Cognition and maths in children referred for ADHD assessment

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Declaration

I hereby declare that this thesis was composed by me and that the work presented here is my own, except where due acknowledgements are made. I certify that this work has not been submitted for any other degree of professional qualification.

The thesis includes three chapters submitted for publication which are under review:

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Abstract

Attention Deficit Hyperactivity Disorder (ADHD) is a lifelong neurodevelopmental disorder. ADHD symptoms manifest as persistent inattention, hyperactivity, and/or impulsivity. Children with ADHD also show pervasive difficulties in cognitive processes including Executive Functions, memory, and processing speed – processes hypothesised to underpin academic success. Many children with ADHD struggle with maths, as demonstrated by lower levels of attainment and higher incidence of maths learning difficulties. Maths abilities predict a range of outcomes in adulthood and therefore represent a particularly important area of investigation in this population. However, much of the previous research relies on broad attainment tests to explore maths performance. Such tests risk masking more intricate sources of maths difficulties. Specifically, three maths components are proposed to support broad maths achievement in children: factual knowledge, conceptual understanding, and procedural skill. These skills have not yet been explored comprehensively in children with ADHD.

Not all children with ADHD show difficulties with maths and some perform similarly to their neurotypical peers. The source of this within group variability has previously been attributed to differences in behavioural symptom presentations, such as inattention. Given that behavioural manifestations are closely linked to differences in neurocognitive abilities, which are also notoriously diverse in ADHD, cognitive mechanisms could offer a better explanation for heterogeneity in maths performance. Keeping the componential nature of maths skills in mind, the broad aim of this thesis was to conduct a comprehensive investigation into their relationship with behavioural and cognitive processes in a clinical ADHD population. Exploring how performance across these components relates to behavioural and cognitive functioning in ADHD

can help inform pathways of risk for maths difficulties and act as a steppingstone to devising educational interventions.

Following the General Introduction, Chapter 2 includes a systematic review of existing literature addressing the association between previously implicated cognitive processes and maths performance in ADHD. To date, studies on the relationship between cognition and maths in ADHD have not been systematically reviewed making it difficult to appraise research in this area. The results showed a positive association between cognition and maths performance in this population. However, very few studies met inclusion criteria and those that did, only assessed a limited number of relevant cognitive domains. The results of this chapter demonstrate a lack of research into the relationship between cognition and maths in clinical ADHD and, via quality appraisal, highlight key methodological considerations for future research.

Chapter 3 contains the General Methodology which explores the methodological decisions employed for the remaining study chapters such as participant inclusion and materials used. This chapter also provides information on procedures used, ethics, participant characteristics, missing data, sample size, and data preparation.

Chapter 4 comprises a comprehensive investigation of cognition, behaviour, and maths in 44 drug naïve children on the waiting list for ADHD evaluation at Child and Adolescent Mental Health Services. The results showed that cognition, rather than ADHD symptoms, correlated with both standardised maths attainment scores and more specific components of maths skills. In particular, verbal, and visuospatial aspects of memory functioning showed the strongest associations with maths across the board. This suggests that cognitive processes, rather than clinical ADHD symptoms, are more informative for maths performance in children with clinically high

ADHD symptoms and represent viable targets for future research on maths interventions. This chapter also demonstrated high rates of co-occurrence with other neurodevelopmental disorders which must be considered when characterising ADHD samples.

Chapter 5 built on the richness of the clinical characterisation in the preceding chapter, which found that around half of the sample showed motor difficulties indicative of Developmental Coordination Disorder (DCD). Specifically, this study divided the sample into two groups – one with high ADHD and DCD symptoms (ADHD + co-occurring motor difficulties) and one who scored lower on the DCD assessment screener (ADHD-only). The results showed that these groups were comparable in terms of maths performance and in many of the cognitive tasks. However, the ADHD + co-occurring motor difficulties group showed significantly poorer performance on visuospatial WM than the ADHD-only group. This highlighted visuospatial WM as a clinically informative and distinguishing feature of children with concurrently high DCD symptoms. Overall, the strength of associations between cognitive processes and maths skills did not differ. This further pointed to cognitive dimensions as more informative mechanisms in relation to maths, than that of diagnostic symptomatology.

The final study chapter, Chapter 6, compared a traditional categorical grouping approach (i.e., clinical ADHD vs no clinical ADHD diagnosis) to that of a data-driven grouping approach (i.e., groups based on children's cognitive data). This chapter demonstrated that a categorical diagnostic approach was not informative of children's maths outcomes. By contrast, the data-driven approaches, which grouped children using relevant cognitive performance, generated meaningful cognitive subgroups which could be differentiated on their maths, as well as intelligence scores. This

suggests that cognitive patterns of performance, rather than children’s diagnostic outcomes, are more informative for identifying meaningful groups of struggling learners.

Collectively, the current thesis is the first to provide a comprehensive investigation of maths skills in a clinically referred and drug naïve sample of children with high ADHD symptoms. Throughout this thesis, practical and theoretical implications for future work in ADHD are discussed.

Lay Summary

ADHD is one of the most common developmental disorders, the effects of which can last a lifetime. Children with ADHD struggle focusing and controlling attention, can be hyperactive, and/or impulsive. Many, but not all, children with ADHD also struggle with maths at school – which is an important academic area for life success. A crucial question is: what causes some children with ADHD problems in maths, while other children with ADHD do not show maths difficulties? It is thought that the reason why some children with ADHD struggle with maths is because of difficulties that they experience with their attention and memory – key thinking processes thought to support maths learning. There is also evidence to show that, just like with maths, children with ADHD vary in their performance on tasks assessing thinking processes like attention and memory. It is therefore possible that variability in maths could be due to underlying differences in thought processes.

Previous work looking at maths in ADHD mainly use maths achievement tests which, using an overall score, tell us how well a child is performing compared to other children their age. However, these are too broad and can overlook which specific skill(s) is causing the child to struggle. For example, is it because the child has difficulties remembering addition and subtraction facts from memory (also known as factual knowledge)? Or is it because of problems with understanding numerical concepts such as the relationship between addition and subtraction (also known as conceptual understanding)? Alternatively, is their underachievement due to difficulties in carrying out numerical computations (also known as procedural skill)? Any one, or all three, of these skills could cause a child to score low on broad attainment tests and be flagged as an ‘underachiever’. It is therefore important to assess these more specific maths components and explore which thinking processes are most closely related to this skill(s). This can help establish which thinking process are related to difficulties with a specific math skill. It can also help researchers decide on what type of intervention strategies they can develop to support maths learning in a way that relates to children's specific needs.

Chapter 2 systematically investigated existing published work which looked at the relationship between thinking processes and maths in children with ADHD. The purpose of this was to collate and assess the quality of existing studies in this area. The review found generally better performance on tasks assessing thinking processes, were related to better performance in maths. However, very few studies actually addressed this issue, which demonstrated that research in this area is scarce and highlighted some important gaps that need to be addressed by research. The broad methodological decisions employed for the experimental study chapters are discussed in Chapter 3.

Chapter 4 assessed ADHD symptoms, thinking processes (e.g., attention and memory), maths attainment, and maths skills (i.e., factual, conceptual, and procedural) in children who were on the waiting list for ADHD evaluation. The results showed that children's memory for verbal (e.g., letters) and visuospatial (e.g., shapes) information was closely associated with their maths performance. By contrast, parent rated ADHD symptoms were not as closely related to maths. This indicated that memory skills could be more important for maths performance than behavioural traits. This study also found that around half of the children showed behavioural characteristics of another disorder – Developmental Coordination Disorder, which negatively affects children's movement and thinking abilities.

In Chapter 5, a study is presented which divided children with high ADHD symptoms into two groups: one with movement difficulties and one who scored low on a measure of movement difficulties. When these two groups were compared in their thinking processes and maths, it was found that they were largely similar except for one specific aspect of memory. Children with high movement difficulties performed more poorly on a measure which assessed children's ability to manipulate visuospatial information (i.e., shapes) in memory. This suggests that manipulation of visuospatial information can distinguish children with ADHD with and without co-occurring movement difficulties.

The final Chapter 6 explored different ways of grouping children and how informative such groupings are to children's maths performance. The findings of this final chapter revealed that grouping children on the basis of whether or not they ended up receiving an ADHD diagnosis (i.e., categorical approach) was not informative to how well children performed in maths. By contrast, grouping children based on their thinking scores (i.e., data-driven approach) resulted in distinct groups that varied in their maths performance. Furthermore, these thinking subgroups did not differ in ADHD symptoms, nor in other co-occurring symptoms. This suggests that data-driven thinking profiles are more useful for identifying groups of struggling learners. Together this work is the first to explore thinking processes and maths skills in ADHD.

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1 Chapter 1: General introduction

The broad aim of this research was to explore cognitive processes and maths performance in a drug naïve sample of children referred for ADHD assessments at the Child and Adolescent Mental Health Services (CAMHS). Specifically, it sought to investigate children's performance on a comprehensive battery of cognitive tasks previously implicated in ADHD and identified as important to maths competencies. Additionally, this research aimed to explore children's performance on broad maths achievement tests as well as more specific maths skills. The present chapter introduces ADHD and other frequently co-occurring disorders, with particular attention to aetiological factors and cognitive characteristics. This will be followed by a brief introduction to children's development of maths components skills before focusing on maths in the context of ADHD.

1.1 ADHD

1.1.1 Definition of ADHD

Attention Deficit Hyperactivity Disorder (ADHD) is one of the most common neurodevelopmental disorders, typically diagnosed at around 7-9 years (Polanczyk et al., 2015). ADHD is included in the Diagnostic and Statistical Manual of Mental Disorders – 5th edition (DSM-5) under the Neurodevelopmental Disorders section (APA, 2013; Kessler et al., 2009). Cardinal features of ADHD include developmentally excessive and persistent (i.e., lasting for at least six months) symptoms of hyperactivity, impulsivity, and/or inattention. To receive a diagnosis, symptoms must manifest across two or more settings including the social, familial, educational, and/or occupational contexts, and should engender a certain degree of impairment to daily functioning (APA, 2013; Biederman & Faraone, 2005). There are three conventional subtypes of ADHD presentations. The ADHD-Inattentive presentation affects between 15-30% of patients and is characterised by difficulties focusing and sustaining attention, distractibility, forgetfulness, disorganization, inability to follow instructions, and carelessness (APA, 2013; Mayes et al., 2000; Rowland et al., 2015). The ADHD-Hyperactive/Impulsive presentation affects approximately 3-15% of cases and is characterised by restlessness, impulsivity, excessive movement and talking, as well as difficulty engaging in playing and leisure activities quietly (APA, 2013; Mayes et al., 2000; Rowland et al., 2015). Lastly, the ADHD-Combined presentation is the most commonly diagnosed profile, affecting between 50-85% of cases, which reflects the amalgamation of core features of both the hyperactive and inattentive subtypes (Setyawan et al., 2018; Mayes et al., 2000).

