyses predicting academic performance and including verbal and nonverbal EF skills.

			Details of Step 3 for each regression					
	Final Model F(df) Adj. R^2		*IQ*	*TD Vs. MD*	*TD Vs. DCD*	*Verbal EF*	*Non Verbal EF*	*ΔR^2 Step 3*
Word Reading	*7.38*(5,79)	β	.46***	.01	.03	-.02	.21	
	.28***	*Unst.β*	.35	*.21*	*1.00*	*-.05*	*.64*	.03
	***p*<.001**	*SE*	*(.08)*	*(2.51)*	*(3.01)*	*(.39)*	*(.41)*	*p=.22*
			p<.001	*p=.93*	*p=.74*	*p=.789*	*p=.12*	
Pseudo-word Reading	*2.97*(5,79)	β	.26*	-.06	-.06	.06	.12	
	.11**	*Unst.β*	.17	*-1.18*	*-1.30*	*.16*	*.30*	.02
	p=.017	*SE*	*(.07)*	*(2.41)*	*(2.89)*	*(.34)*	*(.39)*	*p=.43*
			p=.023	*p=.63*	*p=.66*	*p=.64*	*p=.44*	
Spelling	*4.83*(5,79)	β	.27*	.05	-.11	.04	.25	
	.19***	*Unst.β*	.31	*1.76*	*-4.45*	*.19*	*1.10*	.05
	***p*=.001**	*SE*	*(.12)*	*(3.96)*	*(4.75)*	*(.57)*	*(.64)*	*p=.08*
			p=.014	*p=.66*	*p=.35*	*p=.74*	*p=.09*	
Numeri-cal Opera-tions	*24.72*(5,79)	β	.38***	.01	-.45***	.25**	.10	
	.59***	*Unst.β*	.60	*.50*	*-25.74*	*1.53*	*.62*	**.08*****
	***p*<.001**	*SE*	*(.12)*	*(3.93)*	*(4.71)*	*(.56)*	*(.64)*	***p=.001***
			p<.001	*p=.90*	*p<.001*	*p=.008*	*p=.33*	

Note. For each regression the final model *F* values, degrees of freedom in parentheses, and adjusted R^2 are presented, along with the change in R^2 in Step 2 of the model. Standardized beta values, *unstandardized coefficients*, and *standard errors* (in parentheses) are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .0125$) are indicated in boldface.$^{*}p \leq .05$; $^{**}p \leq .01$; $^{***}p \leq .001$; $^{\dagger}p \leq .06$ non-significant trend.

The final regression model for *word reading* was significant *F*(5, 79) = 12.74, *p*<.001, and accounted for 32% of the variance. IQ was a significant predictor (*p*<.001) of word reading performance, however verbal and nonverbal EF were not. No differences between groups were identified on the word reading measure.

The final regression model for *pseudoword reading* became marginally significant after applying Bonferroni correction $F(5, 79) = 2.97$, $p=.017$, and accounted for 16% of the variance. IQ was a significant predictor ($p=.023$) of pseudoword reading performance, however verbal and nonverbal EF were not. No differences between groups were identified on the pseudoword reading measure.

The final regression model for *spelling* was significant $F(5, 79) = 6.05$, $p=.001$, and accounted for 23% of the variance. IQ was a significant predictor ($p=.014$) of spelling performance, however verbal and nonverbal EF were not. No differences between groups were identified on the spelling measure.

The final regression model for *numerical operations* was significant $F(5, 79) = 24.72$, $p<.001$, and accounted for 61% of the variance. Inspection of the beta-values indicated that IQ was a significant predictor ($p<.001$) of numerical operations performance. In terms of the EF composite variables, verbal EF was a significant predictor ($p=.008$), while nonverbal EF was not. No group differences were identified between the MD and TD groups, whereas children with DCD continued to perform significantly below their TD peers ($p<.001$). This indicated that children with DCD obtained lower scores on numerical operations even after EF was taken into account.

To summarise, verbal and nonverbal EF did not contribute to three of the academic outcome measures (reading, pseudoword reading, spelling), but performance on numerical operations was significantly predicted by *verbal* EF. Importantly, including EF skills in the model did not remove the group differences in performance on numerical operations – children with DCD continued to perform significantly more poorly than TD children on this task after EF skills were taken into account.

4.4. Discussion

The current study investigated academic achievement in children with DCD and MD, taking into account their IQ and EF skills. It is the first study of its kind to assess a range of academic outcomes in children with poor motor skills, whilst taking into account a comprehensive range of verbal and nonverbal EF abilities.

Children in the MD and DCD groups both demonstrated similar performance compared to their TD peers on the reading and spelling tasks. However, on the numerical operations task, although children with MD performed as accurately as their TD peers, children with DCD obtained significantly lower scores than TD children. The significant difference between the TD and DCD groups in mathematics was still evident after the contributions of intellectual and EF abilities were taken into account, indicating that this is a robust difference that cannot be readily explained by differences in other key cognitive abilities. Although not all children with DCD had difficulties in the numerical operations task, a significantly higher number of children than expected based on population norms demonstrated low numeracy skills. Specifically, more than 50% of DCD children scored less than 1SD below the mean on the numerical operations task. This degree of poor performance was not evident in the MD group, suggesting that there are differences in mathematics performance between those with MD and DCD.

Therefore, as expected based on the DCD diagnostic criteria, a certain degree of impact on academic achievement was evident in the DCD group. However, this seemed not to extend to all areas of attainment; nor did it affect all children in this group. These issues will be discussed further below.

4.4.1. Literacy abilities

An important result that emerged from the present study was that children with motor coordination difficulties, with or without a DCD diagnosis, did not demonstrate any difficulties in reading or spelling tasks. This is inconsistent with some of the previous findings identifying low achievement scores in these areas among samples of children with DCD (Alloway, 2007; Alloway & Temple 2007). In these previous studies, however, the mean IQ levels for the DCD groups were below average and were not considered when interpreting results. This could explain the contrast between the current findings and previous research. In particular, the DCD sample in the current study had average IQ levels that did not differ from the TD group. The differences in intellectual ability that were evident (between the TD and MD groups) were, further, taken into account in the analyses by always including IQ as a predictor of academic outcome.

Reading and spelling difficulties have also been identified previously in children with DCD in studies that have included a matched group design with TD comparison children (Dewey et al., 2002; Kadesjo & Gillberg, 1999). However, these studies did not explicitly exclude children with dyslexia, which often co-occurs with DCD. In the current study we screened and excluded children with extremely low reading scores (2SD or more below the mean), which may be indicative of a co-occurring conditions such as dyslexia. This allowed us to isolate academic difficulties that were specifically associated with DCD or with motor difficulties more generally, without the confounding factor of additional reading deficits. Results, therefore, point to a particular academic profile in children with DCD (but not those with MD) that is characterised by appropriate reading and spelling abilities, but impaired numeracy skills.

4.4.2. Numeracy abilities

The current results point to a specific deficit in the ability of children with DCD (but not children with MD) to solve numerical operations. This finding supports existing evidence in the literature suggesting the presence of numeracy difficulties across different mathematical tasks in children with DCD (Gomez et al., 2015; Pieters et al., 2012). In 17.6% of the cases here (*n*=3), scores were below -2SD from the mean, indicating a significant impairment in the ability to solve numerical operations. Further, an additional 35.3% of DCD participants (*n*=6) scored between -1SD and -2SD from the mean. Considering the impact of EF skills on mathematical outcomes (St Clair-Thompson & Gathercole, 2006), and the EF difficulties experienced by children with DCD (Leonard et al., 2015), it was expected that lower EF skills in the DCD group could partly explain academic underachievement in mathematics. In fact, verbal EF did predict performance in the numerical operations task. However, nonverbal EF did not contribute to academic performance in any of the tasks. This was a somewhat surprising result considering the role that visuospatial (not verbal) working memory seems to play in determining academic performance in typical populations (Andersson & Östergren, 2012; McLean & Hitch, 1999; Szűcs, Devine, Soltesz, Nobes, & Gabriel, 2014) and in children with DCD (Alloway, 2007). In future research, each of the five EF areas could be explored separately in order to identify their specific contributions to academic performance in both the verbal and nonverbal domains. This was not possible in the current study, given the limited sample size of 90 participants, for which a maximum of six predictors is recommended in regression analysis. Future studies could, therefore, address the issue of the specificity of EF constructs in influencing educational attainment with larger sample sizes.

Nevertheless, EF should not be considered the only possible underlying mechanism to be addressed in research on academic achievement in children with DCD. The current results show that group differences in numerical operations were still significant after EF abilities were taken into account, suggesting that other cognitive mechanisms could be responsible for underachievement in mathematics (although not IQ as this was also controlled in the analyses). One possibility, for example, relates to the number line task, which is considered an indicator of the development of numerical abilities (Opfer & Siegler, 2007). Gomez and colleagues (2016) reported less accurate and slower numerical estimation in children with DCD. Yet, the mechanisms underlying poorer performance on this task seemed different from those apparent in children with mathematical learning difficulties. These children are less efficient in the understanding of the linear mathematical system. By contrast, children with DCD were able to map the numbers linearly, so the authors suggested that their inaccuracy in the number line task may have been linked to a deficit in visuospatial abilities.

In fact, Alloway (2007) reported that visuospatial short-term memory (as well as visuospatial working memory) was impaired in children with DCD, and was related to performance in numeracy tasks. The current study did not assess short-term memory in any domain, so this remains an area that future research could investigate. If inefficient numerical skills in individuals with DCD contribute to mathematical difficulties, possible remediation strategies such as working memory training may be effective in raising performance levels (e.g., Holmes, Gathercole, & Dunning, 2009).

It is important to note that some children with DCD performed within the average range in the numerical operations task, and, therefore, presented no evidence of academic underachievement. This does not exclude the possible impact that DCD may still have on overall academic productivity, given that the tasks in this study were standardised and laboratory based. It does, however, suggest that when other barriers are bypassed (e.g., handwriting), children with DCD may be able to express their potential, given that the objective academic skills of these children can be appropriate for age and IQ level.

If the numeracy difficulties experienced by children with DCD were directly linked to their motor coordination impairment, we would expect all children with poor motor skills (with or without a diagnosis) to perform below the expected level. Since this was not the case, and children with MD had appropriate levels of academic skills in all areas, other causal relationships need to be explored in explaining the interplay between motor coordination and numeracy skills. In other words, motor difficulties may not directly impact on academic achievement. Some other mediating variable/s may play a role, or children with MD may have some kind of protective factor that prevents motor difficulties from affecting mathematics achievement. In this context, it is interesting to note that the fact that MD children did not demonstrate any academic impairments may be the reason why they have not been flagged up by teachers and parents and their motor difficulties remained undiagnosed.

4.5. Conclusions

In this study a comprehensive assessment of academic achievement in children with typical and atypical motor development revealed that children with DCD have specific difficulties with mathematical tasks, while performing appropriately for their age and

IQ levels on tasks of reading and spelling. Children with MD, without a diagnosis, did not demonstrate any problem with school attainment thus indicating poor motor skills are not necessarily associated with academic difficulties. Verbal EFs were found to be a significant predictor of mathematics, while nonverbal EF was a non-significant predictor in all academic tasks. Despite the contribution of verbal EF to mathematical performance, poorer performance on the numerical operations task was still evident in children with DCD compared to TD children after both verbal and nonverbal EF were taken into account.

CHAPTER 5

5. Study 3 – An exploratory analysis of the role of motor coordination in the relationship between executive function and language abilities.

5.1. Introduction

Chapter 1 has outlined evidence indicating that movement plays a crucial role in development of early language skills (Iverson, 2010) and it is closely coupled to the development of executive function (Diamond, 2000). In turn, executive function (EF) is an area of cognition that has received particular attention for its contribution to the development of language skills (Kuhn et al., 2014), and vice versa for its dependence on language skills (Petersen et al., 2015). However, the relationship between EF and language is still a largely unresolved matter. Given the consistent evidence of EF difficulties in children with language impairments (e.g., Henry et al., 2012) , Bishop and colleagues (Bishop et al., 2014) have recently suggested three possible pathways towards the understanding of this relationship: 1) an EF deficit leads to language impairments; 2) language drives EF outcomes; 3) a third factor is implicated in determining both EF and language. A recent longitudinal study investigating the first two potential pathways has found little evidence for either of the models (Gooch et al., 2016). Given the strong concurrent relationship identified in young children in their study, authors concluded that a third unmeasured factor could contribute to both EF and language (supporting the third suggested pathway).

As discussed in Chapter 1, there is some evidence to support the hypothesis that this third factor may be motor coordination, considering the reciprocal links between movement and both language and cognition. Specifically, early motor skills can predict later cognitive outcomes in typically developing children (Campos et al., 2000; Piek, Dawson, Smith, & Gasson, 2008). Similarly, in atypical development, general movements and spontaneous motor activity (Prechtl et al., 1997) in early postnatal life, as well as sucking ability, predict later neurodevelopmental impairments (Groen et al., 2005; Mizuno & Ueda, 2005). Overlapping brain systems underlie both executive and motor functions (Diamond, 2000), and often when cognitive development is perturbed, motor development is affected too, and vice versa. It is reported that up to 70% of children with Developmental Language Disorder (DLD) demonstrate overlapping motor difficulties (Hill, 2001; Scabar, Devescovi, Blason, Bravar, & Carrozzi, 2006; Wisdom, Dyck, Piek, Hay, & Hallmayer, 2007). Similarly, children with motor coordination impairments, both with a diagnosis of DCD and with motor difficulties (MD) but no diagnosis, demonstrated poor EF skills (Study 1, Leonard et al., 2015; Wilson et al., 2017). Thus, motor coordination is a factor that, interacting with both cognitive and language development, may contribute to explain how EF impacts language ability or, vice versa, how language impacts EF (see Chapter 1, Section 1.3.6 for a review). This hypothesis has not been tested yet in previous research and will be explored in the current study.

An important aspect to take into account when exploring the relationship between EF and language is that EF may be a confounding factor in language tasks and vice versa (Bishop et al., 2014). Language measures that rely on EF or, similarly, EF measures that require comprehension and use of language, may amplify a relationship that is weaker developmentally than it appears in certain tasks. In order to mitigate against this, the language measures selected for the current study relied the least possible on EF skills, while EF measures were separated between those that required processing verbal information and those that did not.

The aim of Study 3 is to explore the role of motor coordination as a moderator of the relationship between EF and language. The hypotheses are constructed on the basis of the interaction between EF and motor skills, as discussed throughout this thesis.

The first and second research questions (RQ1 and RQ2) investigate whether the relationship between EF and language is different across groups of TD, MD and DCD children when EF is the predictor (RQ1), and also when language is the predictor (RQ2). The investigation of the direction of this relationship is exploratory, given previous inconclusive research (e.g., Gooch et al., 2016). However, it is expected that group will be a significant moderator, as it is predicted that the relationship between EF and language will differ for children with DCD and MD, who have EF difficulties (Leonard et al., 2015; see also Study 1), compared to those with typical motor skills (TD group).

In order to examine whether differences in the association of EF and language occur because of diagnostic groupings (MD, DCD and TD) or because of levels of motor skills, two further research questions were put forward, using motor skills as a continuum: RQ3) investigated whether motor coordination moderates the effect of EF on language; RQ4) investigated whether motor coordination moderates the effect of language on EF. These questions are exploratory given the novelty of this research. However, considering the links between motor coordination and EF, which are the focus of this thesis, it may be expected that the interaction between EF and motor coordination will significantly predict language outcomes.