Like many other neurodevelopmental disorders ADHD is historically conceptualised and treated according to dichotomous diagnostic classification systems (Marcus & Barry, 2011). However, more recently researchers have endorsed a compelling case for defining ADHD in terms of symptom dimensions, arguing that conventional categories are an oversimplification of the disorder (Heidbreder, 2015). Rather, evidence shows that ADHD may be best conceptualised on a severity continuum (Frazier et al., 2007; McLennan, 2016). For example, a large twin study found a substantial genetic link between extreme ADHD symptoms and subthreshold symptoms implying that similar etiological factors are involved in symptom manifestation (Larsson et al., 2012). Further, diagnostic categories are developmentally volatile – a child who meets criteria for ADHD-Combined early on in childhood may progress to meet ADHD-Inattentive diagnosis later in life due to the tendency for symptoms of hyperactivity and impulsivity to decline over time (Vergunst et al., 2019). Lastly, ADHD confers significant risk on educational attainment, employment, substance misuse, poor mental health, antisocial behaviour, and criminality (Ramos-Olazagasti et al., 2018; Frazier et al., 2007; Klein et al., 2012; Kuriyan et al., 2013; Taylor et al., 2019; Uchida et al., 2018). Even in cases with high subthreshold ADHD symptoms, which fall short of a clinical criteria for a diagnosis, high symptoms predict a range of adverse outcomes (Czamara et al., 2013; Fergusson & Horwood, 1995; Hong et al., 2014; Karalunas & Nigg, 2020; Marcus & Barry, 2012; Russell et al., 2014; Sayal et al., 2018; Thapar & Langley, 2006). Thus, debilitating ADHD symptoms can negatively impact children's quality of life regardless of whether or not they end up receiving a clinical diagnosis. Not only does this carry negative consequences for the child, but it also incurs increased financial costs on health, education, and social care services (Doshi et al., 2012; Hakkaart-van et al., 2007). This renders timely identification and treatment of clinically high ADHD symptoms as pivotal in alleviating or averting adversities in the long run.

1.1.2 Prevalence of ADHD

In the UK, around 1.5% of school-aged children are diagnosed with ADHD and, of these, boys are more likely to receive a diagnosis than girls (2.2% and 0.5%, respectively; NICE, 2016; Russell et al., 2014). This is comparatively lower than global prevalence estimates of around 3.4% to 5.3% (Polanczyk et al., 2007), although when both diagnosed and undiagnosed children are considered UK prevalence rates increase slightly to 2.13% (Russell et al., 2014). A previous report found that in Scotland prevalence of ADHD have marginally increased from 0.6% in 2007 to 0.7% in 2011, with a male to female ratio of 6:1 and medicated male to female ratio of 4:1 (Services Over Scotland, 2012). In Scotland, diagnosed and treated childhood ADHD prevalence rates are around 1%, with those receiving medication as more likely to be male (Fleming et al., 2017). Lower rates of diagnosis could be attributed to barriers such as negative public attitudes towards ‘medicalisation’ and lack of, or outdated, healthcare service recognition of validity of ADHD (Mynors, 2017).

The male preponderance of ADHD likely reflects the tendency of the disorder to be under-recognised in girls. This is supported by research showing that the male to female ratio of ADHD decreases from approximately 4 to 1 in childhood, to be equal proportions during adulthood (Rao & Place, 2011; Russell et al., 2014). Girls are more likely to present symptoms of inattention – a profile presentation that is less obvious to knowledgeable informants at home or school (Gershon, 2002; Quinn & Madhoo, 2014). Boys, on the other hand, are more likely to show overt symptoms of impulsivity and hyperactivity, resulting in greater clinical suspicion and higher referral rates (Ohan & Visser, 2009). Additionally, in girls higher incidence of co-occurring anxiety and mood disorders can misguide an ADHD diagnosis, whilst higher rates of co-occurring Obsessive Compulsive Disorder (OCD) and perfectionism may forge coping strategies that attenuate or mask tangible symptom presentations (Rucklidge & Tannock, 2001; Quinn & Madhoo, 2014).

Although symptom decline has been documented in some cases, ADHD is recognised as a chronically debilitating disorder. Up to 76% of children qualify for at least one definition of persistence into adulthood (Biederman et al., 2010; Döpfner et al., 2015; Faraone et al.,2006; Harpin, 2005). A meta-analysis of studies following children up longitudinally found that around 15% of adults with a childhood ADHD diagnosis continued to meet criteria for ADHD (i.e., syndromatic persistence), while 65% of these adults now met subthreshold ADHD criteria (i.e., symptomatic persistence; Faraone et al., 2006). Another 10-year follow up study of boys with ADHD showed that rates of syndromatic and symptomatic persistence were 35% and 22% respectively, with an additional 15% qualifying as functionally impaired (Biederman et al., 2010). Notably, although some adults no longer qualified for traditional DSM criteria, just under 80% still showed clinically high symptoms of ADHD, had substantial ADHD impairments, and/or were still undergoing ADHD treatment. A more recent study found that over half of children with ADHD experience fluctuating persistence and remission without clear recovery (Sibley et al., 2021). Risk factors for persistence include severity of ADHD at baseline, pharmacological treatment, higher levels of psychiatric co-occurrences, familial history of mood disorders, and higher rates of educational and interpersonal dysfunction (Biederman et al., 2010; Caye et al., 2016; McAuley et al., 2017). In girls, ADHD persistence is predicted by higher rates of hyperactivity and behavioural difficulties at baseline (Mick et al., 2011). Importantly, negative consequences of both remission and persistence on educational outcomes are documented in childhood ADHD (Wu & Gau 2013; Mick et al., 2011). This highlights the importance of monitoring and combatting educational difficulties during early years, irrespective of the longitudinal trajectory status.

1.2 Co-occurring disorders in ADHD

ADHD co-occurs with other psychological disorders. Albeit non-exhaustive, the section below briefly addresses some of the most frequently co-occurring disorders and explores their relevance in the context of children’s educational outcomes.

1.2.1 Externalising behaviour disorders

Externalizing disruptive behavioural difficulties, namely Oppositional Defiant Disorder (ODD) and Conduct disorder (CD), are amongst the most frequently diagnosed in ADHD with co-occurrence rates ranging between 40%-60% and 10-20%, respectively (Bendiksen et al., 2020; Elia et al., 2008; Jensen & Steinhausen 2015; Larson et al., 2011; Maughan et al., 2004). Cardinal features of ODD include persistent disobedient, uncooperative, and irritable behaviours directed towards authority figures and peers. Children with CD mainly exhibit aggression, destruction of property, and relentless violation of social norms and rights of others (APA, 2013; Hamilton & Armando, 2008; Glicken, 2009). Thapar and colleagues (2006) found that diagnosis and severity of ODD significantly predicted CD trajectory during adolescence, irrespective of ADHD severity at baseline. In another study ODD largely mediated the co-occurrence between ADHD and CD, rendering ODD as an important clinical precursor to CD (Tick et al., 2007). Indeed, ODD and CD appear to be developmentally intertwined (Rowe et al., 2002). Some suggest that the co-existence of ADHD, ODD, and CD could be driven by a common genetic vulnerability to a general disruptive behaviour syndrome, with profile expressions varying as a function of environmental influences specific to externalising disorders (Azered et al., 2018; Ghosh & Sinha, 2012; Nadder et al., 2002). Notably, however, evidence points to greater genetic contributions in ADHD manifestation, than ODD (Azered et al., 2018; de Zeeuw et al., 2015). Environmental factors found to contribute to the development of ODD and CD include familial adversities such as maternal depression, parental substance dependence and crime (Rowe et al., 2002; Knopik et al., 2015)

There is support for augmenting effects of co-occurring ODD and CD on children's school achievement whereby behavioural difficulties and symptoms of ADHD produce additive effects on the number of grades achieved (Sayal et al., 2015). However, Cuffe and colleagues (2020) found that the odds for below-average school performance were twice as high for children with ADHD with or without co-occurring behavioural disorders than that of CD or ODD alone. Thies imples that academic difficulties observed in ADHD predominantly arise from factors other than externalizing behaviour problems (Daley & Birchwood, 2009). Nonetheless, it is possible that ODD and CD negatively impact scholastic performance indirectly via adversities on classroom behaviour and social adjustment (Connor & Doerfler, 2008; Liu, Huang, Kao & Gau, 2017).

1.2.2 Autism Spectrum Disorder

Between 20-60% of children with ADHD meet criteria for Autism Spectrum Disorder (ASD) – a clinical label used to refer to developmental difficulties in social-communicative functioning and restricted repetitive behaviours (Mulligan et al., 2009; Lord et al., 2020, Young et al., 2020). ASD is highly heterogneous, such that the severity of difficulties presented by children are subject to marked variability (Masi et al., 2017). Broadly, ASD is characterised by core difficulties with social functioning and communication, ritualistic behaviours, stereotypies, sensory anomalies, and varying degrees of intellectual functioning (APA, 2013; Lord et al., 2020). Social functioning difficulties are also documented in children with ADHD (Gardner & Gerder, 2013; Stenseng et al., 2016). This includes fewer and lower quality friendships, as well as higher rates of peer rejection and victimization (Hoza, 2007). Further, communication impairments are also frequently found in ADHD (Leitner 2014; Reiersen et al., 2007).