5.2. Method

5.2.1. Participants

Children included in this study were recruited following the procedures outlined in Chapter 2 (Section 2.2). For this study, cross-sectional data collected at Time 1 as part of both the original project (Leonard et al., 2015) and the current project were included. To summarise, for the original wave of recruitment, 91 children (50 males; mean age: 9.51 years, SD: 1.12 years, range: 7.3 – 11.9) satisfied the inclusion and exclusion criteria (See Chapter 2, Section 2.2.2), while the additional wave of recruitment resulted in 60 children (26 males; mean age: 9.10 years, SD: 0.93 years, range: 7.6 – 11.8). A total of 151 children were included in the final sample for this study (76 males; mean age: 9.35 years, SD: 1.06 years, range: 7.3 – 11.9).

As described in Chapter 2, children were divided into three groups depending on whether they demonstrated typical motor skills – typically developing (TD) group (MABC-2 scores at or above the 25th percentile), atypical motor ability (motor difficulties (MD) group, MABC-2 scores at or below the 16th percentile), or a clinical diagnosis of DCD (DCD group, MABC-2 scores at or below the 16th percentile). The current study did not only compare groups but, in some of the analyses, used the complete sample and included motor coordination skills as a continuous variable (MABC-2 total sum of standard scores, see Chapter 2, Section 2.3.2.1). Therefore, the mean, SD and ranges of scores for age and background characteristics are reported in Table 5.1 for each group as well as for the whole sample. When using all participants as one sample, children with poor motor skills (with and without a DCD diagnosis) were oversampled compared to a typical population. This disproportion is reflected on the average percentile score, which falls on the 27th percentile, rather than the 50th percentile as it would be expected in a typical population. However, this allowed a more feasible exploration of group differences.

Table 5.1. Means, standard deviations (in parentheses) and ranges of age and scores on motor and intellectual ability tasks in typically-developing children (TD), children screened positive for motor difficulties (MD) and children with a diagnosis of Developmental Coordination Disorder (DCD), as well as for the whole sample (TD+MD+DCD).

Measure	**TD Group** (*n*=71; 43 girls)	**MD group** (*n*=57; 25 girls)	**DCD group** (*n*=23; 7 girls)	**TD+MD+DCD** (*n*=151; 75 girls)
	Mean (SD) *Range*	Mean (SD) *Range*	Mean (SD) *Range*	Mean (SD) *Range*
Chronological Age (Years)	9.42 (1.02) *7.5-11.8*	8.99 (.96) *7.3-11.4*	10.01 (1.11) *8.1-11.9*	9.35 (1.06) *7.3-11.9*
MABC-2 Percentile	53.38 (22.35) *25-95*	5.20 (3.29) *0.5-16*	5.35 (5.69) *0.1-16*	27.89 (28.69) *0.1-99*
BAS3 GCA	104.69 (12.35) *78-138*	98.26 (15.55) *71-138*	101.35 (19.55) *71-151*	101.76 (15.04) *71-151*

Note. MABC-2 = Movement Assessment Battery for Children; BAS3 = British Abilities Scales; GCA = General Conceptual Ability score.

5.2.2. Measures

Tests used for the assessment of language, motor skills and executive functioning are described fully in Chapter 2 and are identical to those administered for Study 1 and Study 2. They are briefly outlined below.

Language was measured using two subtests of the CELF-4-UK: Formulated Sentences subtest for expressive language and the Word Classes subtest for receptive language. The standard scores for each subtest were used as the language variables in the analyses.

Executive functioning was examined using the EF battery described in Chapter 2. The same procedure as Study 2 was applied to obtain a composite score of verbal

EF and nonverbal EF. To summarise this procedure, z-scores were calculated from each of the EF raw scores based on the TD group mean and SD. Verbal/nonverbal EF z-scores were summed into the verbal EF composite score and nonverbal EF composite score respectively, which were used as the two EF variables in the subsequent analysis. Missing values in isolated EF tasks (*n*=4 in total) were substituted with the group median before calculating the EF composite score, so that all participants could be included (e.g., one missing value for a participant in the DCD group in the verbal fluency task was substituted with the DCD group median for verbal fluency before calculating the sum of verbal EF scores).

Motor skills were assessed with the MABC-2, which is divided into different sections and subtests: three Manual Dexterity subtests; two Aiming and Catching subtests; and three Balance subtests. The standard score for each of these eight subtests (population mean=10, SD=3) was summed to obtain a total standard score, which was used as the moderating variable in the analyses for RQ3 and RQ4. According to the MABC-2 manual, total standard scores can be converted into percentile scores (e.g., scores between 63 to 67 correspond to the 16th percentile; see Appendix E for a full conversion table). The total standard score was preferred to percentile scores for analysis so that the variability across individuals could be fully captured rather than reduced to percentile ranks.

5.2.3. Statistical Analysis

For all four research questions, moderation models were tested. Expressive Language and Receptive Language were used as two separate language variables, and similarly, Verbal EF and Nonverbal EF were used as two separate EF variables.

For RQ1 and RQ2, investigating whether the relationship between EF and language differed between groups, two sets of four separate regression analyses were conducted. For RQ1, Language (Expressive or Receptive) was the outcome variable, while the predictors included: EF (Verbal *or* Nonverbal); dummy coded Group variables (TD vs. MD *and* TD vs. DCD); interaction terms (Verbal/Nonverbal EF x TD vs. MD and Verbal/Nonverbal EF x TD vs. DCD). For RQ2, an identical procedure was followed: EF (Verbal or Nonverbal) were the outcome variables, while predictors in each regression included: Language (Expressive *or* Receptive), dummy coded Group variables (TD vs. MD *and* TD vs. DCD); interaction terms (Expressive/Receptive Language x TD vs. MD and Expressive/Receptive Language x TD vs. DCD).

For RQ3 and RQ4, investigating the moderation effect of motor skills (as a continuous variable) on the relationship between EF and language, moderation analyses were performed using the Process macro for SPSS (Hayes, 2013). Moderation models explored the interaction effect of EF x motor skills on language outcomes (RQ3), and the reverse – the interaction effect of language x motor skills on EF outcomes (RQ4). Motor Skills were used as the moderating variable in both. For each research question, four different regression models were conducted, which included either Verbal or Nonverbal EF as predictors (RQ3) or outcomes (RQ4), and either Receptive or Expressive Language as outcomes (RQ3) or predictors (RQ4). Each regression model included as predictors both Motor Skills and the interaction term (Motor Skills x EF (RQ3) or Motor Skills x Language (RQ4)). Therefore, a total of four moderation models were run for RQ3: 1) Verbal EF predicting Expressive Language; 2) Nonverbal EF predicting Expressive Language 3) Verbal EF predicting Receptive Language; 4) Nonverbal EF predicting Receptive Language. A total of four moderation models were run for RQ4: 1) Expressive Language predicting Verbal EF; 2) Expressive Language predicting Nonverbal EF 3) Verbal EF predicting Receptive Language; 4) Nonverbal EF predicting Receptive Language. Bonferroni corrections were applied to all final regression models ($p \leq .0125$). Predictor variables were centred around the mean before running each regression model.

When an interaction was found to be significant, the effects of the moderation were investigated in each model using slope analysis, by considering the relationship between EF and language at different levels of motor skills (Field, 2013). This method examines predicted outcome values when motor skills are at one SD below the sample mean, at the sample average levels of motor skills, and at one SD above the sample mean (Aiken & West, 1991). It is important to note that this method interprets interaction effects by examining predicted outcomes at a given value of the moderator (using the regression line), rather than exploring observed outcomes at a range of values of the moderator. Therefore, in order to construct simple scatter plots with observed values, the cut-offs of one SD below or above the mean were used in the current sample. Low levels of motor skills corresponded to values at or below -1SD from the sample mean, average levels of motor skills were represented by values between -1SD and +1SD from the sample mean, high levels of motor skills corresponded to values at or above +1SD from the mean.

5.3. Results

The means, standard deviations and ranges of scores for EF, language and motor abilities that are relevant to subsequent regression analyses are reported in Table 5.2. The table includes raw scores for each EF domain, from which composite EF scores were calculated and included in the analyses.

Table 5.2. Means, standard deviations and ranges (in parentheses) of executive function (EF) and language abilities in typically-developing children (TD), children screened for motor difficulties (MD) and children with a diagnosis of Developmental Coordination Disorder (DCD), as well as for the whole sample (TD+MD+DCD).

Domain	**Measure**	**TD+MD +DCD** (*n*=151)	**TD** (*n*=71)	**MD** (*n*=57)	**DCD** (*n*=23)
		Mean; *SD* (Range)	Mean; *SD* (Range)	Mean; *SD* (Range)	Mean; *SD* (Range)
Working Memory *Verbal*	WMTBC *Total Correct*	13.82; *3.05* (6 – 24)	14.24; *3.05* (8 – 24)	11.12; *3.86* (6 – 19)	13.88; *3.14* (10 – 23)
Working Memory *Nonverbal*	Odd-One-Out *Total Correct*	8.66; *3.73* (1 – 17)	11.53; *3.20* (6 – 17)	6.88; *3.44* (1 – 14)	7.82; *3.19* (1 – 15)
Fluency *Verbal*	D-KEFS Verbal Fluency *Total Correct*	29.47; *8.09* (3 – 53)	30.65; *8.08* (15 – 53)	26.24; *5.98* (16 – 39)	24.50; *7.79*^{a} (3 – 38)
Fluency *Nonverbal*	D-KEFS DesignFluency *Total Correct*	13.82; *4.31* (1 – 27)	14.76; *4.25* (7 – 27)	10.35; *4.44* (1 – 20)	12.12; *3.71* (5 – 21)
Inhibition *Verbal*	VIMI Verbal *Total Errors*	12.31; *7.41* (0 – 38)	9.47; *6.50* (0 – 23)	12.35; *6.65* (5 – 29)	16.53; *9.96* (4 – 38)
Inhibition *Nonverbal*	VIMI Motor *Total Errors*	40.23; *14.87* (3 – 74)	28.94; *14.17* (3 – 51)	43.53; *12.39* (21 – 61)	48.82; *16.62* (21 – 74)
Planning *Verbal*	D-KEFS Verbal Sorts *Total Correct*	2.41; *1.08* (0 – 5)	2.24; *.97* (1 – 5)	2.00; *1.06* (0 – 3)	2.65; *1.06* (1 – 4)
Planning *Nonverbal*	D-KEFS PerceptualSorts *Total Correct*	5.38; *2.22* (0 – 10)	7.12; *1.65* (3 – 10)	4.41; *2.45* (0 – 7)	4.47; *2.24* (0 – 8)
Switching *Verbal*	D-KEFS Trail Making	42.73; *56.85* (-101 – 244)	34.65; *41.16* (-8 – 162)	86.60; *87.09*^{b} (-31 – 244)	24.81; *47.75*^{c} (-101 – 102)
Switching *Nonverbal*	CANTAB IEDS *Total Errors*	27.25; *11.99* (8 – 57)	20.29; *12.90* (8 – 42)	29.53; *14.92* (8 – 57)	29.53; *11.59* (8 – 51)
EF *Verbal*	*Sum of z-scores*	-1.10; *3.59* (-12.06 – 8.09)	-.0001; *3.05* (-7.47 – 8.09)	-2.77; *3.89* (-12.06 – 2.69)	-1.73; *3.29* (-7.53 – 5.75)
EF *Nonverbal*	*Sum of z-scores*	-.76; *2.92* (-9.82 – 8.10)	-.76; *2.92* (-6.35 – 6.08)	-3.24; *3.07* (-7.56 – 2.55)	-3.52; *3.27* (-7.97 – 5.46)
Language *Expressive*	CELF-4-UK *Standard Score*	10.34; *2.87* (1 – 17)	10.72; *2.41*) (4 – 16)	10.03; *3.18* (1 – 17)	10.03; *3.18* (3 – 17)

Language	CELF-4-UK	11.25; *2.96*	11.68; *2.52*	10.88; *3.26*	10.72; *2.41*
Receptive	*Standard Score*	(3 – 19)	(6 – 19)	(3 – 18)	(4 – 16)
Motor Skills	MABC-2 Sum Standard Scores	64.93; 17.06	80.48; 8.36	52.07; 7.43	48.78; 11.80
		(27 – 103)	(68 – 103)	(32 – 67)	(27 – 67)

Note. WMBTC=Working Memory Test Battery for Children; D-KEFS=Delis-Kaplan Executive Function System; VIMI=Verbal Inhibition, Motor Inhibition; CANTAB=Cambridge Neuropsychological Test Automated Battery; IEDS=Intra-/Extra-Dimensional Shift; MABC-2 = Movement Assessment Battery for Children 2nd Edition; Clinical Evaluation of Language Fundamentals 4th Edition.

[a]1 Missing data point; [b]2 missing data points; [c]1 missing data point

RQ1 and RQ2 considered motor skills categorically using original groupings, and will be labelled 'Group Data' in the next section. RQ3 and RQ4 considered motor skills as a continuum and will be labelled 'Continuous Data' in the next section.

5.3.1. Group Data: motor skills are considered categorically using original groupings

5.3.1.1. RQ1) Is the effect of EF on language different across TD, MD and DCD groups?

The details of the regression analyses on language outcomes are reported in Table 5.3. Two of the four models were significant (*p*s ≤ .002). Nonverbal EF significantly predicted receptive language (*p*=.001), although EF did not predict language in the other models. The dummy-coded Group variables (TD vs. MD and TD vs. DCD) did not predict any language outcome and neither did any of the interaction terms. These findings indicate that the relationship between EF and language did not differ between TD children and children with DCD or MD.

Table 5.3. Summary details of regression analyses testing how the relationship between EF and language differs in TD children compared to children with MD and DCD, specifically how EF variables interact with Group variables in predicting language outcomes.

Outcome	**Expressive Language**		**Receptive Language**	
Predictor	***Verbal EF Model***	***Nonverbal EF Model***	***Verbal EF Model***	***Nonverbal EF Model***
Final Model				
F(df)	*4.15*(3,147)	*1.81*(3,147)	*2.63*(3,147)	*4.56*(3,147)
Adj. R^2	**10.****	02.	.05*	**11.*****
	p=.002	*p*=.116	*p*=.026	*p*=.001
EF				
β	.186	.096	.020	.322**
SE	*.116*	*.116*	*.120*	*.114*
	p=.111	*p*=.407	*p*=.866	*p*=.005
TD vs. MD				
β	.157	-.040	-.543	.207
SE	*.519*	*.589*	*.547*	*.578*
	p=.763	*p*=.946	*p*=.323	*p*=.722
TD vs. DCD				
β	-.518	-.320	.014	.766
SE	*.687*	*.779*	*.726*	*.767*
	p=.452	*p*=.682	*p*=.984	*p*=.320
TD vs. MD * EF				
β	.113	.106	.215	-.014
SE	*.148*	*.167*	*.155*	*.166*
	p=.445	*p*=.529	*p*=.167	*p*=.934
TD vs. DCD * EF				
β	.217	.209	.343	.063
SE	*.204*	*.213*	*.215*	*.210*
	p=.291	*p*=.327	*p*=.113	*p*=.766

Note. For each regression the final model *F* values, degrees of freedom in parentheses, and adjusted R^2 are presented. Unstandardized beta values, and *standard errors* are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .0125$) are indicated in boldface.

*$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$; $^{\dagger} p \leq .06$ non-significant trend.

5.3.1.2. RQ2) Is the effect of language on EF different across TD, MD and DCD groups?

Results for each of the regression analyses exploring the effect of language on EF in typically developing children and in children with MD and DCD are reported in Table 5.4.

Table 5.4. Summary details of regression analyses testing how the relationship between language and EF differs in TD children compared to children with MD and DCD, specifically how Language variables interact with Group variables in predicting EF outcomes.