Children with ADHD have substantial pragmatic language difficulties (i.e., social use of language) when compared to neurotypical children (Staikova et al., 2013). Pragmatic difficulties in ADHD tend to be of a similar magnitude as their high functioning ASD peers (Geurts & Embrechts, 2008). However, children with ASD struggle more substantially with specific aspects of pragmatic language than those with ADHD, which includes non-verbal communication use (e.g., eye contact), social relationships, and use of context during conversation (Geurts & Embrechts, 2008). Lower verbal IQ scores are found in both ASD and ADHD and these tend to cluster with symptoms of inattention and impulsivity, as well as social difficulties (Sokolova et al., 2017). Possibly, this is due to their imperative role in self-directed speech which requires self-control, expressive language, and language comprehension.

Like children with ADHD, those with ASD show diminished neurocognitive functioning when compared to neurotypical children (Craig et al., 2016). Additionally, Theory of Mind (i.e., the ability to mentalise) and emotion recognition difficulties are common to both disorders, although tend to be more pronounced in ASD than in ADHD (Bora & Pantelis, 2016). Nonetheless, whilst socio-cognitive difficulties in ADHD are typically attributed to broader cognitive complications, difficulties with Theory of Mind are more commonly linked to ASD traits (Lukito et al., 2017). This supports the additivity model according to which co-occurrence between ADHD and ASD stems from distinct yet correlated risk factors (Siznig et al., 2008; Lukito et al., 2017). Crucially, co-occurrence between these disorders carries increased risk for educational adversities in writing, maths, general academic performance, and attitudes towards school (May et al., 2013; Sikora et al., 2012; Zajic et al., 2018).

1.2.3 Developmental Coordination Disorder

Another neurodevelopmental disorder that overlaps with ADHD is Developmental Co-ordination Disorder (DCD; also frequently referred to as *dyspraxia*) with co-occurrence rates estimated to be as high as 50% (Fliers et al., 2008; Gibbs et al.,2007; Gillberg et al., 2004; Lange, 2018). DCD is characterized by marked and persistent perceptual motor difficulties that limit daily functioning, particularly in self-care and at school (APA, 2013, Dewey et al., 2002). DCD affects (1) fine motor abilities (e.g., using pencil and tying shoelaces), (2) gross motor abilities (e.g., running and hopping), or (3) both (Jane et al., 2018). Children with DCD lag on motor skills expected for their age, and their movement abilities are characterised by clumsiness, slowness, and inaccuracy (APA, 2013). Children with DCD also show diminished sensory-perceptual processing, visuospatial processing, internal modelling (i.e., predictive estimates of body position), and difficulties with executive functioning (Alloway, 2011; Asonitou et al., 2012; Bernardi et al., 2018; Rigoli et al. 2013; Sartori et al., 2020; Sumnet et al., 2016; Tsai et al., 2008; Vaivre-Douret et al., 2011; Wilson et al., 2013).These difficulties impede upon children’s functioning, including self-care, academic attainment, engagement in leisure activities, and socioemotional well-being (Alloway, 2007; Lingam et al., 2012; Missiuna et al., 2008; Piek et al., 2005).

In the context of ADHD, children with the ADHD-Inattentive presentation mainly show problems with fine motor skills, whereas those with ADHD-Combined subtype have poorer gross motor skills (Kaiser et al., 2015; Piek et al., 1999). Attention deficits, common to both the inattentive and combined ADHD presentations, have been proposed to underpin motor difficulties in ADHD (Fliers et al., 2008; Goulardins et al., 2015). This is also supported by evidence showing that methylphenidate (a common

ADHD treatment medication) improves motor functioning in ADHD (Bart et al.,2013). However, clinically significant improvements are only found in about a third of children with ADHD + DCD, suggesting that for some children factors other than inattention are at play (Bart et al., 2010). Indeed, medication tends to be more effective for improving outcomes in children with ADHD who show mild motor difficulties at baseline, rather than those with more significant motor difficulties (Kaiser et al., 2015). There is also evidence to show that children with DCD and ADHD + DCD struggle more substantially in motor skills than those with ADHD alone (Licari & Larkin, 2008). This implies that motor difficulties in ADHD could be secondary to concomitant risks posed by DCD (Goulardins et al., 2017). Further evidence for this comes from significant neurological abnormalities found in frontal regions of the corpus callosum (area highly implicated in attention and motor functioning) in children with ADHD, and exclusively in parietal regions connecting with primary and somatosensory motor areas in DCD (Langevin et al., 2014). The most profound insults to white matter integrity in both regions are found in children with co-occurring ADHD + DCD. Additionally, co-existence of the two disorders is associated with more generalised cortical thickness reductions than that of children with either disorder alone (Langevin et al. 2015). A study by Farran and colleagues (2020) found that around half of children with ADHD showed severe motor difficulties, in the absence of clinical DCD diagnosis. Additionally, their movement difficulties were unrelated to ADHD symptoms, but rather were closely linked to cognitive performance (Farran et al., 2020). Like ADHD, hallmarks of DCD include lower neurocognitive functioning (Asonitou et al., 2012; Piek et al., 2007; Rigoli et al. 2013). However, identifying cognitive features specific to each disorder is challenging as the ADHD literature frequently fails to screen for DCD, and vice versa (Goulardins et al., 2015).

Despite high rates of co-occurrence, research into the effects of co-existence between ADHD and DCD on educational outcomes is surprisingly scarce. Rasmussen & Gillberg (2000) followed children with ADHD with and without DCD between ages 7 and 22 years. Result showed that having a concurrent ADHD + DCD diagnosis during childhood has been linked with significantly higher risk for a range of psychosocial adversities in adulthood, including academic underachievement. There is also some evidence to show that the co-occurrence between ADHD and DCD generally results in higher difficulties in maths than either of the disorders alone, although further research is evidently necessary (Visser et al., 2020).

1.2.4 Learning difficulties

Poor academic outcomes are widely documented in ADHD (Czamara et al., 2013; DuPaul et al., 2013; Loe & Feldman, 2007, Mayes et al., 2000; Reale et al., 2017). Pupils with ADHD have poorer academic progression trajectories, score lower on achievement tests, and are more likely to repeat a year at school or drop out of school than their neurotypical classmates (Barkley et al., 2008; Frazier et al., 2007; Loe & Feldman, 2007). According to the clinical symptom model, academic underachievement in ADHD stems from disorder-specific symptoms, and particularly inattention, which hinder processes supporting optimal classroom learning (e.g., attending to and following instructions; Breslau et al., 2009; Calub et al., 2019). However, there is little evidence for academic improvements following pharmacological treatment that targets ADHD symptoms, suggesting factors other than behavioural symptoms modulate academic performance (Baweja et al., 2015; DuPaul et al., 2016; Kortekaas-Rijlaarsdam et al., 2018; Molina et al., 2009). Another model – the intellectual deficit model, suggests that academic problems in ADHD are driven by generally lower IQ levels which are highly associated with educational outcomes (Calub et al., 2019; Duckworth et al., 2012; Frazier et al., 2004; Mayes et al., 2009). However, IQ tests are heavily reliant on higher order cognitive processes with which many children with ADHD struggle, and so it is possible that this could be driving the high associations between IQ and achievement (Calub et al., 2019). This points to the role of higher order cognitive processes in modulating educational achievement.

Beyond broad scholastic underachievement, children with ADHD carry a threefold risk of developing a specific learning difficulty, and the risk of ADHD in children with learning difficulties is approximately seven times higher than the general population (DuPaul & Stoner, 2003; Polanczyk et al., 2007). Learning difficulties adversely affect acquisition of basic academic and functional skills, despite average/above average IQ (Graham, 2017). Dyslexia and dyscalculia represent two of the most common learning difficulties found in school-aged children (Peterson & Pennington, 2012; Rapin, 2016). Estimates of learning difficulties in ADHD vary across studies (7-92%), although are relatively comparable in reading, written expression, spelling, and maths domains (Czamara et al., 2013; DuPaul et al., 2012; Mayes et al., 2000; Pham & Riviere, 2015). Much of the previous literature on learning disorders has focused on literacy disorders (e.g., DuPaul et al., 2013; Greven et al., 2013; Willcutt et al., 2005) with difficulties in maths comparelatively understudied (Sturm et al., 2018). The section below briefly discusses dyslexia and dyscalculia in the context of ADHD.

1.2.4.1 Dyslexia

Dyslexia is a learning disorder that hinders decoding print and acquisition of spelling, reading, and writing abilities (Snowling & Hulme, 2012). Such difficulties must be independent from sensory anomalies, brain injury, or intellectual capacity (APA, 2013). Dyslexia co-occurs in around 25-40% of ADHD cases (Boada et al., 2012). Features of dyslexia include weaknesses in letter knowledge, phonological awareness, and reading fluency, as well as expressive and receptive vocabulary (Gabrieli, 2009; Lyon et al., 2003; D’Mello & Gabrieli, 2018). Further, children with dyslexia show neurocognitive vulnerabilities in linguistic and viusospatial cognitive domains (Menghini et al., 2010; Varvara et al., 2014). Dyslexia and dyscalculia frequently co-occur, leading some to argue that maths difficulties arise due to language deficits akin to dyslexia (Vellutino et al., 2004). Echoing this idea, language skills such as phonological awareness are shown to account for the overlap between reading and maths problems in children (Child et al., 2018; Peterson et al., 2017; Snowling, Moll, & Hulme, 2021). However, others advocate a distinction between the two disorders arguing that maths difficulties are exacerbated, rather than caused, by reading difficulties (Jordan, 2007; Jordan et al., 2003). Moreover, phonological deficits tend to be unique to dyslexia whereas visuospatial processing difficulties are prevalent in dyscalculia and dyscalculia with concurrent dyslexia (Landerl et al., 2009). Similarly, in a study of twins, maths ability showed high genetic associations with ADHD symptoms (particularly inattention), and these were only partially explained by reading (Greven et al., 2013).

1.2.4.2 Dyscalculia

Between 18%-42% of children with ADHD experience a learning disability in maths (Capano et al., 2008; Czamara et al., 2013; Desoete, 2008; Silva et al., 2020). Studies differ in their definitions of maths learning difficulties, an ambiguity that is fuelled by diverse terminology (e.g., *dyscalculia*, *math learning difficulty*, *math learning disability*) and variable cut-off criteria (de Souza Salvador et al., 2019; Mazzocco & Myers, 2003; Soares et al., 2018). Low achievement levels are generally attributed to extrinsic factors such as the child's sociocultural environment or poor instruction (Soares et al., 2018). Contrary to this, a maths learning difficulty is defined as a severe and persistent impairment in acquiring basic maths skills despite age-appropriate IQ, and independent from psychosocial adversities (Kaufmann & von Aster, 2012; Mazzocco, 2007). Researchers further distinguish between (1) *primary developmental dyscalculia* arising from a core deficit in numerical magnitude representation (also known as number sense), and (2) *secondary dyscalculia* stemming from non-numerical cognitive processes such as visuospatial memory and attention – domains that are adversely affected in ADHD (Kaufmann et al., 2013; Price & Ansari, 2012; Rubinsten & Henik, 2009). In line with this conceptualization, dyscalculia is characterized by substantial herteoegentiy in impairment profiles (Geary, 1993; Kaufmann et al., 2013; Skagerlund & Träff, 2016). Some dyscalculic children show domain-specific numerical functions difficulties (e.g., magnitude reasoning and number processing) whilst others show predominantly domain-general cognitive deficits, and mixed profiles are also highly prevalent (Szucs et al., 2013; Träff et al., 2017). Notably, even children with primary dyscalculia show poor performance on cognitive tasks which are characteristic of ADHD (Ashkenazi et al., 2009; Geary, Hoard, Byrd-Craven, Nugent & Numtee, 2007; Szucs et al., 2013). The distinction is further complicated by DSM-5 requirements to rule out a learning difficulty in the presence of a developmental disorder such as ADHD (APA, 2013). Agreement does exist in relation to dyscalculia as generally referring to a severe maths learning difficulty (MLD) and, as such, it will be henceforth referred to as MLD in the context of concurrent ADHD.

Criteria used to identify children with MLD range between below the 3rd and 25th percentiles on standardised achievement tests and this variability arises due to a lack of consensus regarding the definition of the disorder (Devine et al., 2013; Murphy et al., 2007). Ranging cut-offs across studies result in rather different groups of children classified as having MLD, mixed findings, and consequently, questionable implications (Kaufmann et al., 2013). Children scoring below the 10th percentile tend to show greater difficulties on basic arithmetic fact retrieval and numerical magnitude representations than those scoring between 11th and 25th percentiles (Mazzocco et al., 2008; 2011). Additionally, they experience a more substantial plateau trajectory in maths performance over time than those in the more liberal cut-off MLD groups (Murphy et al., 2007). Typically, however, a score below 10th percentile is regarded as a significant maths difficulty, whilst children scoring between the 11th-25th percentile are regarded as low achievers (Geary et al., 2007; Szucs et al., 2013). Although a cap of < 10th percentile is more conservative, it is considered to be better aligned to durable MLD characteristics (Kaufmann et al., 2013).

1.2.5 Co-occurrences summary

Evidently, ADHD seldom occurs in isolation and rather co-exists with other neurodevelopmental disorders. Co-occurrence rates vary within the literature, and this can be attributed to diverse methods of defining ADHD, with some studies relying on behaviour ratings of community-based samples, whilst others utilizing more comprehensive clinical diagnostic sampling processes (DuPaul et al., 2013). Although the aforementioned disorders were explored individually in the context of ADHD, symptoms of other disorders (e.g., ODD/CD, ASD, DCD, and/or learning disability) can cultivate or exacerbate symptoms relating to another disorder. For example, co-existence between ADHD + ASD has been associated with increased tantrum rates, aggression, opposition, and conduct difficulties than in either of these disorders alone (Geurts & Embrechts, 2008; Guttmann-Steinmetz et al., 2009). Moreover, difficulties with motor skill are not exclusive to ADHD + DCD and are also documented in children with ADHD + ASD (Papadopoulos et al., 2013). Indeed, over half of children with ADHD meet criteria for two co-occurring disorders (Kadesjo & Gillberg, 2001). Despite this, much of the ADHD literature either fails to screen for co-occurring symptom constellations or opts to exclude children with other neurodevelopmental disorders from participating (Colombi & Ghaziuddi, 2017; Goulardins et al., 2015). This makes it difficult to characterise functional outcomes in a way that reflects children's diagnostic complexities. Overlap with multiple disorders may complicate the treatment process as each unique combination will require a tailored treatment approach (Reale et al., 2017). Thus, it is imperative to characterise ADHD samples as holistically as possible when using findings to inform practice.

1.3 Aetiology of ADHD

A causal pathway characterising the precise aetiology of ADHD has yet to be elucidated, however, researchers agree that ADHD can be best understood as an epigenetic disorder characterised by a multifaceted gene-environment interaction

(Nigg, 2012; Nigg, Nikolas & Burt, 2010). A casual developmental model of ADHD requires the amalgamation of various levels of analysis and precisely, the genetic, neural, cognitive, and behavioural systems (Morton & Frith, 1995). More recently, environmental, and social risk factors have been recognised for ADHD pathogenesis in terms of the (1) causal presentation of the disorder, and (2) contextual expression of the disorder (Coghill et al., 2005; Sonuga-Barke & Halperin, 2010). Broadly, the prevailing causal pathway identifies ADHD as developing from heritable genetic factors which generate functional anomalies in fronto-striatal neural pathways that in turn cause cognitive vulnerabilities, ultimately manifesting in the conventional behaviours of inattention, impulsivity, and/or hyperactivity (Castellanos & Tannock, 2002; Coghill et al., 2005). Factors relating to this hypothesised pathway are discussed sequentially below.

1.3.1 Genetic risk factors

ADHD is a genetically heritable disorder (Eilersten et al., 2019; Faraone & Larsson, 2017; Hinshaw, 2018; Langley, 2018). Candidate genes contributing to pathophysiology of ADHD include genes responsible for coding of proteins and enzymes of the dopaminergic, noradrenergic, and serotonergic pathways (Gizer et al., 2009; Klein et al., 2017; Faraone & Larsson, 2019). Converging evidence points to the pathophysiology of ADHD as arising from irregularities in metabolism and transportation of these monoamines in frontal and subcortical brain areas (Albrecht et al., 2015; Pliskza, 2005). Particular focus has been devoted to dopamine – a neurotransmitter implicated in regulating attention, emotion, motivation, motor control, and reward processing, all of which are weakened in ADHD (Sonuga-Barke, 2005). Children with ADHD have higher concentrations of dopamine re-uptake inhibitors causing an accelerated expulsion of dopamine between the synapses and, consequently, lower dopamine transmission. Clinical efficacy of dopaminergic drugs (e.g., methylphenidate) in alleviating core ADHD symptoms supports dopamine as a plausible causal agent (Gizer et al., 2009; Cortese et al., 2018). However, studies examining specific genes yield mixed results and identifying specific ADHD genes is challenging, leading researchers to suggest that an amalgamation of numerous genes are necessary to increase susceptibility to ADHD (Franke et al., 2011; Faraone & Mick, 2010; Hinshaw, 2018). This inconsistency could be attributed to genetic effect modulation via environmental agents that vary across samples (Wermter et al., 2010), discussed in the following subsection.

Evidence for heritability of the disorder comes from studies showing higher familial history of ADHD – parent and sibling ADHD increases children's risk for developing the disorder (Franke et al., 2011; Starck et al., 2016). However, such research has been criticised for failing to separate the probable effects of shared familial environment (Thapar & Stergiakouli, 2008). Yet, even in the absence of shared environmental contexts, biological relatives of adopted ADHD child probands are more likely to develop ADHD (Sprich et al., 2000). The most robust case for the genetic basis of ADHD comes from twin studies demonstrating heritability rates of around 70-80% (Nikolas & Burt, 2010; Chen et al., 2017; Faraone & Larsson, 2019). Heritability estimates tend to be comparable in males and females, as well as across studies conceptualising ADHD in terms of symptom dimensions and diagnostic categories (Faraone & Larsson, 2019; Langner et al., 2013; Nikolas & Burt, 2010; Thapar et al., 2000). Although compelling evidence exists for the heritability of ADHD, a considerable segment of variance remains unaccounted for by genetic factors

(Banerjee et al., 2007; Hinshaw, 2018). This has led researchers to argue for the role of environmental factors in moulding developmental trajectories.

1.3.2 Environmental risk factors

It is now widely accepted that although ADHD is heritable, children's environment interacts with protective and harmful genes to decrease or amplify the risk for developing the disorder (Thapar et al., 2007; Wermter et al., 2010). Thus, the presence of a candidate gene may, or may not, engineer a psychopathological profile depending on the environment to which the child is exposed (Thapar et al., 2012). Genes deploy indirect risk by increasing sensitivity to specific environmental risks such as psychosocial adversity (Rutter et al., 2009). For example, decreased *monoamine oxidase A* gene activity (responsible for oxidizing neurotransmitters such as dopamine and serotonin) amplifies children's sensitivity to adverse environments and to developing behaviour problems (Quellet-Morin et al., 2016). Inversely, exposure to environmental risks can be influenced by the child's genetic composition and factors relating directly to the child via reverse causation (Thapar et al., 2012). For example, although the risk of developing ADHD is higher in children with early head injury, it is equally possible that children at risk for ADHD show more risky behaviours that subsequently result in greater risk for injury (Keenan et al., 2008). Thus, environmental and genetic factors are not mutually exclusive but rather operate harmoniously to orchestrate outcomes specific to each child.