Outcome	**Verbal EF**		**Nonverbal EF**	
Predictor	***Expressive Language***	***Receptive Language***	***Expressive Language***	***Receptive Language***
Final Model				
F(df)	*7.06*(3,147)	*5.31*(3,147)	*11.12*(3,147)	*15.34*(3,147)
Adj. R^2	**18.*****	**13.*****	**26.*****	**32.*****
	p<.001	*p*<.001	*p*<.001	*p*<.001
Language				
β	.262	.026	.150	.431**
SE	*.167*	*.158*	*.157*	*.138*
	p=.118	*p*=.871	*p*=.341	*p*=.002
TD vs. MD				
β	-3.965	-6.490**	-3.703	-2.068
SE	*2.326*	*2.523*	*2.159*	*2.181*
	p=.091	*p*=.011	*p*=.089	*p*=.345
TD vs. DCD				
β	-5.353	-4.887	-6.583*	-1.882
SE	*3.293*	*3.065*	*2.979*	*2.513*
	p=.106	*p*=.113	*p*=.029	*p*=.455
TD vs. MD * Language				
β	.170	.378	.024	-.103
SE	*.213*	*.217*	*.199*	*.188*
	p=.425	*p*=.084	*p*=.904	*p*=.585
TD vs. DCD * Language				
β	.434	.304	.326	-.135
SE	*.315*	*.254*	*.288*	*.212*
	p=.170	*p*=.233	*p*=.260	*p*=.527

Note. For each regression the final model *F* values, degrees of freedom in parentheses, and R^2 are presented. Unstandardized beta values, and *standard errors* are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .0125$) are indicated in boldface.

*$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$; $^{\dagger}p \leq .06$ non-significant trend.

All final models were highly significant (*p*s<.001). Receptive Language significantly predicted Nonverbal EF (*p*=.002) but language did not predict EF in any other model. The dummy-coded Group variable comparing the TD and MD groups was a significant predictor of Verbal EF performance (*p*=.011), while the TD and DCD group comparison was a significant predictor of Nonverbal EF (*p*=.029). The interaction terms between Language and dummy-coded Group variables were non-significant across all models, indicating that no group differences could be identified in the relationship between language and EF.

5.3.2. Continuous Data: motor skills are considered as a continuum using standard scores

5.3.2.1. RQ3) Does motor coordination moderate the effect of EF on language?

Results for the first third question (RQ3), exploring the interaction between EF and motor skills in predicting language ability, are reported in Table 5.5.

Table 5.5. Summary details of regression analyses testing the moderation effect of motor skills on the relationship between EF and language, and specifically the effect of EF, Motor Skills and their interaction (EF x Motor Skills) in predicting language outcomes.

Outcome	**Expressive Language**		**Receptive Language**	
Predictor	***Verbal EF Model 1***	***Nonverbal EF Model 2***	***Verbal EF Model 3***	***Nonverbal EF Model 4***
Final Model				
F(df)	*4.67*(3,147)	*3.75*(3,147)	*4.85*(3,147)	*7.63*(3,147)
R^2	**.16****	**.11***	**.09****	**.15*****
	p=.004	*p*=.012	*p*=.003	*p*<.001
EF				
β	.218**	.161*	.134†	.302***
SE	*.068*	*.071*	*.068*	*.081*
	p=.002	*p*=.025	*p*=.053	*p*<.001
Motor Skills				
β	.008	.017	.017	.002
SE	*.014*	*.016*	*.013*	*.015*
	p=.542	*p*=.286	*p*=.217	*p*=.883
EF*Motor Skills				
β	-.009*	-.013*	-.008*	-.006
SE	*.004*	*.005*	*.004*	*.004*
	p=.037	*p*=.015	*p*=.021	*p*=.127

Note. For each regression the final model *F* values, degrees of freedom in parentheses, and R^2 are presented. Unstandardized beta values, and *standard errors* are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .0125$) are indicated in boldface.

*$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$; † $p \leq .06$ non-significant trend.

All four final regression models were significant and moderation occurred in three of them. In order to interpret the moderation effect of motor skills on the relationship between EF and language, slope analysis was used and results are summarised in Table 5.6. Findings in each model are examined in detail below. It is important to bear in mind that the levels of motor skills analysed below refer to the sample mean and SD, which are going to be different from the population mean and SD, given the oversampling of children with motor impairments (see Appendix E for the MABC-2 conversion table reporting percentile equivalents of total sum of standard scores).

Table 5.6. Slope Analysis: details of the effect of EF on Language at different values of motor skills – values at one standard deviation (SD) above/below the mean and values at the mean.

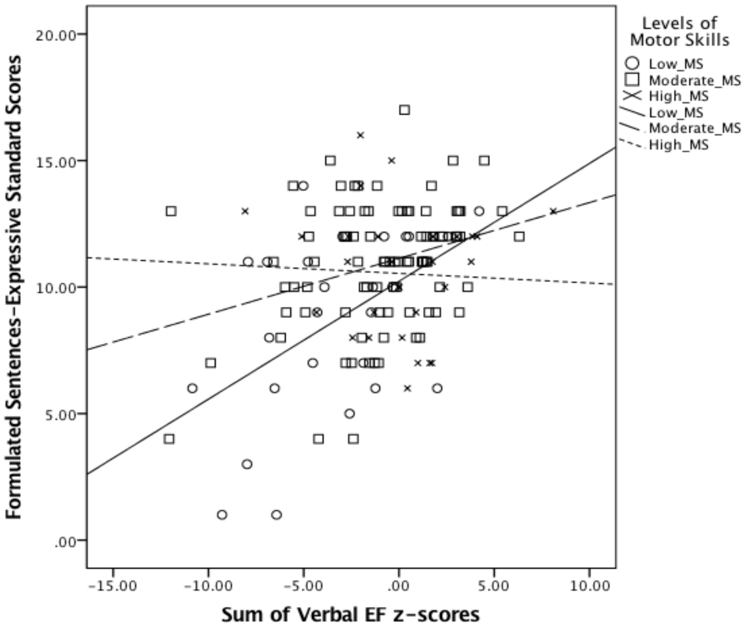
	Expressive Language		**Receptive Language**
EF Effect	***Verbal EF Model 1***	***Nonverbal EF Model 2***	***Verbal EF Model 3***
Motor skills at -1SD			
β	.378***	.372**	.275**
SE	*.107*	*.123*	*.091*
	p<.001	*p*=.003	*p*=.003
Motor skills at mean			
β	.218*	.161*	.134†
SE	*.069*	*.071*	*.069*
	p=.002	*p*=.025	*p*=.053
Motor skills at +1SD			
β	.059	-.051	-.006
SE	*.096*	*.097*	*.091*
	p=.541	*p*=.600	*p*=.945

Note. The unstandardized beta values, and *standard errors* are reported for the EF effect on language in each model.
p* ≤ .05; ** *p* ≤ .01; * *p* ≤ .001; †*p* ≤ .06 non-significant trend.

Model 1: Verbal EF predicting Expressive Language

The final regression model was significant *F* (3, 147) = 4.67, *p*=.004, and accounted for 16% of the variance. Verbal EFs were a significant predictor of expressive language (*p*=.002) although motor skills were not. The interaction effect between motor skills and verbal EF was significant (*p*=.037), indicating that motor skill significantly moderated the relationship between verbal EF and expressive language. Slope analysis revealed that: when motor skills were at one SD below the mean, EF was a significant predictor of language (*p*<.001); when motor skills were average, EF continued to significantly predict language (*p*=.002); but when motor skills were at one SD above the mean, EF was not a significant predictor. Figure 5.1. illustrates this moderation effect for participants with motor skills below one SD from the sample mean, around the sample mean and above one SD from the sample mean.

Figure 5.1. Trajectories of the effect of Verbal EF on Expressive Language for participants with low, moderate and high levels of motor skills.[3]



Note. Low MS = Low Motor Skills, below -1SD from mean; Moderate MS = Moderate Motor Skills, above -1SD from mean; High MS = High Motor Skills, above +1SD from mean; Formulated Sentences-Expressive Standard Score = Expressive language population based standard scores (*M* = 10; *SD* = 3); Sum of Verbal EF z-scores = sum of typically-developing group based z-scores (*M* = 0, *SD* = 1) of 5 nonverbal EF measures.

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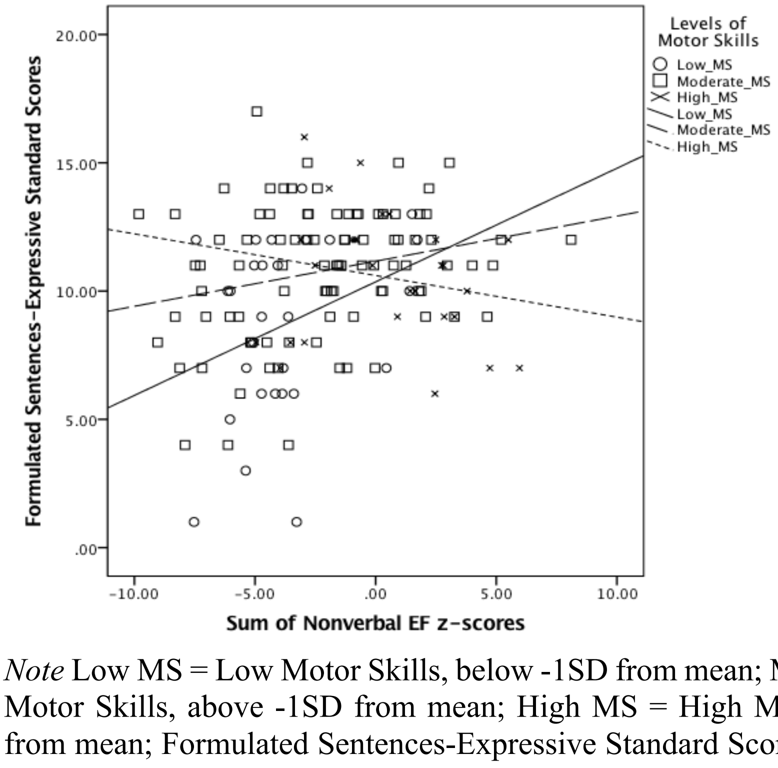
[3] All scatter plots are constructed using actual data points, rather than predicted estimates, thus the slope may vary slightly from the statistics reported in Table 5.4. This statistic is reported in Appendix F.

Model 2: Nonverbal EF predicting Expressive Language

A similar pattern was seen for the role of nonverbal EF in expressive language. The final regression model was significant *F* (3, 147) = 3.75, *p*=.012, and accounted for 11% of the variance: nonverbal EF was a significant predictor of expressive language (*p*=.024) although motor skills were not. The interaction between EF and motor skills significantly predicted expressive language (*p*=.014), indicating that moderation occurred. Slope analysis revealed that at low and average levels of motor skills, EF significantly predicted language (*p*=.003; *p*=.02) while at high levels of motor skills, EF was not a significant predictor. Figure 5.2. illustrates this moderation effect for participants with motor skills below one SD from the sample mean, around the sample mean and above one SD from the sample mean.

Figure 5.2. Trajectories of the effect of Nonverbal EF on Expressive Language for participants with low, moderate and high levels of motor skills

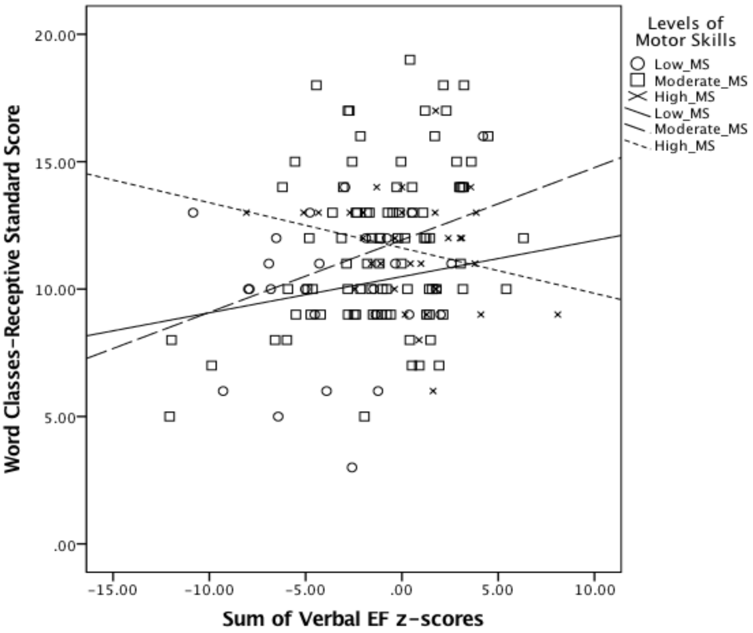


Note Low MS = Low Motor Skills, below -1SD from mean; Moderate MS = Moderate Motor Skills, above -1SD from mean; High MS = High Motor Skills, above +1SD from mean; Formulated Sentences-Expressive Standard Score = Expressive language population based standard scores (*M* = 10; *SD* = 3); Sum of Nonverbal EF z-scores = sum of typically-developing group based z-scores (*M* = 0, *SD* = 1) of 5 nonverbal EF measures.

Model 3: Verbal EF predicting Receptive Language

The final regression model was significant *F* (3, 147) = 4.85, *p*=.003, and accounted for 9% of the variance. There was a non-significant trend (*p*=.053) for verbal EF as a predictor, while motor skill was a non-significant predictor. However, the effect of the interaction between motor skills and verbal EF was significant (*p*=.021) in predicting receptive language. Slope analysis revealed that EF was a significant predictor of language when motor skills were at one SD below the mean (*p*=.003), and that there was a non-significant trend at average levels of motor skill (*p*=.053), while EF did not significantly predict language when motor skills were at one SD above the mean. Figure 5.3. illustrates this moderation effect for participants with motor skills below one SD from the sample mean, around the sample mean and above one SD from the sample mean.

Figure 5.3. Trajectories of the effect of Verbal EF on Receptive Language for participants with low, moderate and high levels of motor skills



Note. Low MS = Low Motor Skills, below -1SD from mean; Moderate MS = Moderate Motor Skills, above -1SD from mean; High MS = High Motor Skills, above +1SD from mean; Word Classes-Receptive Standard Score = Receptive language population based standard scores (*M* = 10; *SD* = 3); Sum of Verbal EF z-scores = sum of typically-developing group based z-scores (*M* = 0, *SD* = 1) of 5 verbal EF measures.

Model 4: Nonverbal EF predicting Receptive Language

The final regression model was significant F (3, 147) = 7.63, $p<.001$, and accounted for 15% of the variance. Nonverbal EF was a significant predictor of receptive language ($p<.001$) although again motor skills were not. The interaction between motor skills and nonverbal EF did not significantly predict receptive language, hence moderation had not occurred. Therefore, no slope analysis was not conducted.

To summarise, for all four models, at low and moderate levels of motor skills, the effect of EF on language is significant, but the relationship becomes non-significant at higher levels of motor skills. As we move through the continuum of motor skills the relationship between EF and language becomes less evident. In other words, motor skills are a significant moderator of the relationship between EF and language in individuals demonstrating low and moderate motor skills.

5.3.2.2. RQ4) Does motor coordination moderate the effect of language on EF?

The details of each moderation model are reported in Table 5.7. All final regression models were highly significant (ps < .001). Furthermore, Motor Skills were a highly significant predictor of EF outcomes in all four models (ps < .001). Different patterns could be identified in the effects of language on EF: Expressive Language significantly predicted Verbal EF ($p<.001$) and did not predict nonverbal EF; Receptive Language significantly predicted Nonverbal EF ($p<.001$) and, marginally, Verbal EF ($p=.045$). The interaction effect of language and motor skills was non-significant for all language outcomes, suggesting that moderation had not occurred in any of the models tested. Therefore, no further investigation was conducted.

Table 5.7. Summary details of regression analyses testing the moderation effect of motor skills on the relationship between language and EF, and specifically the effect of language, Motor Skills and their interaction (Language x Motor Skills) in predicting EF outcomes.

Outcome	**Verbal EF**		**Nonverbal EF**	
Predictor	***Expressive Language***	***Receptive Language***	***Expressive Language***	***Receptive Language***
Final Model				
F(df)	*12.61*(3,147)	*7.69*(3,147)	*23.50*(3,147)	*27.90*(3,147)
R^2	**.21*****	**.18*****	**.26*****	**.33*****
	p<.001	*p*<.001	*p*<.001	*p*<.001
Language				
β	.339***	.196*	.164	.359***
SE	*.097*	*.097*	*.096*	*.092*
	p<.001	*p*=.045	*p*=.089	*p*<.001
Motor Skills				
β	.061***	.065***	.096***	.096***
SE	*.016*	*.016*	*.014*	*.013*
	p<.001	*p*<.001	*p*<.001	*p*<.001
Language * Motor Skills				
β	-.005	-.008	-.002	.007
SE	*.004*	*.007*	*.005*	*.004*
	p=.257	*p*=.276	*p*=.736	*p*=.072

Note. For each regression the final model *F* values, degrees of freedom in parentheses, and R^2 are presented. Unstandardized coefficients, and *standard errors* are reported for each predictor variable. Significant final regression models after Bonferroni corrections ($p \leq .0125$) are indicated in boldface.

*$p \leq .05$; ** $p \leq .01$; *** $p \leq .001$; $^{\dagger} p \leq .06$ non-significant trend.

In summary, when participants were divided into TD, MD and DCD groups ('Group Data'), the moderation effect of Group was non-significant. However, when considered as a continuum ('Continuous Data'), motor skills significantly moderated the effect of EF on language. The interaction between EF and motor skills had a positive and significant effect on language outcomes when motor skills were low and moderate but not when motor skills were high. There was no interaction between language and motor skills in predicting EF outcomes.

5.4. Discussion

The study aimed at investigating how motor skills moderate the relationship between EF and language. Findings revealed a significant moderation effect could be identified only when motor skills were considered as a continuum (rather than categorically using original groupings). The interaction between EF and motor skills affected language levels: at low and moderate levels of motor skills, the effect of EF on language was positive and significant; at high levels of motor skills EF did not have any significant effect on language. To the best of our knowledge, this is the first study to date testing whether motor coordination could represent a third factor contributing significantly to the association between language and EF.

5.4.1. Hypotheses 1 and 2: Diagnostic groups moderate the relationship between EF and language.

It was critical in our sample to examine whether moderation effects of motor skills corresponded to our diagnostic Groups (TD, MD and DCD), since participants were recruited into these different groups using inclusion criteria based on motor performance. Models testing both directions of the relationship between EF and language resulted in non-significant results: Group did not moderate this relationship in any direction, in any domain of language or EF.

Since children were included in the DCD or MD group if their motor performance fell on the 16th percentile or below, this is perhaps a surprising result when considered together with findings for our RQ3 and RQ4, in which the effect of EF on language varied at different levels of motor skills. However, the MD and DCD groups included motor scores that ranged between 0.1 to the 16th percentile. When we conducted slope analysis, significant moderation effects were found at low and average sample scores (up to the 37th percentile norms), which suggest motor scores within *both* the low and moderate range are indicative of significant effects of EF on language, regardless of the presence of a motor coordination impairment (MD group) or a diagnosis (DCD group). Nevertheless, non-significant results might be driven by low power (particularly for the DCD group) and to scores at the extreme end of the distribution.

5.4.2. Hypothesis 3: the interaction between EF and motor skills predicts language outcomes

The third hypothesis, testing the effect of the interaction between EF and motor skills on language, was verified in three out of four of the models tested (Verbal EF and Nonverbal EF predicting Expressive Language, and Verbal EF predicting Receptive Language). In these models, as we moved up through the continuum of motor coordination from poor to skilled, the relationship between EF and language went from positive and significant to non-significant. This result is particularly relevant for the study overall as it depicts a very consistent pattern: at low and moderate levels of motor skills, better EF is associated with higher language; at high levels of motor skills, EF abilities do not predict language. In other words, levels of EF are irrelevant to language performance when motor skills are high, yet predict language when motor skills are low and moderate. These results seem to suggest that poor motor coordination is a risk factor for lower language outcomes, which can be, however, compensated by better EF. Conversely, EF seems to assume the role of a protective factor against low levels of language outcomes in the presence of risk factors (such as poor motor skills).

The idea that motor skills may represent a risk factor for poor language outcomes is supported by research highlighting the role played by motor milestones and behaviours in the development of language abilities (e.g., Iverson, 2010). As discussed in Chapter 1, motor coordination may be a fundamental skill that allows access to opportunities to develop language and communication abilities in early years (Libertus & Violi, 2016). In the absence of those optimal conditions created by early skilled motor behaviours, EF may play a compensatory role. However, one question may be whether poor motor skills continue to represent a risk factor later on in life and particularly in the age range we examined in the current study (7-11 years). It may be that at an early stage of development, motor skills have a large influence on language outcomes when children learn how to crawl and walk (Campos et al., 2000) or how to manipulate objects with fine motor coordination (Soska, Adolph, & Johnson, 2010). As they become older, however, children who are able to communicate effectively with others may be more likely to be involved in social activities and games that allow them to practice movement skills (Cairney et al., 2005). Therefore, the interaction between language and motor skills is likely to be bidirectional and may change developmentally. There is some evidence that initial relationships between motor and linguistic skills (Walle & Campos, 2014) decrease over time (Oudgenoeg-Paz, 2016). This is consistent with results in the current study demonstrating the main effect of motor skills on language was non-significant on its own (see Table 5.5) and motor skills were only a significant predictor of language outcomes when it was associated to EF (significant Motor Skills x EF effect – Table 5.5)

The fact that EF may play a protective role in children at risk is a hypothesis supported by theoretical (Johnson, 2012), empirical (Michel et al., 2016) and neuroimaging (Kaiser et al. 2010) evidence, suggesting better EF abilities and more efficient use of compensatory systems in children at risk compared to children with developmental disorders and to typical peers. This is further discussed in Chapter 6, in relation to results of other studies in this thesis.

In one of the models tested for RQ3, moderation did not occur. Specifically, receptive language was significantly predicted by nonverbal EF at all levels of motor skills. The fact that the interaction between EF and motor skills was not significant in this case does not contradict findings and interpretation of the other three moderation models. Rather, this finding highlights the strength of the effect of nonverbal EF on receptive language, which on its own was highly significant (see Table 5.5). It seems that a pattern could be identified in which receptive language was particularly associated with nonverbal EF, while expressive language was more strongly related to verbal EF. This was not specifically tested in our study but it is worth noticing in light of similar results obtained for the other RQ4, which we discuss below.

5.4.3. Hypothesis 4: the interaction between language and motor skills predicts EF outcomes

The second hypothesis was not verified in any of the models tested, hence motor skills did not interact with language to determine EF abilities. These results complement those for RQ3, highlighting that it is specifically the interaction of motor skills with EF that has an effect on language outcomes rather than vice versa. This is theoretically a very important finding in the attempt of untangling the net that links executive, language and motor functions to each other.

Motor skills and language abilities seem to have separate, yet significant, effects on EF. Motor skills, in particular, were a highly significant predictor of both verbal and nonverbal EF abilities. This is consistent with differences in EF performance between children with MD and DCD compared to TD children identified in Study 1, which were not seen in language ability.

Not only motor skills, but also language abilities were significant predictors of EF in three of the models. The patterns of association between EF and language identified in RQ3 were also evident for RQ4: expressive language significantly predicted verbal EF but not nonverbal EF: receptive language predicted nonverbal EF and, only marginally, verbal EF. The links between expressive language and verbal EF, and between receptive language and nonverbal EF were significant and bidirectional, while links between expressive language and nonverbal EF, and receptive language and verbal EF were unidirectional and only marginally significant. These findings suggest that the association between EF and language may be domain specific in both areas. As mentioned above, the study was not designed to test this hypothesis, although it is one worth exploring in future research.

5.4.4. Overall discussion of findings

In summary, findings seem to demonstrate that when motor coordination is below average, EF plays an important role in determining language outcomes.

The moderation effect was evident when motor skills were used as a continuous variable, particularly at low and moderate levels of motor skills, but not when children were divided into our original groups based on their DCD diagnosis or on the presence of motor difficulties (MD group). Although the protective role of EF in the presence of a risk factor can still be argued to be very relevant in children with DCD and MD, given their low levels of motor skills, taken together these results suggest that neither the DCD diagnosis, nor the cut off at the 16th percentile were the factors determining moderation effects. Rather, what seemed to be contributing to moderation effects was the continuous variability of low motor coordination *including* moderate levels of motor skills (at the 37th percentile) and not only levels of motor skills that would normally be identified as motor difficulties (below the 16th percentile).

It is important to note that any children with both language measures more than two SD below the mean have been excluded from the sample, meaning that these associations do not necessarily extend to children with developmental language disorder. Given the high prevalence of motor difficulties in children with language impairments and the overlap between DCD and SLI (Hill, 2001) it will be important in future research to include these children in the analyses to examine whether EF can still be considered protective when multiple risks factors (poor motor and language skills) are evident.

Another consideration to be made is that this study does not go further in determining the direction of the relationship between EF and language, since when strong associations were identified, these were bidirectional. It only highlights the importance of the interaction between EF and motor skills as opposed to the interaction between motor skills and language. The study also supports the relevance of domains in both areas of language (receptive vs expressive) and EF (verbal and nonverbal) in determining the association, as verbal EF seems to be strongly related to expressive language (and vice versa) and nonverbal EF seems to be strongly related to receptive language (and vice versa). Nevertheless, the models suggested by Bishop and colleagues (2014) are frameworks to be tested in research but cannot uniquely represent the reality of the complex connections between developmental outcomes that share such an intricate and dynamic range of genetic, biological and environmental factors. All three models are likely to be insufficient, or rather, they all are likely to partially explain some part of the association between language and EF at some point of development. Although associations between factors are an important first step in understanding interactions between domains, future research may benefit from testing casual relationship between motor skills, EF and other developmental outcomes.

5.5. Conclusions

The study investigated moderation effects of motor coordination on the relationship between EF and language and revealed that at low and moderate levels of motor skills, the effect of EF on language was positive and significant. The effect of EF on language was non-significant at high levels of motor skills.

Results in this study are consistent with the overall PhD project's theoretical framework developed around the interaction between EF and motor skills; an interaction that, in this study, predicts language outcomes.

CHAPTER 6

6. General Discussion

6.1. Overview

The aim of this thesis was to investigate the relationship between motor coordination and executive function (EF), and its impact on academic achievement and language. A comprehensive battery of EF tasks was used to assess a range of verbal and nonverbal domains, in school-aged children with typical and atypical motor coordination. While previous studies have generally measured EF cross-sectionally and in isolation, the current thesis, importantly, included assessments of academic and language abilities in order to understand the wider and longitudinal interactions of cognitive and motor skills on other domains of development. This was achieved by conducting three experimental studies. Study 1 (Chapter 3) assessed EF longitudinally in typically developing (TD) children, children with developmental coordination disorder (DCD group) and in children experiencing significant motor difficulties (MD group) but without a diagnosis of DCD; Study 2 (Chapter 4) analysed educational attainment in these groups of children and the contribution of EF to such achievement; and Study 3 (Chapter 4) investigated the effect of the interaction between EF and motor skills on language ability.

The general discussion is divided into three sections. First, the three experimental studies conducted are summarised (Section 6.2). Next, the results from all three studies are discussed comprehensively, integrating the overall interpretations that can be drawn from them and considering some of the theoretical and practical implications related to specific results as they are discussed (Section 6.3). The focus concerns the role that motor coordination plays in determining cognitive, academic and language outcomes, by comparing groups of children with and without motor coordination difficulties, or a diagnosis of DCD. In Section 6.4, the implications that emerge throughout the discussion are summarised; further, more general implications for theory, clinical practice and educational practice are discussed. In addition, this section considers the limitations and implications for research, suggesting directions for future investigations in the field of motor coordination, executive function and DCD. The final section discusses general conclusions drawn from the overall thesis.

6.1.1. Summary of the rationales for the experimental studies

6.1.1.1. Study 1

Significant difficulties with EF have been identified previously in children with DCD or at risk of DCD, and it has been reported that EF dysfunction may be even greater in DCD than in ADHD (Wilson et al., 2013). This is particularly noteworthy because there is extensive evidence of EF difficulties in those with ADHD (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). However, little existing research has investigated changes in EFs over time, and such studies are needed because we know that EFs in typical populations have a protracted development throughout childhood and adolescence (Friedman et al., 2015). The only longitudinal research on children with motor coordination difficulties that has been conducted to date concerned young children with poor motor coordination aged 4-7 years (Michel et al., 2016; Michel et al., 2011), by which age a diagnosis of DCD has not usually been assigned. Hence, Study 1 was novel because it was the first to investigate EF longitudinally in older children with motor coordination difficulties, comparing those with and without a diagnosis of DCD.

6.1.1.2. Study 2

Academic underachievement is defined as part of the criteria for a diagnosis of DCD (APA, 2013). However, studies investigating academic problems experienced by children with DCD in specific learning domains have been very limited, and often have not taken into account the individuals' intellectual abilities contributing to attainment (Alloway, 2007). Considering that EF significantly predicts academic outcomes in typical populations (Best et al., 2011), EF difficulties highlighted in children with DCD may be responsible for underachievement. Furthermore, it is not clear whether academic problems extend to children with motor coordination impairments without a diagnosis of DCD. Study 2, therefore, contributed to this literature by addressing the issue of identifying the specific academic problems experienced by children with poor motor skills, with and without a DCD diagnosis. It further investigated whether EF strengths and difficulties contributed to their academic abilities.

6.1.1.3. Study 3

Finally, it is not only that motor coordination is closely interrelated to EF (Diamond 2000), it also plays a role in language development (Iverson, 2000). The research investigating the relationship between EF and language has been inconclusive about understanding the nature of this relationship. One recent study has suggested a third factor may be involved (Gooch et al., 2016). Therefore, the aim of Study 3 was to understand whether motor skills contribute to explain this relationship between EF and language. Specifically, Study 3 tested the hypothesis that the interaction between EF and motor skills might have an effect on determining language ability. Given the unresolved issue of the direction of the relationship between language and EF (see Bishop, Nation, & Patterson, 2014), Study 3 also tested the hypothesis that it was the interaction between language and motor skills that was most important in determining EF abilities.

6.1.2. Methodological considerations and summary of results.

Across the three studies, children in both the DCD and motor difficulties (MD) groups had motor skills at or below the 16th percentile on the MABC-2 (Henderson et al., 2007), and these groups did not differ in their motor ability and were classified solely on the presence or absence of a clinical DCD diagnosis.

6.1.2.1. Study 1

In Study 1 participants (*n* = 51) were 7-11 years old at the first time of assessment and were followed up two years later (9-13 years old). Verbal and nonverbal measures of EF were administered at both time points. All groups demonstrated similar developmental gains in EF, although gaps in EF performance between groups persisted with time. Specifically, hierarchical multiple regressions revealed that children with DCD had poorer EF skills than TD children in all *nonverbal* measures of EF as well as in *verbal* fluency tasks at both time points. Children with MD, and therefore no diagnosis, showed persistent difficulties in the *nonverbal* measures of working memory and fluency. Results suggested overall that specific EF difficulties (largely in nonverbal EF domains) affecting children with DCD and MD persist throughout middle childhood and are, therefore, likely to impact on activities of daily living and academic achievement.