Prenatal (i.e., occurring prior to the child's birth) smoking exposure is considered to be one of the environmental risk factors for ADHD (Huang et al., 2018). Research consistently supports a dose-response association between maternal cigarette smoking and offspring ADHD, characterised by more severe clinical and neuropsychological outcomes (Thakur et al., 2013). Foetal nicotine exposure hinders neurotransmitter functioning and has been linked to dopaminergic and noradrenergic hypoactivity and hyperresponsiveness (Berger et al., 2010). However, Thapar and colleagues (2009) found that the association between maternal smoking and offspring ADHD was stronger for genetically related mother-child pairs than genetically unrelated pairs (i.e., surrogate mothers and oocyte or embryo donations). Another study found that exposure to smoking alone did not predict ADHD symptom severity (Bos-Veneman et al.,2010). Instead, a combination of tobacco exposure and having a first-degree relative with a mental health disorder sufficiently predicted risk, further highlighting gene-environment interactions. Other commonly explored substance use risk factors include maternal alcohol consumption and illicit drug use, albeit findings are similarly inconclusive (Banerjee et al., 2007; Burger et al., 2011; Froehlich et al., 2011; Sciberras et al., 2017; Thapar et al., 2012).

Another environmental risk factor for ADHD is psychosocial adversity (Froelich et al., 2011; Thapar et al., 2012). Psychosocial stressors interfere with cortical maturation in frontal, temporal, and occipital areas thereby amplifying ADHD symptom severity and contributing to co-occurring conduct problems (Barkley, 2014). Biederman and colleagues (2002) compared children and adolescents with and without ADHD on a range of psychosocial variables and found that low socioeconomic status (SES), maternal psychopathology, and family conflict increase risk for ADHD, even after accounting for other factors such as parent’s ADHD and prenatal exposure to maternal smoking. In another study, which followed children up from birth, ADHD diagnosis at 8 years was associated with maternal depression, low SES, as well as less supportive and less stimulating home environment (Sagiv et al., 2013). Previous work also supports other predisposing family factors such as maternal stress, warmth and negativity, marital complications, family dysfunction, and conflict (Biederman et al., 1995; Angew-Blais et al., 2016). Equally plausible, however, is the idea that interpersonal family difficulties arise in response to the child’s ADHD, referred to as child effects (Breaux & Harvey, 2019; Lifford et al., 2008). It could also reflect synergistic operation of both the child and their parent ADHD, such that high child and parental ADHD symptoms result in interpersonal difficulties in the home context (Burt et al., 2005; Psychogiou et al., 2007; Deater-Deckard, 2017). This association is complex and will likely be mediated by various confounders which co-occur with low SES (e.g., maternal smoking during pregnancy and family conflict during early childhood). Other studies show reverse causality whereby child-ADHD causes a loss of parental income due to factors such as child-care expenses, job loss, and stress-associated illnesses although the evidence for this is less consistent (Doshi et al., 2012; Russell et al., 2014; 2016).

1.3.3 Natal risk factors

Premature birth (gestational age of < 37 weeks) and low birth weight (LBW; < 2500g) are linked to ADHD pathogenesis (Anderson et al., 2011; Franz et al., 2018). Specifically, a gradient association is found whereby a higher degree of prematurity or LBW increases risk for ADHD (Horwood et al., 1998; Sucksdorff et al., 2015). Rates of ADHD are approximately 9-11% in very preterm (VPT; < 32 weeks) and very low birthweight children (VLBW; < 1500g) and 17-20% in extremely premature (EPT < 26 weeks), and extremely LBW children (ELBW; < 1000g; Johnson & Marlow, 2011). Moreover, the risk magnitude is comparable across different ADHD presentations (Franz et al., 2018). LBW and premature birth predict more stable ADHD diagnoses across the lifespan (Breeman et al., 2016). Previous population-based research supports premature birth as an important risk factor for ADHD, with associations prevailing even after controlling for a range of potentially confounding factors (Halmøy et al., 2012; Sciberras et al., 2017; Silva et al., 2014). Findings relating to LBW are less consistent and often blurred by the fact that studies fail to report on what proportion of LBW sample are also premature (Lim et al., 2018; Riechi et al., 2011; Sciberras et al., 2017). Children born prematurely or of LBW show difficulties on a range of cognitive functions that support scholastic achievement including executive control and attention, language, motor abilities, and visuospatial skill (Marlow et al., 2007; Orchinik et al., 2011; Simms et al., 2015). Notably, Taylor and colleagues (2019) found that ADHD diagnosis and higher ADHD symptoms in kindergarten predicted delayed reading and maths achievement in the first 3 years of school, above and beyond prematurity and LBW. Thus, prematurity/LBW likely make additive contributions to scholastic difficulties, such that being born prematurely and having an ADHD diagnosis puts the child at higher risk for poorer scholastic outcomes than either of the conditions alone (Krasner et al., 2018; Taylor et al., 2019)

1.3.4 Cognition and behaviour

Early ADHD theories argued that volitional disinhibition due to poor moral control was at the core of ADHD (Still, 1902). Indication of behavioural difficulties rooted in cerebral weaknesses and brain injury also began to emerge during the early 19th century, with interest in ADHD rekindling much later (Still, 1902; Strauss & Lehtinen, 1947). Chess (1960) argued that motor restlessness was the main cause of ADHD, however, this stance was later challenged by findings that hyperactive children also show difficulties in sustaining attention and controlling impulses (Douglas, 1972).

Nonetheless, attentional difficulties were often inconsistent across different types of situations leading to their role to be probed by researchers (Anastopoulos et al., 1994). Alternative explanations for difficulties included deficits in behavioural inhibition parallel to contextual demands, self-directed instruction, and rule-governed behaviour (Barkley 1981; Barkley et al., 1990; Kendall 1985; Shue & Douglas, 1992). A converging argument began to emerge for the role of higher order cognitive processes responsible for governing behaviour in response to the environment (Anastopoulos et al., 1994).

1.3.4.1 Executive Functions

Executive Functions (EF) is a collective term for higher order cognitive processes linked to the prefrontal cortex which regulate goal directed behaviour (Best & Miller, 2010). EF is regarded as a multifaceted construct, encompassing distinct yet highly correlated cognitive processes (Miyake et al., 2000; Lehto et al., 2003). The "unity and diversity" of EF was addressed by Miyake and colleagues (2000), who showed individual differences in three separable but related functions: (1) inhibitory control – the ability to supress task irrelevant information or unwanted responses, (2) working memory (WM) updating – the capacity to store, update, and manipulate information in a given context, and (3) set shifting/cognitive flexibility – the ability to flexibly shift attention between different tasks/perspectives. Another key EF construct is planning – monitoring, re-evaluating, and updating a sequence of planned behaviours (Diamond, 2013).

Development of EF follows a sequential trajectory parallel to the development of the prefrontal cortex (DeLuca & Leventer 2008). Sensitive periods of EF development occur as early as 6 months (Thompson & Steinbeis, 2020). Inhibition and WM typically develop around the age of 2 years, followed interdependently by more complex operations of attentional shifting (Carlson, 2005, Zelazo et al., 2003). Finally, the ability to plan and schedule sequences of thoughts and actions emerge around age four (Espy et al., 2001; Anderson, 2002). Theoretical conceptualisations of EF further complement this sequential trajectory of increasingly specialised cognitive mechanisms. During preschool years, research assessing inhibition, WM, and planning typically supports a unitary model of EF comprising a single general cognitive factor (Hughes et al., 2009; Wiebe et al., 2008; 2011). This implies that during early childhood different EF operate uniformly and differences between children's performance on these tasks are likely affected by broad cognitive capacity such as attention (Messer et al., 2018). Using a comprehensive battery of tasks to index WM and inhibition, Lerner and Lonigan (2014) found support for a two-factor model of separable EF processes in 3–5-year-old pre-schoolers. Notably, the correlations between WM and inhibition were substantially higher for younger children, suggesting EF structures evolve with age. Evidence from children aged 6-12 years lends support to a variety of factor structure models (Messer et al., 2018). Some studies demonstrated two factor models in which inhibitory control and set shifting are distinguished from WM (van der Sluis et al.,2007; Van der Ven et al., 2013), whilst others show evidence for WM and inhibition as two distinct factors (Messer et al., 2018; St Clair-Thomson & Gathercole, 2006). Three factor solutions are also identified in school-aged samples constituting inhibition, shifting, and WM (Lehto et al., 2003; Wu et al., 2011). Lee and colleagues (2013) found that the organisation of EF changes from a two-factor structure during childhood to a three-factor structure in mid adolescence, with marked reductions in correlations with increasing age. This implies that EF processes are subject to considerable structural refinement, becoming increasingly specialised and independent with age. Notably, planning abilities have seldom been addressed within confirmatory factor analytics studies of EF (Lee et al., 2013).

Prominent models of ADHD hold that EF difficulties are at the core of this disorder (Barkley, 1997; Lyon & Krasnegor, 1996; Johnson et al.,2009; Penningron & Ozonoff, 1996). ADHD is characterised by atypical physiological, anatomical, and biochemical functioning of the frontal cortex as well as fronto-parietal and fronto-striatal circuits directly linked to EF (Vaidya, 2011; Rubia, 2018; Willcutt et al., 2005). Additionally, performance on neuropsychological measures that tap into EF processes is substantially lower in children with ADHD when compared to their neurotypical peers (Toplak et al., 2008; Willcutt et al., 2005). Evidence of impairment in ADHD relating to each of the EFs is discussed below.

Diminished inhibitory control was previously proposed to be the primary casual factor in ADHD that underpins other more complex EF difficulties (Barkley, 1997; Sonuga-Barke, 2002). According to this top-down model, phenotypic behavioural manifestations of ADHD are a by-product of response disinhibition arising from: (1) diminished inhibition of dominant pre-potent responses, (2) difficulty inhibiting responses to ongoing thoughts or actions, and (3) inability to suppress information relating to irrelevant stimuli by means of selective attention (Barkley, 1997; Nigg, 2001). This frequently manifests at the behavioural level as symptoms of impulsivity. Children with ADHD show difficulties on Stop Signal Response tasks assessing the ability to cancel an initiated response to dominant signals when presented with a ‘stop signal’ (Alderson et al., 2007; Dalen et al., 2004; Lipszyc & Schachar, 2010). However, this task taxes a range of other abilities that could be driving difficulties including stimulus anticipation, response preparation, processing speed and maintenance of task instructions online – distinguishing between these can be methodologically challenging (Castellanos et al., 2006). Performance on the Go/No Go paradigms, in which children must restrain a response to an established dominant response, is also compromised in children with ADHD (Baijot et al., 2017; Hunh et al., 2017; Paul-Jordanov et al., 2010). Nonetheless, one study comparing children with and without ADHD found comparable error rates on No-Go trials, implying that not all children with ADHD struggle with this task (Rhodes et al., 2005). Schachar and colleagues (2007) found that although an ADHD group showed poorer ability to cancel and restrain a motor response, performance on these inhibition subcomponents was highly correlated in controls but not in the ADHD group, implying reliance on distinct neurocognitive mechanisms. Lastly, difficulties in interference control, as measured by the Stroop task (i.e., responses incongruent with stimuli characteristics), can be confounded by slower reaction times (RTs), diminished accuracy, and greater time variability than in matched controls (Elosúa et al., 2017; Homack & Riccio, 2004; Kóbor et al., 2015; Lansbergen et al., 2007; Nigg et al., 2002). Inhibitory control difficulties are not consistently found in all children with ADHD (Coghill et al., 2014). Thus, the questionable 'purity' of inhibitory control tasks coupled with non-universal evidence for inhibition deficits dispute the validity of disinhibition as the prominent causal factor in ADHD (Castellanos et al., 2006; Coghill et al., 2018).