6.1.2.2. Study 2

In Study 2 participants (*n* = 90) completed a comprehensive battery of EF tasks at Time 1 (aged 7-11 years) and were followed up two years later at Time 2 (aged 9-13) when they completed standardised assessments of academic achievement. The assessments of academic achievement revealed that reading, spelling and mathematical abilities of children with MD were similar to those demonstrated by TD children. Children with a diagnosis of DCD also performed as accurately as their TD peers on measures of reading and spelling, however, they had significantly poorer scores on the test of mathematical ability. Performance on this numerical operations task was not only poorer for children with DCD compared to TD children (although note that the TD group comprised a high achieving sample of participants), but was also significantly below the population norm. Importantly, numerical abilities remained significantly poorer for children with DCD compared with TD children even when verbal and nonverbal EF skills were included in the analyses as separate predictors of academic performance. Nonverbal EF did not predict performance in any of the academic achievement tasks, whereas verbal EF was a significant predictor for both spelling and numerical operations. Results, therefore, suggested that academic underachievement in children with DCD is specific to mathematics, rather than being generalised to all educational domains. These mathematical difficulties seemed not to be generated by the EF problems identified in Study 1, although verbal EF contributed to performance. Hence, cognitive mechanisms other than EF may underlie numerical difficulties in children with DCD.

6.1.2.3. Study 3

In Study 3, the moderation effect of motor coordination on the relationship between EF and language was first studied using Group as the moderating variable. Thus, these analyses focused on whether the relationship between EF and language was different for TD children (*n*=71), children with DCD (*n*=23) and children with MD (*n*=57). Results suggested that the variable Group did not moderate the relationship between EF and language in any direction (not when the predictor was EF, nor when the predictor was language). Next, the interaction effect was studied using continuous motor skills data (i.e. across groups) as the moderating variable. Moderation effects were significant when EF was the predictor of language outcomes, but not when language was the predictor of EF outcomes. Specifically, the interaction between motor coordination and *verbal* EF had a significant effect on both expressive and receptive language, while the interaction between motor skills and *nonverbal* EF had a significant effect on expressive language only. In all these models, the relationship between EF and language was positive and significant at low and moderate levels of motor skills, but not at high levels of motor skills. The relationship between *nonverbal* EF and receptive language was significant at all levels of motor skills. These results suggested that EF abilities play a role in contributing to language abilities when motor skills are below average.

6.2. Discussion of overall results

This thesis has made a significant contribution to further understanding of the interaction between motor coordination and EF. A very important and novel feature of the research in this thesis is the inclusion of both a group of children with a clinical diagnosis of DCD and a group of children with identical motor coordination impairments but no diagnosis. The pathways to receiving a diagnosis of DCD are varied, particularly given the poor awareness of the condition amongst teachers and professionals (Kirby et al., 2008), and may include a range of effects on daily life in a very heterogeneous clinical population (Visser et al., 2003). Importantly, the motor difficulties (MD) group included in the current thesis can be considered as a group with “pure” motor impairments, as no diagnosis or other difficulty was identified in this group. Therefore, in the next section it is argued that the cognitive features shared by these two groups are those characterising the overlap between motor and cognitive systems. Similarly, where cognitive differences between these two groups are identified, additional non-motor underlying mechanisms should be considered for interpretation of findings across the three studies.

6.2.1. Fluency and working memory difficulties in the nonverbal domain persist across time in the DCD and MD groups

Examining the relationship between EF and motor skills longitudinally, Study 1 revealed that two EF skills, namely visuospatial working memory and design fluency, were continuously affected across time in children with poor motor skills regardless of whether a diagnosis of DCD was assigned. Therefore, it may be that nonverbal working memory and nonverbal fluency are two of the EF constructs that most relate to weak motor skills. Evidence to support this proposal, along with some alternative explanations of the deficit seen in children with poor motor skills in these domains, are discussed below.

For nonverbal fluency, there were no previous investigations of its links to motor skills apart from the original project (Leonard et al., 2016) - which the longitudinal study (Study 1) in the current thesis followed up. However, Suchy and colleagues (Suchy, Kraybill, & Larson, 2010) did examine this task in some detail using adult samples. Specifically, they examined the two subtests of the design fluency task from the D-KEFS used in this thesis (i.e., empty dots and filled dots). Suchy and colleagues' study (2010) revealed how performance on both of the design fluency tasks relied on *motor planning*, measured via the ability to repeat from memory a sequence of hand movements, and on *motor sequence fluency*, measured via the ability to generate as many different sequences of given hand movements within a certain time limit (e.g., push, turn, tap-tap), tasks that were designed in a previous study by the same research group (Suchy, Derbidge, & Cope, 2005). Suchy and colleagues (2010) also found that design fluency scores did not rely on verbal fluency, nor on cognitive flexibility measures, which were both found to be significantly poorer in children with DCD than in children with MD in Study 1, and could have represented alternative explanations for the deficits in design fluency. Therefore, these results from Suchy and colleagues (2010) support those from Study 1 in suggesting a link between motor skills and the ability to generate novel visual patterns in a design (nonverbal) fluency task.

For visuospatial working memory, previous studies have identified this domain as a weakness in children with DCD (Alloway, 2007; Alloway & Temple, 2007) and teacher-reported motor difficulties (Giofre, Cornoldi, & Schoemaker, 2014). Such findings are in line with the results from Study 1. Furthermore, in a relevant study looking at a typically developing population, motor skills explained a significant amount of the variance in visuospatial working memory (not in verbal working memory), with the aiming and catching component score of the MABC-2 accounting for unique variance in performance (Rigoli et al., 2012).

To explain the link between visuospatial working memory and motor skills, the role of the cerebellum may be illuminating in terms of relevant neurocognitive mechanisms. Specifically, typically developing children performing a visuospatial working memory task were found to recruit the left lateral cerebellum (Scherf, Sweeney, & Luna, 2006), which is an area considered to be involved in motor planning and monitoring of motor errors (Thach, 1998), as well as in motor learning (Van Mier & Petersen, 2002). Moreover, the dorsolateral prefrontal cortex, which is recruited during visuospatial working memory tasks (D'Esposito, Postle, Ballard, & Lease, 1999), was found to co-activate with the contralateral neocerebellum, which is crucially involved in movement control (Koziol et al., 2014), during non-motor EF tasks (Diamond, 2000). The two areas form a neural network that has been found to under-activate in children with DCD compared to typically developing children (Zwicker et al., 2011). An alternative, or additional, neurocognitive account to explain the overlap between visuospatial working memory and motor skills has been suggested by a study using a visuospatial working memory paradigm that required children to compare the position of two stimuli presented on a grid one after the other with varying time delays (Tsai, Chang, Hung, Tseng, & Chen, 2012). The neurophysiological differences in brain activation using event-related potentials (ERPs) suggested that children with DCD allocated fewer neural resources to the comparison of spatial location during the retrieval process phase (i.e., remembering the spatial location of the previous stimulus). This reduced activity has been linked to the smaller size of the corpus callosum, reflecting lower inter-hemispheric transfer speed, and may be responsible for the overlapping deficit between motor and visuospatial working memory (Tsai et al., 2012).

One important distinction needs to be made between visuospatial working memory (which is executive-loaded) on the one hand, and visuospatial short-term memory and visuospatial processing (which are not executive-loaded) on the other. It needs to be considered whether or not the impairment in visuospatial working memory may be explained by deficits identified in children with DCD in visuospatial processing (Wilson & McKenzie, 1998), or visuospatial short-term memory (Alloway, Rajendran, & Archibald, 2009). This distinction is particularly relevant for the visuospatial working memory task adopted in the current thesis, the odd-one-out task (Henry, 2001). As mentioned in the discussion section of Study 1 (Chapter 3), one of the strategies often used by children to complete the task was rehearsing the sequence of words corresponding to the location of the odd-one-out (i.e., right, middle, left). The use of this strategy meant that, although the processing demand of the task remained visuospatial, the storage phase became verbal for those children using the rehearsal strategy. Therefore, future research including measures of visuospatial processing and short-term memory could clarify the component skills that may be affecting visuospatial working memory performance in children with motor impairments.

6.2.2. Are EF deficits related to academic ability?

The deficit in visuospatial working memory identified in Study 1 in children with DCD and MD might be expected to impact on their academic achievement, particularly on mathematical ability. Some studies have suggested that visuospatial working memory has a unique contribution to mathematical achievement (Andersson & Östergren, 2012; McLean & Hitch, 1999; Szűcs et al., 2014), and that impairments in visuospatial working memory (but not verbal working memory) are found in children with mathematical learning disability (Andersson, 2010; Schuchardt, Maehler, & Hasselhorn, 2008). However, Study 2 identified significant mathematical difficulties in children with DCD, which were not apparent in the MD group. One explanation for the incongruent mathematical abilities between the two groups, despite similar visuospatial working memory deficits, could be the fact that nonverbal EF more generally (i.e., the composite nonverbal EF measure) did not significantly contribute to performance in the numerical operations task administered in Study 2.

By contrast, what instead contributed to performance in the numerical operations task was verbal EF. There is evidence that verbal working memory is equally important, or more important, than visuospatial working memory in typical mathematical achievement (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Cragg et al., 2017; Friso-van den Bos et al., 2013). However, poor verbal working memory skills would not fully explain the DCD group's deficit in mathematics identified in Study 2. This is because children with DCD in Study 1 showed typical profiles of performance in the verbal working memory task (listening recall) and these were consistent over a period of two years. In fact, differences between children with TD and children with DCD in the numerical operations task remained even after EF skills were taken into account as additional predictors in the regression analyses, further suggesting that verbal working memory skills cannot account for the group differences in mathematics.

Overall, the current results suggest that to understand mathematical underachievement in children with a diagnosis of DCD, underlying mechanisms other than motor or EF impairments need to be explored. The next section discusses evidence for some of the possible explanations of such deficit.

6.2.3. Accounts to explain mathematical deficit in DCD other than EF

There is some evidence that one of the domains that may be implicated in arithmetic is visuospatial short-term memory (Reuhkala, 2001), which is indeed an area of weakness in children with DCD as already mentioned (Alloway et al., 2009). Specifically, Alloway (2007) found that 56% of children with DCD scored more than one standard deviation below the mean in measures of visuospatial short-term memory. These scores were averaged with those obtained in visuospatial working memory to form a composite score and children with DCD were divided into two groups. Those with a visuospatial composite score below 85 (*M*=100; *SD*=15) had significantly poorer performance than those with a score above this cut-off in attainment subtests of word reading, mathematical reasoning and numerical operations, even after IQ scores were taken into account. Visuospatial short-term memory has also been found to predict mathematics achievement in typically developing children (Bull et al., 2008; Swanson & Kim, 2007; Szűcs et al., 2014), therefore measuring its specific contribution to academic performance in children with DCD may help to understand their poor mathematical ability.

Another domain that may be related to mathematical underachievement in children with DCD is numerical cognition. There is some evidence suggesting that the approximate number system is affected in children with DCD (Gomez et al., 2015). The approximate number system refers to the intuitive ability nonverbally to form an abstract and approximate representation of numerical magnitude, which seems to be a foundational skill to develop representations of symbolic numbers (Feigenson, Dehaene, & Spelke, 2004; Piazza & Izard, 2009). It is measured through the ability to make a judgement about the numerosity of two stimuli, for example by indicating without counting which one of two arrays of dots is the one containing more dots, in increasingly harder trials (i.e. higher similarities in numerosity). Children with DCD have been shown to perform significantly worse than typically developing children on this task, by being less accurate in comparing the numerosity of sets of dots, and by responding correctly only in trials of lower complexity (i.e. higher difference in numerosity between the two stimuli; Gomez et al., 2015). Children with DCD also tend to be less accurate than typical children when comparing symbolic numbers and when solving simple additions, two skills which were both found to correlate with performance in the approximate number system task in this same study (Gomez et al., 2015). Therefore, it may be that rather than the motor or EF impairments, deficits in the approximate number system contribute to poorer symbolic number processing, which in turn could underlie the significant difficulties in calculation ability found in children with DCD in Study 2. It is important to note that the study by Gomez and colleagues (2015) found a significant visuospatial impairment in the DCD group, which did not correlate with any of the numerical tasks, suggesting that visuospatial and mathematical processes are independent in DCD. This finding further supports the finding discussed earlier that nonverbal EF did not predict academic performance in Study 2.

Research investigating cognitive numerical processes underlying mathematical ability in those with atypical motor development is, however, very limited. Some investigations into typical development have suggested that fine motor skills predicted early mathematical (not reading) ability (Pitchford, Papini, Outhwaite, & Gulliford, 2016), although EFs have also been closely linked to mathematics achievement (Best et al., 2011; Blair & Razza, 2007; Bull et al., 2008). Indeed motor skills may have an indirect effect on mathematical achievement through EF, which has been found to mediate this relationship in both children (Schmidt et al., 2017) and adolescents (Rigoli, Piek, Kane, & Oosterlaan, 2012). Although EF did not explain group differences in mathematics between DCD and TD groups in Study 2, it may be that motor skills have an indirect effect on mathematical ability through EF. EF has been found to have a significant moderating effect on mathematical achievement in the presence of risk factors for poor achievement, such as low-income family background (Blair et al., 2016), or low mathematical ability at school entry (Ribner et al., 2017). Future research could explore the hypothesis that EF plays a compensatory role in the presence of a risk for low achievement, because of poor motor coordination, in order to better understand the multiple interrelations between these domains.

It is important to emphasise that not all children with DCD demonstrated mathematical difficulties in Study 2, although the majority of them did. This raises the important issue of individual differences in children with poor motor skills, which will be discussed in the next section.

6.2.4. Within-group variations in academic and EF performance

In Study 2, 47% of children with DCD were classified as having average mathematical abilities. This result is in line with a previous study indicating some heterogeneity in mathematical ability in a clinical DCD sample (Pieters et al., 2012). That study measured mental computation (e.g., 255 + 87 = …) as well as number system knowledge (e.g., ordering numbers) and arithmetic number problems (e.g., 5 + 2 = …; 7 – 3 = …), finding that there was wide variation in performance. Nevertheless, more than half of the sample of children with DCD in Study 2 had severe problems with mathematics. From a clinical perspective, this result suggests that an assessment of the individual needs of children with DCD is crucial to shape intervention and educational support. However, future research should attempt to isolate the specific mechanisms that are implicated in determining whether children with motor coordination impairments do or do not develop problems in mathematical achievement.

The consideration of heterogeneity in the DCD population is equally relevant for EF ability. It may be that, although significant group differences were revealed by Study 1, not all children with DCD or MD experience EF difficulties. Given that some of the EF measures used in this thesis were not standardised, it was not possible to calculate the proportion of children in the MD and DCD groups who performed within the normal range. EF performance in these groups could only be compared to that of the TD group, and not to that of the normal population. Therefore, it is important to acknowledge that group differences in EF performance may not be evident at the individual level in all children with DCD or MD. It may be that the population of children with DCD and MD could be separated into children with additional cognitive problems, and those for whom problems are confined to the motor domain. In fact, the possibility of a subgroup of DCD children with key EF deficits has been put forward previously by other authors in the literature (Vaivre-Douret, 2014). Using cluster analysis, one study found a number of subgroups within samples of DCD children, but these were defined by different combinations of specific subdomains of motor *and* cognitive ability, rather than by the presence or absence of cognitive impairments (Asonitou & Koutsouki, 2016). None of the subgroups appeared to have a strong separation between cognitive and motor capacity, which was consistent with results in similar attempts to identify subgroups within the DCD population in previous studies (Green, Chambers, & Sugden, 2008; Macnab, Miller, & Polatajko, 2001). An interesting further development arising from the research reported in this thesis would be to identify possible cluster of abilities within the groups of children with DCD and MD, considering not only motor and EF skills, but also language and academic abilities.

6.2.5. Difficulty vs deficit

An important issue to address is whether the EF problems demonstrated by children in both the DCD and MD groups, and the mathematics difficulties demonstrated by children with DCD, should be considered difficulties or deficits. A difficulty may become a deficit when significant. Throughout this thesis, when identifying group differences between TD children and children with MD or DCD, it was concluded that some degree of difficulty was experienced by both groups of motor impaired children compared to TD peers (e.g., EF tasks). To establish whether there was a deficit in a specific domain, standardised tests would be needed in order to compare results to the population norm, and several EF measures administered in Study 1 were not standardised, thus such conclusions could not be drawn.

For those tests in which standardised scores were available (e.g. numerical operations), the issue became which cut-offs to use in order to differentiate a difficulty from a deficit. In previous research and clinical practice, this lower limit has often been two standard deviations below the mean, (e.g. the cut-off for the intellectual disability range is generally a score below 70 on measures with a mean of 100 and standard deviation of 15).

In Study 2, three children with DCD scored below a standard score of 70 in the numerical operations task (*M* = 100; *SD* = 15). These children could be considered to have a specific learning disorder, which would obviously need a comprehensive clinical assessment to be diagnosed (APA, 2013), but that may be co-occurring with DCD. A recent cluster analysis with a large group of children with DCD only, children with mathematical learning disability only, and children with both diagnoses, supported a significant comorbidity between the two (Pieters, Roeyers, Rosseel, Van Waelvelde, & Desoete, 2015). However, Pieters et al. (2015), and many other authors, have often adopted a cut-off of 85 and identified children scoring one standard deviation below the mean as having a specific learning disability in mathematics (Mazzocco & Myers, 2003).

More than half of the children with DCD in Study 2 scored below 85 on the numerical operation task. This cut-off corresponding to one standard deviation below the mean has also been used in research in reading disorders (Snowling, 2001), with some studies using a standardised reading test score (e.g., TOWRE) below 90 as a cut-off for dyslexia (Hoeft et al., 2011). Similarly, scores below 1.25 standard deviations or more below the mean in multiple subtests of language have been considered valid cut-offs for developmental language disorder (Tomblin et al., 1996), criteria which have been shown to predict longitudinal language problems (Tomblin, Norbury, & Bishop, 2008). In order for a disorder to be specific, often an additional criterion used by researchers and practitioners is that standard scores in other cognitive domains should be average, such as nonverbal reasoning being within one standard deviation from the mean in studies investigating language disorders (Henry et al., 2012) or reading disorders (Hoeft et al., 2011).

In this thesis, children were included with broader ranges of language, reading and intellectual ability, in fact, children were excluded only if their scores fell below two standard deviations from the mean. The aim was to exclude children with severe impairments on any of these other cognitive abilities in order to ensure they could access the assessment instructions and demands. It is important to note that these procedures are stricter compared to most investigations in the field of motor coordination impairments, but more inclusive than studies in the field of language and reading impairments. Hence, some children in all three studies conducted in this thesis may have met research criteria for language or reading disorders. Nevertheless, these criteria were identical for the experimental and comparison groups. Thus, the procedure adopted here was consistent with the aim of understanding profiles of all children with poor motor skills that are not explained by intellectual disability, as indicated in the DCD diagnostic criteria (APA, 2013).

However, a careful discussion of cut-offs within the cognitive domain is relevant to understand cut-offs in the motor domain, and has both clinical and research implications. In this thesis children in the DCD and MD groups had scores on standardised measures of motor coordination at or below the 16th percentile, which corresponds to one standard deviation below the mean. Therefore, some of the children in the MD and DCD groups scored between -1 and -2 standard deviations from the mean in measures of motor skills, *and* language, and/or reading, and/or reasoning. This has implications for future research because in order to delineate EF and academic profiles that are specific to children with motor coordination impairments, we may need to isolate children with low motor ability but average cognitive functioning (above one standard deviation from the mean). On the other hand, the gap between cognitive and motor domains could possibly have limited clinical relevance, as children may respond to targeted intervention regardless of the presence of a gap with other domains (Thornton et al., 2016). Additionally, many children with lower cognitive skills have average motor skills. Thus, once those with intellectual disability are excluded, low cognitive abilities accompanying poor motor skills could be seen as a correlate rather than an explanation. This approach was recently adopted in a consensus paper about diagnostic criteria for developmental language disorder (Bishop, Snowling, Thompson, & Greenhalgh, 2016), as exclusionary criteria based on nonverbal IQ-language discrepancy are no longer used for this condition. Similarly, the validity of traditional criteria which rest on an IQ-reading discrepancy have also been challenged in reading disorder (Stuebing et al., 2002).

However, the issue remains of what should be considered the core difficulty of children with generally low levels of ability across several domains (i.e., between -1 and -2 standard deviations from the mean). This question has implications for clinical and educational practice, as it may be that some individuals experience concurrent motor, executive and language difficulties, even if none of these domains is below the threshold of two standard deviations from the mean. Perhaps the question can be answered within the context of individual needs, as only a thorough and careful assessment may reveal areas with greater impact on daily life. Even intellectual ability itself has been suggested to require a broader definition in order to reflect reasoning and judgement used to function adaptively in everyday life (Greenspan & Woods, 2014).

Furthermore, the questions raised here challenge the notion of developmental disorders being characterised by fixed, domain-specific behavioural impairments, in which selective deficits are accompanied by typical development in other systems. Developmental interactions between systems are likely to occur in atypical development over time, as has been observed through computational modelling techniques (Thomas & Karmiloff-Smith, 2014). Within this view, development itself is seen as contributing to produce behavioural deficits (Karmiloff-Smith, 1998). Therefore, assessment and diagnosis are likely to capture one's individual ability at a given point, while reciprocal interactions between domains may fluctuate with development. The results from the moderation analysis conducted in Study 3 are best interpreted within this framework, as associations between variables (language, EF and motor coordination) were explained by their interaction rather than by diagnostic groups. In the case of EF and language ability, attempts to determine causal relationships between complex domains and to predict developmental trajectories have so far failed (Gooch et al., 2016).

6.2.6. Difficulty/deficit vs delay

An alternative explanation for group differences in EF and academic achievement in Study 1 and Study 2 is that the development of these abilities in MD and DCD groups is delayed, in that profiles may be similar to younger children rather than representing a persistent deficit. Results from Study 1 suggest that this is a plausible account of group differences in EF, because EF developed at the expected rate of growth in all groups, even if the gap in performance persisted with time. Further longitudinal research investigating EF development into adolescence and adulthood in those with DCD and MD is needed to clarify whether specific EF domains reach typical levels of ability at a later stage during development. However, cross-sectional studies in adulthood support the hypothesis that a gap in EF skills between individuals with typical and atypical motor coordination continues to persist later in life and, therefore, can best be described as a deficit. More than 50% of adolescents and young adults with DCD have reported problems with organisation, planning, memory, preparation and time management (Kirby et al., 2008). Further, self-reported executive functioning using the BRIEF-A (Roth, Isquith, & Gioia, 2005) was found to be significantly poorer in young adults with DCD or at risk of DCD than control groups (Tal-Saban et al., 2014). Although the gap in EF performance between those with motor coordination impairments and TD comparisons seems to not have expanded with age in Study 1, executive dysfunction may still have a growing impact on daily activities as the environmental and organisational demands increase with age (e.g., the transition to secondary schooling). Therefore, within an interactive framework of neurocognitive development (Karmiloff-Smith, 1998), even if EF difficulties were due to delayed maturation, the effect of the interaction of this delay with the environment is likely to result in a cascade of subtle effects on the development of other systems.

The mathematical difficulties identified in children with DCD in Study 2 may also be the result of delayed maturation of numerical cognitive ability, and there is some evidence to support this hypothesis in the DCD population. Pieters et al. (2012)

reported that the ability of 9-year-old children with severe DCD to solve addition and subtraction problems as quickly as possible was similar to that of control children who were two years younger, and performance of children with mild DCD was similar to that of control children who were one year younger. Since this is the only study conducted to date comparing academic skills in children with DCD to those of younger children, and since it did not assess other areas of achievement, more research is needed to support the developmental delay hypothesis. This study does, however, illustrate that the severity of motor coordination impairment may need to be taken into account in future work when testing this hypothesis. Similarly to EF difficulties, numerical problem solving skills may have a varied effect on the individual's general functioning and development, depending on the environmental demands, which change significantly with age. Therefore, what is identified as a delay in a research setting, may represent a difficulty or deficit from a clinical and educational perspective.

6.2.7. The differences between the MD and DCD groups

An important methodological feature of this thesis was to include children with motor coordination impairments, with and without a diagnosis of DCD. Previous studies have used either participants with clinical diagnoses (Piek et al., 2007) or participants with motor impairments but no diagnosis (Michel et al., 2011). Very rarely have studies used both methods (e.g., Sinani, Sugden, & Hill, 2011) and no previous study has included both of these recruitment methods to investigate executive function, academic achievement or language.

Study 1 explicitly compared children with DCD and MD, finding that the DCD group performed significantly more poorly on measures of verbal fluency and nonverbal switching at two time points, approximately two years apart. Children with DCD also showed persistent impairments in nonverbal inhibition and nonverbal planning compared to TD children, while children with MD did not (they showed these impairments only at Time 1). The two groups did not, however, differ in their rate of developmental change in EF. Study 2 did not compare the two groups directly, although it was found that children with MD did not demonstrate mathematical impairments, while those in the DCD group did. Across the three studies there were no significant MD/DCD group differences on the language measures; and Study 3 further found that the relationship between EF and language was similar between the two groups.

Results from Study 1 and Study 2, therefore, revealed some differences between a population of children with a clinical diagnosis of DCD, and children with MD who scored poorly on standardised measure of motor skills but had no diagnosis. This is an important finding for research in the field of DCD, since results from previous studies on these two groups are often interpreted as if they were interchangeable. The current findings emphasise that results in the area of executive and academic abilities should be interpreted taking into consideration the method of recruitment of participants. Specifically, findings from studies in which participants were screened for poor motor skills may not apply to a clinical population of individuals with DCD. This suggestion is further supported by the fact that, in this thesis, the DCD and MD groups differed in their diagnosis only, as children with additional conditions or difficulties in reading, language and intellectual ability were excluded from both groups. In other words, comorbid conditions or overlapping difficulties in children with DCD were not an explanation for group differences, nor was the degree of motor impairment, which was of similar severity.

The fact that children with DCD demonstrated additional difficulties in EF and mathematics over and above those demonstrated by children with MD may be expected. Academic underachievement is likely to represent a ‘red flag’, which parents and teachers are likely to notice and consider a reason for further investigation. The widespread and persistent EF difficulties demonstrated by children with DCD in the nonverbal domain are also likely to impact significantly on the child’s ability to organise and complete tasks successfully at school and at home, which could also be evident to parents and teachers. In a group of self-referred adults who were later diagnosed with DCD, problems with EF were reported as the primary reason for seeking a clinical assessment, followed by difficulties in activities of daily living, changes in routine, distractibility and multi-tasking, which are all likely to depend on EF (Purcell et al., 2015). These additional difficulties may be those that lead to a referral and, therefore, to a diagnosis in children too.

For children with MD, reasons for concern may not be as apparent and obvious because these children might be able to deal with academic and everyday tasks more effectively than children with DCD. However, this assertion is made on the basis of a relatively better *group* profile for those with MD, which may not apply at an individual level. EF difficulties in the area of visuospatial working memory and nonverbal fluency identified in Study 1 at both time points for both the DCD and MD groups are likely to have some degree of impact on everyday life, perhaps by hindering children’s ability to express their potential for learning. For example, visuospatial working memory (Bull et al., 2008) and inhibitory control (Blair & Razza, 2007) were found to predict early academic outcomes. Besides weaker visuospatial working memory and nonverbal fluency compared to TD peers, children with MD demonstrated poorer motor response inhibition and nonverbal planning than TD children at Time 1. These difficulties, even if not evident at Time 2, should not be ignored. Furthermore, children with MD are still experiencing motor difficulties, in many cases at severe levels, which have not been identified by adults in their surrounding environment. The impact of poor motor skills on other areas of functioning should not be underestimated. Longitudinal studies in very large samples of school-aged children with probable DCD, which were identified using similar criteria as for the current MD group, showed a greatly reduced participation in physical activities such as free-time play, seasonal recreational pursuits, school sports, community sports teams and clubs, and sport and dance lessons (Cairney et al., 2005; Cairney, Hay, Veldhuizen, Missiuna, & Faught, 2010). Other studies investigating children with motor difficulties (without a DCD diagnosis) have found poorer emotion recognition, with consequent negative effects on social behaviour (Cummins et al., 2005), higher probability of facing social rejection and poorer socialisation than TD peers (Kanioglou, Tsorbatzoudis, & Barkoukis, 2005).

Some authors have attempted to propose a common terminology that should be adopted by researchers to describe DCD populations in papers, and the results from Study 1 and Study 2 support this suggestion. For example, when one or more criteria for a diagnosis of DCD are not evaluated, participants may be described as having *probable* DCD and when children meet the DSM-5 criteria but are younger than 5 years, they should be described as *at risk for* DCD (Smits-Engelsman, Schoemaker, Delabastita, Hoskens, & Geuze, 2015).

Some of the children identified in Study 1 and 2 as having MD at Time 1 did not continue to demonstrate poor motor skills two years later at follow-up, namely eight children from a total of 40 children with MD. Although most children with MD continued to demonstrate motor impairments across the two time points, there might be a subgroup of children for whom poor motor skills are a transient difficulty. Furthermore, some of the children identified as TD at Time 1 showed poorer than expected motor skills at follow-up (five children from 45 in total). A possible extension of the research conducted in this thesis would be to investigate the cognitive and academic profiles of a larger group of children with fluctuating motor skills. There might be some key differences within this group that explain the transient nature of their difficulties, for example they may have better EF if they overcome motor impairments with time. This hypothesis is supported by a study conducted by Michel and colleagues (2016) in which children between 4 and 6 years of age were assessed on a number of motor and cognitive measures. Within the motor impaired group, half of the children caught up with their peers at follow-up, ceasing to show poor motor coordination. When compared to children who had persistent motor impairments, children with typical motor skills at follow up demonstrated significantly better inhibition skills (Michel et al., 2016).

In the next section I will argue that such results, together with findings reported in this thesis, would support the idea that poor motor skills could be considered a risk factor for poorer outcomes in cognitive and academic domains, while levels of executive function may represent a protective factor against developing deficits in other areas of development in children at risk.

6.2.8. Risk and protective factors

In Study 1, children with DCD and MD had similar impairments in motor coordination. However, they differed in some specific areas of EF. The relatively better EF abilities identified in children with MD may allow these children to deal with everyday situations in a more effective way. In other words, they may have some additional EF resources that help them to limit the impact of poor motor skills on everyday life, protecting them from developing the overall clinical condition. In Study 3, language skills in children with low and moderate levels of motor skills were significantly predicted by their EF ability, while EF skills did not have any effect on the language abilities of children with high motor skills. Therefore, poor to moderate motor coordination skills could represent a risk factor for language ability, with EF skills acting as a potential protective factor in these children. Numerous studies support the concept of poor motor skills as a risk factor for lower levels of social, language, academic (Son & Meisels, 2006) and cognitive functioning (Leonard, 2016; Leonard & Hill, 2014). The concept of EF as a protective factor has been proposed by Johnson (2012), who argues based on individual variability, neuroimaging and genetic evidence, that EF acts as a compensatory system in the presence of atypical development. This view is partly supported by the significant genetic origins of individual differences in EF, which would indicate EF skills are largely independent from the development of other domains of functioning (Friedman et al., 2008).

6.2.9. Domains and subdomains

One important feature of the measures adopted in this thesis was that each domain was assessed using multiple subdomains. The EF battery was particularly comprehensive because it included five different subdomains, there were multiple academic achievement and language subdomains, and also several different motor subdomains. It may be possible to further isolate and assess specific underlying processes in each of these subdomains. For example, it may be important to understand which specific numerical and cognitive problems contribute to the difficulties in mathematics demonstrated by children with DCD in Study 2. There is some evidence for subgroups of DCD children with procedural calculation problems, with or without number fact retrieval problems (Pieters et al., 2015). A further clarification of underlying mechanisms in mathematical underachievement would help to suggest a framework to better understand its origin and provide direction for educational intervention.