Others argue for WM as the core deficit in ADHD (Rapport et al., 2001; Rapport et al., 2008). WM difficulties are frequently documented in ADHD and manifest at the behavioural level during cognitively demanding activities such as attending to and following instructions, multi-tasking, and classroom learning (Gathercole et al., 2008;

Alloway et al., 2009; Holmes et al., 2014). WM difficulties are also linked to inattentive and hyperactive behaviours (Kofler et al., 2019; Rapport et al., 2009). According to Baddeley's multicomponent model, WM is made up of a capacity limited attentional component, the central executive, and two subordinate mechanisms – the phonological loop and visuospatial sketchpad, responsible for short term storage and rehearsal of verbal and visuospatial information, respectively (Baddeley & Hitch, 1974). According to this model the domain-general central executive is responsible for overseeing and coordinating the domain-specific storage/rehearsal systems. The central executive mobilizes other EF processes such as suppression of dominant or pre-potent responses, flexible shifting of strategies during engagement in multiple tasks, updating irrelevant information, and sequencing actions (Miyake et al., 2000). Barkley (1997) argued that difficulties with inhibitory control underpin WM vulnerabilities by impairing the ability to supress distracting or irrelevant information from entering the WM system. However, given that external stimuli must first be granted access and evaluated in the WM system before they can be inhibited, others argue that disinhibition is a product rather than the cause of WM difficulties (Alderson et al., 2010; Rapport et al., 2001; Kofler et al., 2008). For example, in Stop Signal tasks, children must first pay attention to the go-stimuli to expend a correct response, attend to auditory tones which signal a 'stop' response, and appraise these signals within the WM system to decide whether or not to withhold a response. Alderson and colleagues (2010) addressed these competing predictions and found that the central executive fully mediated the relationship between children's diagnostic status and performance on the Stop-Signal inhibition task. By contrast, Stop-Signal performance only partially mediated the association between ADHD diagnosis and WM performance. This finding challenges the proposition of disinhibition as a ubiquitous phenomenon in ADHD, and instead points to inhibitory control difficulties arising from deficits in central executive’s attentional control.

Research consistently demonstrates that children with ADHD struggle with all three subcomponents of the WM system, and these difficulties are marked by substantially higher effect sizes when compared with other EF domains (Rapport et al., 2008; Kofler et al., 2019). The central executive tends to be most affected, followed by the visuospatial sketchpad, and the phonological loop (Martinussen et al., 2006; Rapport et al., 2008; Willcutt et al., 2005). Although verbal WM performance is comparatively less affected in children with ADHD, evidence for deficits in the verbal component is equally compelling (Gremillion & Martel 2014; Gremillion et al., 2018; Willcutt et al., 2005). The discrepancy in findings relating to verbal WM could be explained by co-occurrence with other disorders such as ODD (Rhodes et al., 2012). Moreover, tasks used to index WM performance are subject to methodological contamination of supervisory central executive estimates in modality-specific WM assessments. For example, common WM tasks that require children to recall digits or spatial locations in reverse order likely depend on both domain-general and domain-specific WM capacities. Rapport and colleagues (2008) partitioned the different components using statistical regression technique to estimate central executive and the subsidiary phonological and visuospatial systems. Their findings showed that the ADHD group performed substantially worse on all WM factors than neurotypical children.

Cognitive flexibility difficulties are also documented in ADHD, although evidence for these is less robust (Corbett et al., 2009; Geurts et al., 2004; Rhodes et al., 2005; Willcutt et al., 2005). Cognitive rigidity can manifest at the behavioural level in difficulties managing or focusing on multiple tasks simultaneously, changing between different activities, and inability to switch between conflicting perspectives (Farrant et al., 2014). Children with ADHD make more preservative errors and take longer to respond on measures of set shifting that require response modifications based on corrective feedback (e.g., shift between thinking about stimuli colours to stimuli shapes; Hale et al., 2009; Pennington & Oznoff, 1996; Willcutt et al., 2005). Others fail to show evidence for set shifting difficulties in ADHD, and instead attribute these to lower-level cognitive processes such as processing speed (Rommelse et al., 2007). Set shifting tasks also depend on other EF processes such as WM and inhibition (Kofler et al., 2019). For example, to avoid making preservative errors on a set shifting task the child must shift attention between a dominant stimuli characteristic to a novel one. To do this, the child must first inhibit appraisal of the pre-potent, preceding characteristic and load the new ones into the active WM system. Cognitive flexibility deficits tend to be less characteristic of ADHD than other developmental disorders such as ASD and thus, could be driven by specific co-occurrence profiles (Geurts et al., 2004; Piek et al., 2007).

Planning difficulties are also observed in ADHD (Boyer et al., 2018; Gau & Shang, 2010; Nigg et al., 2002; Rhodes et al., 2005; Toplak et al., 2008). Planning helps children integrate both internal and external information to organise/formulate a strategic and efficient behaviour response (Diamond, 2013). A meta-analysis by Petros and colleagues (2019) found small-moderate magnitude planning difficulties in ADHD when compared to neurotypical children. Notably, studies using younger children and higher proportion of girls were more likely to generate larger between group effects in planning performance. This was interpreted to reflect improvement of planning abilities with age and greater visuospatial processing difficulties in girls

(Halpern & Collaer, 2005; Qian et al., 2013). In another review, planning difficulties were found to be more common in children with ASD and ASD + ADHD, than ADHD alone implying that planning difficulties could be a product of co-occurring ASD (Craig et al., 2016). Notably, planning task performance largely depends on the integrity of other earlier developing EF processes, such as WM and inhibition (Best, Miller & Jones, 2009). For example, inhibition helps supress irrelevant information from impeding upon goal-oriented actions, whilst WM is responsible for storing and manipulating incoming information. Disentangling the role of each of the processes is notoriously difficult especially where different functions are examined in isolation (Kofler et al., 2019).

At the core of the EF literature is evidence for intra-individual reaction time variability on computerised tasks (Epstein et al., 2010; Tamm et al., 2012). This variability is suggested to reflect lapses in attention processing during task performance and may underpin behavioural difficulties such as staying on task in the classroom (Hervey et al., 2006; Antonini et al., 2013). Some researchers suggest that reaction time variability in ADHD stems from increased cognitive load due to difficulties suppressing activation of the default mode network (a collective of brain regions responsible for resting state), resulting in weakened signal-to-noise ratios of neural transmission (Fassbender et al., 2009; Tamm et al., 2012). However, children with ADHD consistently show reduced frontal lobe activations during cognitive task performance (Suskauer et al., 2008; Epstein, 2009). According to Tamm and colleagues (2012) this juxtaposition may be due to children's inability to supress task-negative activation of the default mode network which defeats frontal task-positive activation due to the latter's activation deficiency. This in turn manifests as longer reaction times and increased reaction time variability. Thus, non-executive processes underpinning higher order EFs may supplement functional difficulties.

Others explain ADHD in terms of ‘hot’ EFs – motivational style difficulties specifically related to reward processing and delay aversion (Sonuga-Barke et al., 1992; Sonuga-Barke et al., 1996; Nigg, 2001; Rubia et al., 1999; Rubia, & Smith, 2001). According to Zelazo and Carlson (2012) ‘hot’ EF capacity uses stimuli of high motivational significance and develops relatively later than ‘cool’ EF task competencies (i.e., the aforementioned EFs) which are relatively independent of motivational and emotional influences. Sonuga-Barke (2002) proposed the dual pathway model according to which ADHD is an umbrella term comprising overlapping yet dissociated cognitive profiles which stem from specific difficulties in: (1) an inhibitory control pathway, or (2) a motivational/reward pathway (Castellanos et al., 2006). In support of this conceptualisation, one study found that baseline inhibitory control and delayed reward performance of preschoolers predicted ADHD symptoms a year later, but not the other way around (Pauli-Pott et al., 2019). Furthermore, the two pathways independently predicted an increase in symptoms between ages 4 and 5, suggesting these are dissociable from one another (Sonuga-Barke, 2002; 2005; Nigg et al., 2005). Specifically, children with ADHD prefer immediate small rewards over delayed large rewards manifesting behaviourally as impulsivity (Kuntsi et al., 2001; Marco et al., 2009). Initial drive for immediate rewards is linked to brain reward circuits and, specifically, reduced activity in frontal regions and the ventral striatum (Van Dessel et al., 2018; van Hulst et al., 2017). This impairment in reward processing can over time promote delay aversion whereby situations with a delay component generate negative affective states. To avoid negative affect associated with the subjective experience of suspension, some children with ADHD will seek out stimulating environments by devoting attention to aspects of the environment that accelerate passage of time (Antrop et al. 2006; Sonuga-Barke et al., 2004). In this ‘top-down’ fashion behavioural symptoms of inattention and hyperactivity can emerge (Van Dessel et al., 2018).