Furthermore, although Study 2 and Study 3 identified a significant effect of EFs on academic achievement and language respectively, composite EF scores had to be used in order to comply with acceptable standards of power given the sample size, and to limit multiple comparisons. Future research with larger samples is needed to identify the role of specific domains of EF in language and academic ability in children with poor motor skills.

Although EF composite scores were used, a major distinction between verbal and nonverbal EF subdomains was maintained throughout this thesis. This distinction was revealed to be particularly important for children with poor motor skills, whose EF difficulties were largely associated with nonverbal domains of EF at both time points. Since nonverbal EF measures involved a motor or visuospatial demand, results suggest that EF difficulties in DCD are specifically linked to their core impairment. Recent studies have suggested poor ability of children with DCD to effectively couple online motor control, which refers to the ability of adapting and updating movements in a dynamic environment, with executive function, and specifically with inhibitory control (Ruddock et al., 2016). Ruddock and colleagues suggested that a maturational delay of the motor-cognitive networks may be responsible for the reported difficulties. In fact, atypical functioning was identified in the activation of the dorsolateral prefrontal cortex, the cerebellum and the parietal cortex (see Chapter 1 for a review) in children with DCD, suggesting a higher than expected executive demand was required to effectively execute motor tasks (Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013). This account may also explain the results from Study 1 in which deficits in motor skills were coupled with deficits in nonverbal EF ability.

These findings have general implications for theory, practice and research, which will be discussed in the next section.

6.3. Implications of Findings

The implications of the specific findings that have been discussed in the above section will now be summarised and expanded, with more general implications for theory, educational practice and clinical practice. Some of the methodological limitations of the research in this thesis are also raised and summarised, and indications for future research are suggested.

6.3.1. Theoretical Implications

The results of the studies in this thesis offer important insights for understanding the interrelations between motor and EF systems. The areas of EF that most related to motor coordination were visuospatial working memory and design fluency, since these were consistently impaired at two time points (over two years) in children with poor motor skills, with or without a DCD diagnosis. As both of these tasks were nonverbal, the nonverbal domain of EF seems to have stronger links with the motor system, which is in line with recent neurocognitive accounts of atypical motor development (Debrabant et al., 2013; Ruddock et al., 2016).

There was also some evidence that the EF difficulties demonstrated by children with MD and DCD, compared to their TD peers, reflected a developmental delay rather than a deficit, since all groups demonstrated similar gains in EF skills over time. This hypothesis could be challenged by studies revealing significant EF difficulties in adolescents and adults with DCD or probable DCD (Kirby et al., 2008; Purcell et al., 2015; Tal-Saban et al., 2014), given that the ‘delay’ does not seem to disappear once EF development is complete. Study 1 was the first to explore EF longitudinally in primary school age children with either DCD or MD and demonstrated a continuing delay in performance compared to TD peers, yet no differences in the rate of maturation. Therefore, it might be that although a maturational lag is initially generating EF difficulties, the atypical interaction with the environment has multiple effects on the development of the executive system itself (Thomas & Karmiloff-Smith, 2014), thus manifesting as a deficit later in life.

The results from Study 2 revealed that when differentiating between verbal and nonverbal EF domains in terms of their contribution to academic achievement, only verbal EF significantly predicted performance on tests of mathematics. This is an important step towards understanding the relationship between EF and academic skills, as previous research has tended not to differentiate between verbal and nonverbal EF domains (e.g., Best et al., 2011) even when making a distinction between verbal and nonverbal academic domains (e.g., Wu et al., 2011). However, the predictive value of EF was assessed on the overall sample of children, including those with and without motor impairments, thus Study 2 could not reveal whether verbal and nonverbal EF domains had separate effects on academic achievement in all groups. It remains possible, therefore, that this distinction is only relevant for children with poor motor coordination impairments.

Although children with DCD demonstrated mathematical problems compared to TD peers, Study 2 suggested that this lower mathematical ability may not to be driven by EF difficulties as suggested in previous studies (Alloway, 2007), since performance remained poorer even after differences in EF were taken into account in the analyses. Furthermore, poor motor skills did not seem to be associated with lower academic achievement in other learning domains. Since previous research found that motor skills are significant predictors of early maths ability (Pitchford et al., 2016), poor motor skills may represent a risk factor early in development, rather than a direct cause for difficulties in mathematics.

In this thesis, poor motor skills seemed to represent a risk factor not only for mathematical ability but also for language levels. In the case of language however, EF played a crucial role as a protective factor, impacting positively on expressive and receptive language when motor skills were low or moderate. Finally, EF may also protect children with poor motor skills from a wider impact on daily life that could lead to developing the clinical condition of DCD, as those with a diagnosis had more pervasive EF difficulties.

6.3.2. Implications for Practice

A number of important implications for practice can be drawn from the studies conducted in this thesis. Below, findings are discussed that have clinical and educational implications for children with DCD and MD, as well as for the general population of children who do not have motor coordination difficulties.

Firstly, children with DCD and MD seemed to have higher risks of poor EF, particularly in the nonverbal domain. Hence, everyday tasks that require both executive and motor or visuospatial processing demands may be difficult for them to complete effectively. Reducing the executive demands from motor tasks, for example by breaking down activities into their component parts, or excluding motor or visuospatial processing from tasks with high executive demands, may be an effective strategy to support children with DCD and MD and facilitate learning and retention.

Breaking down tasks into simpler skills is one of the main strategies used by the Neuromotor Task Training (NTT) intervention (Schoemaker, Niemeijer, Reynders, & Smits-Engelsman, 2003), which is a task-oriented programme of intervention effective for children with motor coordination problems (Ferguson, Jelsma, Jelsma, & Smits-Engelsman, 2013; Niemeijer, Smits-Engelsman, & Schoemaker, 2007; Schoemaker et al., 2003). By reducing the complexity of tasks, children experience success more readily and thereby increase their motivation. Similar strategies are also included in the Cognitive Orientation to daily Occupational Performance (CO-OP; Polatajko et al., 2001), which is another intervention with a large evidence base for effectiveness in treating motor problems in children with DCD (Banks, Rodger, & Polatajko, 2008; Martini, Mandich, & Green, 2014; Missiuna et al., 2012). Generally, task-orientated motor skill programmes are most effective in improving motor skills in children with DCD (Preston et al., 2017). The CO-OP is also a task-oriented approach, in which the performance on a child-chosen task is facilitated or improved by the development of cognitive strategies that are specific to the task, the child and his/her environment, enabling him/her to achieve functional goals. The child is guided verbally to use planning, self-regulation, self-monitoring and evaluation (Missiuna, Mandich, Polatajko, & Malloy-Miller, 2001). This provides the child with meta-cognitive strategies that are largely verbal, hence lowers nonverbal EF demands.

Although EF ability was reduced in the nonverbal domain for children with MD and children with DCD (Leonard et al. 2015; Study 1), it should be noted that verbal fluency was additionally affected in children with DCD only (Study 1). Further, longer response times were required by children with DCD (not MD) to perform as accurately as their TD peers in the verbal part of the VIMI (Bernardi et al., 2016). These findings are particularly relevant when considering that *verbal* EF contributed to performance in mathematical tasks in Study 2. Therefore, to support children with DCD effectively, it remains important to focus not only on reducing nonverbal EF demands in everyday and school-related tasks, but also to consider the overall cognitive load of activities, considering that everyday situations require the ability to master both verbal and nonverbal domains of EF simultaneously and adaptably.

Another way of supporting children with DCD and MD may be to focus on improving EF skills. No studies to date have assessed the effect of EF training in children with DCD. However, the literature on typical populations is extensive and does indicate that EFs can be improved in children (Diamond & Lee, 2011) and even in infants as young as 7 months old (Kovács & Mehler, 2009). However, there is little convincing evidence of the transfer of computerised EF training effects to other untrained cognitive skills (Melby-Lervåg & Hulme, 2013; Melby-Lervåg, Redick, & Hulme, 2016), and it is not even established whether transfer effects can be seen across domains of the same EF constructs: for example, whether training nonverbal working memory transfers to verbal working memory (Diamond & Ling, 2016). Importantly, children with initially poor EF abilities benefit the most from training programmes, including children at higher risk of EF problems such as those with ADHD (Holmes et al., 2010). It is possible, therefore, that EF training interventions may be helpful for children with DCD and MD. However, training effects tend to disappear when practice stops (Diamond & Lee, 2011), even in high-risk children such as those with ADHD (Klingberg et al., 2005), so successful interventions may need consistent follow-up.

One finding from EF training research in typical populations that is particularly relevant for children with motor coordination impairments is that interventions with combined motor and cognitive demands tend to yield the greatest effects. These effects are reported to be larger than for purely physical training programmes. For example, the effect of standard PE training on a range of EF domains was significantly smaller compared to traditional martial arts (Lakes & Hoyt, 2004) or yoga and mindfulness training (Manjunath & Telles, 2001) in 5 and 12 year old children respectively. Both martial arts and yoga require inhibition, planning, concentration and problem-solving, as well as learning specific movements. Studies with adults also found that interventions including both physical and cognitive demands produced significantly greater cognitive benefits than physical exercise alone or cognitive training alone (Moreau, Morrison, & Conway, 2015); and in one study these greater benefits were still evident five years later (Oswald, Gunzelmann, Rupprecht, & Hagen, 2006). In children, there is emerging evidence that motor coordination training impacts on cognitive development (Chang, Tsai, Chen, & Hung, 2013; Koutsandréou, Wegner, Niemann, & Budde, 2016; Pesce, Masci, et al., 2016). Essential ingredients of motor interventions that successfully benefit cognitive performance seem to be novelty, diversity, and effort (Pesce, Croce, et al., 2016), which are all aspects crucial to EF.

These results are relevant for children with motor coordination impairments, for whom EF difficulties were mostly evident in domains requiring a visuospatial or motor demand (Study 1; Leonard et al., 2016), and who demonstrated deficits with the coupling of motor control with executive systems (Ruddock et al., 2016). Furthermore, if poor motor skills represent a risk factor whereas EF represents a protective factor, as suggested by the academic and language outcomes in this thesis (Study 2 and Study 3), results showing that combined training is more effective than motor or cognitive training alone are relevant to early educational practice. EF skills, particularly working memory, were found to be already at risk at pre-school age (3-5 years) in children with motor coordination difficulties (Houwen, van der Veer, Visser, & Cantell, 2017). Early education approaches that integrate motor and cognitive components may facilitate the effective coupling of the two systems and, therefore, mitigate motor difficulties before they start to interfere with cognitive and academic competence.

Some school programmes integrating physical activity in the teaching of academic subjects have been developed and researched (see Watson, Timperio, Brown, Best, & Hesketh, 2017, for a recent review). For example one of these programmes (TAKE 10!®) uses action and movements to reinforce academic concepts, such as learning calculations through jumping, or contracting muscles to understand word contractions (Peregrin, 2001). There is extensive evidence that this and similar programmes improve academic performance, both when measured with standardised academic tasks and through school grades (Erwin, Fedewa, & Ahn, 2012; Kibbe et al., 2011). There is also evidence that integrating academic instructions with physical activity facilitates EF itself (Vazou & Smiley-Oyen, 2014) and improves on-task behaviour, which is intrinsically related to self-control and EF (Goh, Hannon, Webster, Podlog, & Newton, 2016; Mahar et al., 2006). Although the roots of the association between physical activity and academic success are still poorly understood, research suggests it is mediated by changes in executive function, memory and fluid intelligence (Tomporowski, McCullick, Pendleton, & Pesce, 2015).

These studies and the results of the current thesis indicate that combining cognitive challenges and physical or hands-on activities and integrating these into leaning experiences may be particularly beneficial in early educational practices for children with typical and atypical motor development. However, such practices may not be suitable for older children who have already developed a clinical condition of DCD with complex cognitive and motor implications. In this case, reducing the executive and motor demands from academic tasks may allow children to express their best potential, to better understand the information delivered during teaching and enhance their learning. Importantly, although this thesis has revealed academic underachievement in mathematics and EF problems in children with DCD, these difficulties were not evident in all children in this group. As discussed in the previous section, the heterogeneity of the DCD population (Vaivre-Douret, 2014) requires that educational and clinical intervention are child-centred and developed on the basis of the specific needs of the child in his/her environment.

One crucial implication for practice of the findings from this thesis is the identification of a group of children with motor difficulties who did not have a diagnosis. Although in Study 2 academic problems were not evident in children with MD, their motor and EF difficulties may represent a risk for *future* academic success, and for other aspects of everyday life such as social engagement (Cummins et al., 2005; Kanioglou et al., 2005), self-perceived competence and participation in physical activities (Cairney et al., 2005; Cairney et al., 2010). Motor difficulties experienced at school-age, when not addressed, may expose children to higher risks of anxiety, depression and lowered self-esteem in adolescence (Skinner & Piek, 2001) and continue to impact academic and non-academic function in adulthood (Tal-Saban et al., 2012). Therefore, poor awareness of the functional impact of motor impairments amongst teachers and practitioners (Kirby et al., 2005) needs to be addressed in order to facilitate early identification and intervention, and mitigate the possible long-term effects of such difficulties.

6.3.3. Limitations and Directions for Future Research

The studies in this thesis have some limitations that should be addressed in future research, as discussed below.

Although the sampling procedure was rigorous, and comprehensive data were collected for each child in a variety of relevant domains, one methodological limitation was the relatively small sample sizes. Specifically, in Study 1 complex statistical techniques such as multi-level modelling and cross-sequential design were not appropriate for the total sample size of 51 participants, hence some more subtle differences in age-related changes in EF ability between groups may not have been captured. Younger children may also be expected to show greater improvements than older children in specific EF domains. Therefore, further longitudinal research addressing the development of EF in children with motor coordination impairment is needed and should aim to recruit larger, age-stratified samples in order to address these issues. In Study 2 and Study 3, although the overall numbers of participants were appropriate for the aims of the studies, the DCD group was small relative to the TD and MD groups. The main reason for this small final DCD sample was that children with additional diagnoses (e.g., ADHD, ASD) and children who showed impairments in other domains (language, reading, intellectual ability) had to be excluded.

This rigorous exclusion procedure was necessary in order to isolate the executive and academic difficulties associated with poor motor coordination impairments. However, the process also reveals another important limitation of the study, namely that the DCD group may not be representative of a ‘real-life’ clinical population of children with DCD because overlapping deficits and comorbid disorders are the rule rather than the exception (Kaplan et al., 1998). Further research investigating EF and academic profiles in children with DCD and co-occurring conditions is important in order to inform clinical and educational practices in relation to how to support *all* children with DCD.

One issue worth considering is the nature of the EF assessments and how relevant they are to everyday life. The EF measures adopted throughout this thesis were standardised and/or experimental measures of EF in which task demands were set by the experimenter. Such measures may not necessarily represent the demands of EF tasks in everyday life. It has been suggested that questionnaire measures of EF may involve a somewhat different skill set than behavioural EF tasks such as those used here (Toplak, West, & Stanovich, 2013). Rating scales, such as the BRIEF (Gioia, Isquith, Guy, & Kenworthy, 2000), have been developed to assess behaviours that are relevant to everyday functioning, which may be very different than EF assessed through performance-based measures administered in highly standardised conditions. More ecologically valid performance-based measures of EF assessing real-life situations, in which participants face unconstrained and complex problem-solving situations, might further contribute to understanding EF difficulties associated with poor motor skills (Leonard & Hill, 2015). Furthermore, it will be important in future research to use EF measures that include emotional and motivational aspects of behaviour, which are also referred to as ‘hot’ EFs. These are related to self-control and emotional regulations and some recent research has revealed atypical patterns of functioning in measures of hot EF in children with DCD (Rahimi-Golkhandan, Piek, Steenbergen, & Wilson, 2014; Rahimi-Golkhandan, Steenbergen, Piek, & Wilson, 2015).