1.3.4.2 Memory

Cognitive manifestations in ADHD also include difficulties in ‘*passive*’ memory storage without executive manipulation and updating requirements akin to *working* memory. For example, Rhodes and colleagues (2004) found that stimulant naïve boys with ADHD had substantial impairments in visuospatial WM and on delayed short term recognition memory – a difficulty which could not be explained by previous contenders such as WM, inhibitory control, nor delay aversion. Notably, difficulties were not evident for visuospatial stimuli presentation with a 0 second delay and were more pronounced at 12 second delays. This implies that children mainly struggled to retain or recall the information, rather than encoding or attending to stimuli during its initial presentation. In another study, ADHD-associated difficulties were found for visuospatial recognition memory and short-term memory (STM) tasks (Rhodes et al., 2005). Importantly, although children with ADHD were generally more impulsive on incorrect trials, there was no evidence that response latencies were driving the difficulties (Rhodes et al., 2004; 2005). Furthermore, methylphenidate significantly improved performance on memory storage components but not on task relating to EF, further highlighting difficulties with memory storage processes in ADHD (Rhodes et al., 2004; Rhodes et al., 2006).

Another aspect of memory implicated in ADHD is long term memory, crucial for retrieval and application of learned information (Rhodes, Park, Seth, & Coghill, 2012). Long term memory draws on WM capacities to retrieve information from its storage system using attentional processes (Baddeley, 2000; Unsworth & Engle, 2007). Thus, long term memroy difficulties could be due to decay of information in WM during initial encoding stages and disruptions in visuospatial and linguistic codes processing. Alternatively, long term memory weaknesses could reflect inadequate access to information including generation of internal retrieval cues, such that strategic scanning of search long term memory for previously encoded information becomes inefficient. Much of the previous research shows that long term memory difficulties are not characteristic of ADHD once initial encoding is accounted for, implying origins in immediate learning deficits (Kaplan et al., 1998; Kibby & Cohen, 2008; Skodzik et al., 2017).

1.3.4.3 Cognitive heterogeneity

ADHD is notoriously heterogeneous and not all children with ADHD show the same pattern and level of cognitive difficulties (Coghill et al., 2014; Rhodes et al., 2012; Kofler et al., 2019). Up to a quarter of children with ADHD show intact performance on all cognitive tasks administered to them (Rhodes et al., 2005; 2006; Willcutt et al., 2005; Coghill et al., 2014). Evidence for heterogeneity also comes from studies showing that different ADHD subtypes are characterised by varying cognitive profiles. For example, ADHD-Inattentive subtype is predominantly linked with EF and WM difficulties, as well as poor academic outcomes, whilst the ADHD-Hyperactive-Impulsive subtype is primarily associated with vulnerabilities in delay aversion (Chhabildas et al., 2001; Martinussen & Tannock, 2006; Solanto et al., 2001; Sonuga-

Barke et al., 2003). This implies heterogeneity in the neural and/or risk factors (Nigg et al., 2005). Further, different cognitive difficulties do not always correlate with each other, implying that ADHD stems from multiple and distinct neural network risks (Solanto et al., 2001).

Evidence for cognitive heterogeneity in ADHD has kindled an interest in identifying ADHD subtypes beyond clinical categories. Lambek and colleagues (2010) examined behavioural, academic, cognitive, and motivational functioning in an ADHD sample with and without EF difficulties. They found that those with EF difficulties had lower IQ and higher intra-individual response variability, than the ADHD group with intact EF performance. Roberts, Martel and Nigg (2017) were able to identify three ADHD cluster groups: (1) poor inhibitory control, (2) poor set shifting/speed, and (3) intact EF. These three groups differed on behavioural and neurocognitive profiles, such that children in the poor set shifting/speed cluster had substantially higher hyperactivity/impulsivity and ODD symptoms, as well as lower IQ and academic performance than the other clusters. Using a wider range of neuropsychological measures, Takács and colleagues (2014) identified six different cluster groups from children with and without ADHD that corresponded to severity of EF impairment. Two of these clusters resembled neurotypical child characteristics (few ADHD symptoms and moderate WM difficulties) and two subgroups with mainly or exclusively ADHD children (severe WM deficits and mild/severe shifting difficulties). The final two clusters comprised mixed samples and were regarded as subthreshold/subclinical clusters due to moderate cognitive difficulties. Interestingly, conduct and learning difficulties were lowest in the typically-developing-like cluster, whereas co-occurring learning difficulties were highest in the ADHD-like severe WM difficulty group. This implies that diminished WM processing heightens risk for academic difficulties. Collectively, the above findings implicate higher order cognitive abilities in children’s academic performance. The purpose of the following section is to focus specifically on the maths domain, and factors that underpin maths development in children.

1.4 Development of maths in children

Maths refers to the scientific study of numbers, quantities, structures and space (Ziegler & Loos, 2017). School curriculums typically follow a sequential progression trajectory increasing in difficulty with simple arithmetic introduced during early primary school years, advancing through to algebra, geometry, trigonometry, functions, and calculus (Steen, 2001). In Scotland, a spiral curriculum is employed whereby topics are revisited iteratively over time with increasing difficulty, meaning that new learning is embedded within previously learned knowledge (Education Scotland, 2009; Harden & Stamper, 1999). Early maths achievement predicts later academic, occupational, and socioeconomic outcomes in adulthood (Duncan et al., 2007; Ritchie & Bates, 2013). Numerical illiteracy is estimated to cost the UK economy around £20.2 billion per year, equating to around 1.3% of GDP (Pro Bono Economics, 2014). This renders the successful development of numerical skill as a compelling priority from both the individual and societal perspective.

The exploration of maths learning and comprehension predates to the early 20th century (Geary, 2007). The ancestry of experimental psychologists explored a range of contemporary themes, including speed and accuracy of object quantity apprehension, problem solving strategies, varying problem difficulty levels, as well as factors influencing maths learning, such as practice-related advancement and transference of skills (Brownell, 1928; Thorndike & Woodworth, 1901; Washburne & Vogel, 1928; Winch, 1910; all in Geary 2006). Individual differences in paper-and-pencil maths tests led to the scrutiny of the origins of inter-individual variability of numerical skill acquisition. Findings support a distinction between domain-specific and domain-general factors in modulating maths competency (Gilmore et al., 2018). Furthermore, the implications of functional innumeracy across the lifespan prompted interest in cognitive phenotypes of maths difficulties in children (Geary, 2004). The following section explores these issues in more detail.

1.4.1 Factors underpinning maths development

1.4.1.1 Domain-specific factors

Evidence suggests that maths performance is predicted by a range of domain-specific skills. Fundamental to maths competence is arithmetic – the ability to deal with numbers (Butterworth, 2005). Identifying, representing, and manipulating numbers is hypothesized to be an innate ability, and so difficulties with pre-verbal quantity processing systems could drive difficulties in maths (Dehaene, 2011; Karagiannakis et al., 2014; Xu & Spelke, 2000). Studies using habituation paradigms consistently demonstrate that infants as young as six months look longer at stimuli increasing in quantities with a 1:2 ratio, and by nine months this precision improves to a 2:3 ratio, even after controlling for stimulus parameters such as density and area covered (Xu, 2003; Xu et al.,2005; Xu & Arriaga, 2007). By 11 months infants are sensitive to ascending and descending stimuli sequence presentations, reflecting a pre-requisite for ordinal relationship comprehension (Brannon, 2002). Furthermore, 18-month-old infants prefer watching a correct counting sequence specific to their native language (Slaughter et al., 2011).

The post-infancy milestone includes the development of concrete counting abilities that bridge innate number sense with culturally supplied conceptual instruments (Butterworth, 2005). According to Gelman and Gallistel's (1990; 1992) domain-specific theory, five innate principles govern counting abilities during preschool years: (1) *stable order* (counting words follow a consistent sequence e.g., 'one, two, three'), (2) *one-to-one* (number words correspond to objects), (3) *cardinality* (the number label ascribed to the final counted object corresponds to the quantity of items in the set e.g., 'one, two, three' corresponds to a numerosity of three objects), (4) *abstraction* (counting can be applied to any items, tangible or not), and (5) *order-irrelevance* (items can be counted in any order, and this does not affect the set's cardinality). Fuson (1988) argued that rather than being purely innate these principles are consolidated through observation of cultural mechanisms such as number concepts and counting behaviours typically introduced by the environment (e.g., parent-child play or nursery rhymes) coupled with children's attempt to bind the verbal counting list onto non-verbal analogue magnitude representations (Butterworth, 2005; Fuson, 2012; Geary,2000; 2006; Nieder, 2016). This pre-verbal number system gradually fuses with the child's developing language competencies to advance to verbal counting (Geary, 2000). By applying initially meaningless processes of counting (e.g., modelled by parents) to a subitising range (e.g., a visual display from which a child can accurately derive the number of objects), children master the idea that distinctive numerosities match verbal labels of numbers. This facilitates a shift between relying on perceptual cues, such as spacing of objects, to purely numerical information when establishing which of two sets is bigger (Fuson, 2012). Wiese (2007) argued that by using visual tallies to maintain track of counted objects (e.g., using fingers to count a sequence), children develop a corresponding stable sequence of number-words. The salience of the last number-word substantiates the discovery that, in sets with a specific cardinality, the last number consistently stays the same and, therefore, must index the total number of objects, also known as the principle of cardinality.

This subsequently paves a more concrete path for the concept of ordinality – the understanding that consecutive number words reflect consecutively larger quantities (Butterworth, 2005; Piaget, 1952). Children develop a dependent link between the number position within the sequence and the object position within the set, promoting an understanding that the total number of objects corresponds to the element sequence from beginning to end of a counting list (Wiese, 2007). The child can now assign a numerical order to each of the objects, thereby establishing that number assignments within a sequence represent numerical rankings (Fritz, Ehlert and Balzer, 2013). This is achieved through the 'mental number line' – a mental representation of the order of numbers (Dehaene, 2011; Schneider et al., 2009). Using this non-linguistic approximate number system children can mentally represent and manipulate increasingly large, approximate numerosities from left to right in an ascending order, resulting in the association of numbers with spatial locations (Dehaene, 2011).