The academic achievement measures also had some limitations, specifically the fact that only one aspect in each academic domain was assessed. For example, although no deficits were identified in word reading and spelling tasks, future research may benefit from including measures of: reading comprehension because poor motor skills may represent a risk when reading involves complex understanding of written text (Cheng et al., 2011); written expression, as it may be that when compositional demands are added to the task of writing, spelling mistakes appear (Prunty et al., 2016); and oral expression, since these are all tasks expected to be performed on a daily basis at school. Furthermore, given the difficulties of children with DCD in the numerical operations task, future research should include further measures of verbal mathematical reasoning, thus excluding the written component of the task (i.e., its motor demand), as well as more specific measures of numerical cognition, to understand the root of mathematical difficulties in children with DCD.

Finally, for both Study 2 and Study 3, EF composite scores were used in order to maintain appropriate statistical power given the sample sizes. Future research with larger samples could unpick which particular aspects of EF contribute the most to academic and language performance, and whether these are best explained by specific EF constructs or by a continuous model of EF impairments in which the number of affected EFs provides the best indicator of outcomes (Leonard & Hill, 2015).

6.4. Summary and Conclusions

The studies reported in this thesis are the first to investigate a range of EF constructs longitudinally, and to consider the impact of EFs on academic and language outcomes, in children with and without motor coordination impairments. Study 1 identified EF difficulties that were persistent and pervasive in children with a diagnosis of DCD, but that were also present in children with MD. EF difficulties were mostly related to nonverbal domains of EF, suggesting a specific dysfunction in the coupling of executive and motor or visuospatial ability. These nonverbal EF difficulties did not explain the poorer mathematical achievement demonstrated in Study 2 by children with DCD compared to TD children and to the population norm. Poorer EF and maths performance in children with DCD indicate that the broader cognitive implications of the condition need to be taken into account when planning educational and clinical support for these children. However, not all children with DCD demonstrated such difficulties, therefore individual assessment in the contextual situation of the child remains crucial to effective management and intervention. Children with MD had adequate academic performance but persisting EF difficulties in visuospatial working memory and design fluency. Poor motor and EF skills may, therefore, impact on the everyday life of children with MD. Importantly, these children are likely to experience difficulties without being recognised as ‘children at risk’ and without receiving the support that is provided to children with a diagnosis. Early identification of poor motor skills is crucial to mitigate long-term negative effects on cognition, learning, socialisation and participation.

A composite score of verbal EFs predicted overall performance in mathematics, and both verbal and nonverbal EFs predicted language outcomes through their interaction with motor coordination. Study 3 was the first investigation to identify motor coordination as a moderator of the effect of EF on language. This finding contributes significantly to the research in this area, considering that recent studies on the relationship between EF and language suggest that a third factor may be involved.

EF predicted language at low and moderate levels of motor skills, indicating that EF abilities are particularly relevant to language when a risk factor such as poor motor coordination is present. This was true regardless of the diagnostic group these children were assigned to, and included typically developing children with moderate motor skills. The same pattern may be identified in other developmental outcomes, including academic achievement, and future research should attempt to explore these issues.

In conclusion, a reciprocal interaction between EF and motor coordination produced complex effects on academic and language outcomes. Results from this thesis support the notion that an integrated and dynamic approach to typical and atypical development is most adequate to investigate the close relationships between cognitive and motor domains, and argue that such an approach should guide clinical, educational and research practices.

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Appendices

Appendix A. Ethical Approval

CITY UNIVERSITY
LONDON

16 January 2015

Dear Marialivia / Lucy / Nikki

Reference number: PR/LCS/PhD/14-15/01

Name: Marialivia Bernardi

Title of project: Executive Functioning in Children with Poor Motor Skills

I have reviewed the changes to your forms, and am happy to approve the application from today's date.

Best of luck with your project.

Please note the above reference number which identifies this application and **must be quoted in all correspondence.**

Kind regards

[redacted]

pp Lucy A. Henry

[redacted]

Appendix B. Information sheet and consent form

CITY UNIVERSITY LONDON

Goldsmiths UNIVERSITY OF LONDON

Moving on Up

A study of movement and complex thinking skills in children

Dear Parents/Carers,

We would like to invite you to take part in a research study. Before you decide whether you would like to take part it is important that you understand why the research is being done and what it would involve for you. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

The study will help us understand the ways in which children differ from one another and lead to a better understanding of their cognitive development. Last year a number of children took part in the *Moving on Up* study, looking at the relationship between movement and complex thinking skills. This research tested the idea that the development of motor abilities, such as balancing, throwing, catching and drawing, can change the way that we process the world around us and, therefore, how we develop complex thinking skills. We have obtained very interesting results, which we have explained in the leaflet attached. These findings need further research so this project is a follow-up study to understand how complex thinking skills change after two years, and how movement impacts on educational achievement. The project will take up to three years to be completed.

Why have I been invited?

You are invited to consent for your child to participate in a number of activities which are appropriate for children between 7 and 14 years of age. We are hoping to recruit a total number of 250 children, which will allow us to make interesting conclusions about children's learning at this stage of their life, but we need your help to reach this number.

Do I have to take part?

Participation is voluntary. It is up to you and your child to decide whether or not to take part. You can choose not to participate in part or all of the project. If you do decide to take part you will be asked to sign a consent form. If you decide to take part, you and your child are still free to drop out at any time, at any stage of the project, without giving a reason and without being penalised or disadvantaged in any way.

What will happen if I take part?

The study will involve a number of questionnaires for you to complete, in addition to the tasks in which your child will participate. Questionnaires will be related to movement and behaviour of your child across a range of different situations and some demographic information about your family. The questionnaires are attached to this form. We are happy to help you with any items that you find difficult or for which you need clarification and we can complete the questionnaires over the phone with you. The questionnaires will take around 20 minutes to complete. We are also going to gather information from your child's teacher concerning his/her strengths and difficulties in school and end of year results. All information collected will be anonymous so that your child's data cannot be linked to his/her identity. The tasks that your child will complete are outlined below, and will take place at [your home or at City University/ [name of school] Primary School]

'*Sports Stars' games*

These fun and active games will measure ball skills and balance. After throwing, catching, balancing and jumping your child will feel like a 'sports star champion' by the end!

'*Words and Pictures' games*

This collection of short games will measure your child's vocabulary and reasoning skills. Some elements are timed, so we make it into a fun race to complete the task!

These tasks will take around an hour and a half to complete, and will be split up into shorter sessions to ensure that your child does not [miss out on lessons/become too tired].

Some children will also be asked to complete some extra tasks, including memory, reading, drawing and speaking and listening games. Other games involve copying the researcher's words / actions (or learning to do the opposite), switching between different rules of a game and sorting cards into different categories. Also, some games will involve solving problems with numbers, and understanding a story while reading or listening. All of these individual tasks are very short, and they will be split up so that your child will not [spend too long out of the classroom/become too tired] at any one time. In total, these tasks will take up to two hours. Tasks will be explained at the beginning of each session and your child will be asked if she/he wish to take part in the games. After approximately **two years**, your child will be followed up and will complete the same range of tasks one more time.

Expenses and Payments

If you visit the University for the project any travel expenses will be reimbursed. Otherwise, we will test your child at school involving no expense on your part.

What do I have to do?

Once you return the signed consent form and completed questionnaires, your child will participate in the tasks described above. If at any time you or your child do not wish to take part in the activities, we will not expect you to do so.

What are the possible disadvantages and risks of taking part?

There are no risks of harm or side effects related to participation in the study. The activities are all enjoyable and fun for children to complete. However, we will make sure that your child does not [spend too much time out of the classroom / become too tired] and we will be monitoring his/her engagement at all time. All researchers involved in the project have extensive experience of working with children of all ages and also hold a current CRB check, enabling us to work with the children individually.

What are the possible benefits of taking part?

There are no direct benefits to you or your child. However, movement and complex thinking skills are extremely important in the classroom and everyday life, and understanding the factors that affect these skills will help us to identify children at risk of falling behind and give them extra support.

What will happen when the research study stops?

Data collected for the study will be stored securely and anonymously for a minimum of ten years, in order for them to be available for future longitudinal studies.

Will my taking part in the study be kept confidential?

We will keep all information collected in confidence. This means we will only tell those who have a need or right to know. None of your child's data will be passed on to the school or your GP without your explicit consent. Exceptions to confidentiality include information concerning the personal safety of your child. Published reports based on these studies will not mention individuals. Your child's file will be given a code number rather than a name for us to identify it and will be kept in secure cabinets and password-protected computers, with only research team members having any access to identity information. After ten years, paper records of data collected for the research will be shredded. Audio/video recording, computer files and electronic copies of the data will be permanently deleted from all storage sources.

What will happen to results of the research study?

The results of the research study will be included in articles published in academic journals and professional magazines, will form part of a PhD thesis and will be presented at conferences. Anonymity and confidentiality will be kept at all times and published reports based on these studies will not mention individuals. We will share our findings with you and you will receive a feedback leaflet giving a summary of the implication of results.

What will happen if I don't want to carry on with the study?

Participation is voluntary and you or your child may choose to drop out, including while your child is completing the tasks and up until the study results are accepted for publication. You will not have to give any reason and there will be no adverse consequence for your decision.

What if there is a problem?

If you have any problems, concerns or questions about this study, you should ask to speak to a member of the research team. If you remain unhappy and wish to speak to someone independent from the study, you can do this through the University complaints procedure. You need to phone 020 7040 3040. You can then ask to speak to the Secretary to Senate Research Ethics Committee and inform them that the name of the project is: 'Moving on Up. A study of movement and complex thinking skills in children'

You could also write to the Secretary at:
Anna Ramberg
[redacted]
Email: [redacted]

Who has reviewed the study?

This study has been approved by City University London Language and Communication Sciences Proportionate Review Research Ethics Committee.

Further information and contact details

If you have any questions about the research at any time, please feel free to contact Livia, ([redacted] or [redacted]), who will be conducting most of the activities with your child. You can also contact the lead researcher Professor Lucy Henry on [redacted] or on [redacted]

Thank you for taking the time to read this information sheet.

Yours faithfully,

The research team,

Professor Lucy Henry, Professor Nicola Botting and Marialivia Bernardi (City University, London)

Professor Elisabeth Hill and Dr Hayley Leonard (Goldsmiths, University of London)

Moving on Up

A study of movement and complex thinking skills in children

Please initial box

1.	I agree to take part in the above City University London research project. I have had the project explained to me, and I have read the participant information sheet, which I may keep for my records. I understand this will involve: • Complete questionnaires asking me about my child's behaviour and my familiy's demographic information • My child taking part in a range of activities including movement games, thinking games, number games, reading and listening games. • My child being videotaped during some of the tasks	
2.	This information will be held and processed for the purpose of understanding the relationship between movement, complex thinking skills and academic achievement. I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party. No identifiable personal data will be published. The identifiable data will not be shared with any other organisation. I consent to the videotapes being shown to other researchers and interested professionals	
3.	I understand that my participation is voluntary, that I can choose not to participate in part or all of the project, and that I can withdraw at any stage of the project without being penalized or disadvantaged in any way.	
4.	I agree to City University London recording and processing this information about me. I understand that this information will be used only for the purpose(s) set out in this statement and my consent is conditional on the University complying with its duties and obligations under the Data Protection Act 1998.	
5.	I agree to take part and consent to my child's participation in the above study	

________________	______________________	__________
Name of Participant	Signature	Date
________________	______________________	__________
Name of Child	Date of Birth	School Class

When completed, 1 copy for participant; 1 copy for researcher file.

Appendix C. Assent Form

CITY UNIVERSITY
LONDON

Goldsmiths
UNIVERSITY OF LONDON

Moving on Up Study

I'd like you to play some games with me, and before we do each activity, I will tell you exactly what I want you to do. If you're not sure what I mean, you can ask me to explain some more.

When we're doing the activities, if you don't like any of them, or you don't feel like doing them anymore and want to stop, then you just have to tell me and we'll stop as soon as you say so. You don't have to tell me why you want to stop, as long as you tell me as soon as you want to stop that's fine.

Your parents have said that you can do it, but I need to make sure that you want to play the games with me and that you know that you can stop playing if you need to. Would you like to play the games with me?

Any questions?

Child Signature
……………………………………………………………………………………………………

Researcher Signature ……………………………………………

Date……………………………………………………

Appendix D. Follow-up Form

CITY UNIVERSITY LONDON

Goldsmiths UNIVERSITY OF LONDON

[Date]

Dear Parents / Carers,

We would like to thank you for your kind participation in our *Moving on Up* project. As explained in the information sheet we would like to follow-up participants in the study after two years. If your child is currently in Year 5 or 6, or if you are planning to change school in the future, we would like to take your contact details so that we can get in touch in two year time after your child has left primary school. Please note that if your child is in Year 5 or 6 you will need to attach this information to the consent form in order for your child to be included in the research. As for the rest of the data, your contact details will be stored securely, in locked filing cabinets and on password-protected computers for a maximum of ten years, with only research team members having any access to identity information.

Thank you for your cooperation.

The research team,

Professor Lucy Henry, Professor Nicola Botting and Marialivia Bernardi *(City University, London)*

Professor Elisabeth Hill and Dr Hayley Leonard *(Goldsmiths, University of London)*

Contact Details

Date completed________

Name of child ____________________

Age of child ____________________

Year group ____________________

School to be attended ____________________

Name of parent / carer ____________________

*Telephone ____________________

*Address ____________________

*Email

*Name of relative ____________________

Relationship of relative to child ____________________

Telephone number of relative ____________________

*We ask that you provide at least one of these methods of contact, but would appreciate as much information as possible in case you move house or change phone number etc. We also ask for the contact details of a grandparent or relative for the same reason, although this is not compulsory.

Appendix E. Percentile equivalents for the MABC-2 Total Sum of Standard Scores

Total Sum of Standard Scores	Percentile
108+	99.9
105-107	99.5
102-104	99
99-101	98
96-98	95
93-95	91
90-92	84
86-89	75
82-85	63
78-81	50
73-77	37
68-72	25
63-67	16
57-62	9
50-56	5
44-49	2
38-43	1
30-37	0.5
<29	0.1

Appendix F. Details of regressions analyses plotted in Figures 5.1-5.4

for the effect of EF on language in participants with motor skills less than one SD below the sample mean, around the sample mean, and more than one SD above the sample mean.

	Expressive Language		**Receptive Language**	
EF Effect	***Verbal EF Model 1***	***Nonverbal EF Model 2***	***Verbal EF Model 3***	***Nonverbal EF Model 4***
Motor skills ≤ -1SD				
R^2	$.255^{**}$	.096	.036	$.164^{*}$
β (SE)	*.471 (.159)*	*.443 (.267)*	*.142 (.148)*	*.474 (.210)*
	p=.007	*p*=.109	*p*=.346	*p*=.032
Motor skills around the mean (-1SD<motor skills <+1SD)				
R^2	$.090^{*}$	$.062^{*}$	$.096^{**}$	$.104^{**}$
β (SE)	*.229 (.076)*	*.176 (.073)*	*.284 (093)*	*.278 (.086)*
	p=.005	*p*=.017	*p*=.003	*p*=.002
Motor skills ≥ +1SD				
R^2	.002	.037	.065	$.141^{*}$
β (SE)	*.041 (155)*	*-.162 (.163)*	*-.178 (.125)*	*.288 (.132)*
	p=.809	*p*=.328	*p*=.165	*p*=.038

Note. The total R^2 unstandardized beta values, and *standard errors* are reported for the EF effect on language in each model.

p* ≤ .05; ** *p* ≤ .01; * *p* ≤ .001; † *p* ≤ .06 non-significant trend.