Once cardinal quantities and ordinal sequences are mastered, these can be integrated into the quantity concept: the mental number line represents a sequence of increasingly larger cardinal elements adhering to a fixed order (Butterworth, 2005). The child can now make magnitude judgements about larger/smaller quantities based on the number of elements (e.g., two is less than three because quantity two is made up of less elements than quantity three). The concept of quantity underpins the shift between counting the individual elements (e.g., ‘one, two, three’ equates to number three) to cardinal conceptualizations (e.g., the number three is a composite unit made up of all its individual elements). Thus, the ‘number-sense’ is crucial for other numerical activities including quantity, magnitude, and number processing, as it helps children determine which number is larger/smaller and conceptualise about number relationships (Fritz et al., 2013; Kuhn & Holling, 2014).

The mastery of cardinality and ordinality is an important prerequisite for basic arithmetic skills of addition (Butterworth, 2005). This is because counting two separate cardinality sets, for example, (1) ‘one, two’, and (2) ‘one, two, three’, corresponds to counting the total quantity where the number translates into a composite unit of ‘five’ (i.e., five distinct objects become a single quantity ‘five’). To do this, children initially rely on their fingers to help represent numerosities of the first addend (‘one, two’) and the second addend (‘one, two, three’), following which the total number of fingers are counted to get the answer (counting all strategy; Butterworth, 2005). Children eventually realise that they can start with the first set (‘three’) and count the second quantity onto the first addend (‘one, two’) using their fingers without counting the first quantity (counting on strategy; Butterworth, 2005; Fritz et al., 2013; Fuson, 1992). The last counting strategy is acquired when the child realises that counting from the smaller addend (i.e., starting with two fingers when doing 2 + 3 =?) is more effortful (Butterworth, 2005). In order to reduce cognitive load, children opt for adding on from the larger quantity (3 + 2 =? Baroody & Gannon, 1984). Through repeated practice, children create numerical associations between number quantities and correct answers, referred to as factual fluency (knowing from memory that 3 + 2 = 5). These associations are found to be stored in Large + Smaller addend format (e.g., 3 + 2 = 5) rather than Smaller + Larger addend format (e.g., 2+ 3= 5), as reflected by slower reaction times for solving the latter-type sums (Butterworth et al., 2001; Butterworth et al., 2003). Additionally, the size of the sum/product overrides the effects of practice frequency, contradicting the hypothesis that factual retrieval is based on passive rote memory and verbal association practice as a function of frequency (Aschcraft et al., 1992; Butterworth et al., 2001). Rather, memory representations appear to be re-organised parallel to number size and principles of commutativity (i.e., altering order of quantities does not change the result). Thus, it appears that memory-based factual knowledge interacts with children's conceptual understanding to actively mould more efficient arithmetic solutions.

Domain-specific numerical skills contribute to broader maths achievement (Andersson & Östergren, 2012; Booth & Siegler, 2006; Chu et al., 2016; De Smedt, et al., 2013; Gilmore et al., 2011; LeFevre et al., 2010; Passolunghi & Lanfranchi; 2012). Accuracy on number-line estimation tasks, which requires participants to estimate numbers on a horizontal line, predicts maths achievement in children, and such estimations tend to be less precise in children with MLD (Geary et al., 2008; Schneider et al., 2009; Sasanguie et al., 2013;). Similarly, symbolic quantitative knowledge such as number recognition, and quantity reasoning, as well as number naming, and magnitude comparisons, are all found to predict maths competencies in children (Andersson and Östergren, 2012; Landerl et al., 2004; Chu et al., 2016). These effects are more consistent for symbolic magnitude representations (e.g., digits) than non-symbolic ones (dots; Andersson & Östergren, 2012; Chu et al., 2016; Schneider et al., 2017). Children with maths difficulties tend to rely on less efficient finger counting procedures during arithmetic computations for longer than their neurotypical peers, reflecting a delayed counting strategy shift (Geary et al., 1993; Jordan et al., 2003).

The aforementioned precursors of early maths proficiency map on to three domain specific math components skills (Passolunghi & Lanfranchi, 2012). Specifically, this includes factual knowledge, conceptual understanding, and procedural skill (Dowker, 2003; 2005; Hiebert & Lefevre, 1986). *Factual knowledge* refers to the ability to retrieve arithmetic facts quickly and efficiently from memory without engaging effortful calculations (Geary, 2004; Dowker 2003). Using factual knowledge, arithmetic problems such as 5 + 3 =? can be solved quickly and automatically by retrieving the answer directly from memory instead of using explicit calculations (Baroody & Tiilikainen, 2013). During initial stages of learning children count the two sets of a sum in their entirety (e.g., 1, 2, 3, 4, 5 and 6, 7, 8 – counting all strategy). The next level involves counting from the smaller number of the set (e.g., 1, 2, 3 – counting on strategy) before realising that adding from the larger number is more efficient (e.g., 5, 6, 7, 8). Through practice, the sum is repeatedly paired with its answer in WM and representations are embedded in long term memory (Pigon, 2017; Tenison & Anderson, 2016). Eventually counting strategies should be abandoned in favour of more sophisticated memory-based retrieval, decreasing cognitive load posed by manual calculations, which are more time consuming and prone to error (e.g., verbal and finger counting; Geary et al., 1991; Lemaire & Siegler, 1995; Siegler & Shrager, 1984). Notably, children with greater factual fluency performed better on solving more complex double digit arithmetic sums and geometric reasoning, highlighting the role of basic arithmetic in facilitating more advanced computational skill (Geary & Hoard, 2005; Geary et al.,1999).

Conceptual understanding, or the ‘knowing why’, refers to the ability to derive inferences, analogies, and shortcuts using rules governing maths (Gilmore & Bryant, 2010; Gilmore et al., 2017). Conceptual understanding includes understanding of basic maths laws and procedures (e.g., knowing that addition is inversely related to subtraction; Dowker, 2005). Hiebert and Lefevre (1986) define it as the comprehension of numerical relationships, arithmetic operations, and the ability to use these associations to solve a problem. Conceptual understanding is hypothesised to develop as a result of a linking process between existing knowledge and newly learned material, whereby repeated exposure of associations leading to a 'satisfying states of affairs' are reinforced in memory and facilitate the establishment of relevant rules and concepts (Groth & Bergner, 2006; Butterworth, 2005; Thorndike,1922;). For example, repeatedly being exposed to sums such as 3 + 1 = 4 and 4 - 3 = 1 gradually enhances the understanding that addition is inversely related to subtraction. This also highlights the interdependence between factual retrieval processes and the mastery of arithmetic concepts.

During early stages of arithmetic learning, children master a variety of fundamental conceptual rules. The shift between counting from the smaller addend (e.g., 3, 4, 5, 6, 7, 8 in 5 + 3 =?) to initiating the counting sequence from the larger addend (i.e., 5, 6, 7, 8) reflects the realisation that changing the order of quantities does not change the product of the sum (a + b= b+ a; Baroody & Gannon, 1984; Butterworth et al., 2001). This principle of *commutativity* can halve the number of arithmetic facts that a child must learn and helps adjust to more advanced aspects of arithmetic such as multiplication (a × b = b × a; Reys et al., 2014). Another important maths principle is *inversion* – the understanding that addition is inversely related to subtraction (e.g., 5 + 3 = 8; 8-3 = 5) and multiplication is inversely related to division (e.g., 5 × 3 = 15, 15 ÷ 3 = 5; Greer, 2012). Children who master inversion are more likely to use conceptual shortcuts to eliminate the addition and subtraction of the same quantity, without applying explicit computations (e.g., eliminating the 4's in 3 + 4-4 =?

Gilmore & Papadatou-Pastou, 2009). It also represents a fundamental structure of later acquisition of algebraic equations (e.g., $3 + x = 7$ thus $x = 4$) where children must “undo” operations by inverse transformations (Greer, 2012).

Another important conceptual principle is *associativity*. Children who master the concept of *associativity* can flexibly use building elements of previously learned knowledge to solve a sum (e.g., employing the decomposition strategy 7 + 6 = 6 + 6 + 1 = 13; Kennedy, Tipps & Johnson, 2007). The associativity principle promotes manipulation of maths forms and engagement of previously learned generalised knowledge, particularly where the child faces a new or more complex problem (e.g., 15 + 16 = 15 + 15 + 1 = 31). Previous research demonstrates that children employing these conceptually based shortcuts of commutativity, inversion, and associativity outperform their peers who opt for less mature strategies (Canobi, 2004; Cowan & Renton, 1999; Gilmore & Papadatou-Pastou, 2009; Robinson & Dubé, 2009; 2013; Robinson et al., 2006).

Procedural skill, or the ‘knowing how’, refers to the ability to accurately and efficiently execute a sequence of actions/steps to solve a problem (Gilmore et al., 2017; Rittle-Johnson et al., 2001). This includes the ability to select and execute appropriate strategies accurately and efficiently (e.g., ‘carrying’ when adding above 10). Maths rules can often be misapplied, and these strategic errors are often referred to as bugs (Brown & Burton, 1978). To illustrate, systematic procedural errors can arise when a child is presented with a multi-digit sum such as:

Example 1.	Example 2.
36	71
+18	-29
44	58

In the first example the number 6 was correctly added to number 8 reflecting competent understanding of addition principles. However, the child failed to 'carry' when adding above 10 (i.e., computed 3 + 1 instead of 4 + 1). The second example represents a common procedural error during multi-digit subtraction problems where the child invariably subtracts smaller digits from larger ones (i.e., 9-1 = 8 instead of 11-9 = 2) and/or forgets to 'borrow' (i.e., 7 tens become 6 tens). However, it may be plausible to suggest that these types of errors are, in fact, contaminated by the inability to understand or disregard the conceptual basis of the procedure (Van Lehn, 1990). Successful counting procedures during earlier years rely on competent counting-all and counting-on strategies, typically executed verbally or using fingers (Siegler & Shrager, 1984). As procedural practice increases, memory representations for elementary number facts are enhanced, and children opt for more efficient factual strategies (e.g., direct retrieval or decomposition). The gradual shift across these procedural competencies is embedded in children's increasing conceptual understanding of counting and flexible use of conceptually based shortcuts (Geary & Hoard, 2002). For example, in solving a more complex problem (e.g., 15 + 18 =?) children mastering concepts of associativity may select a less cognitively taxing and faster procedure of decomposition (e.g., 15 + 18 = 15 + 15 + 3 = 33) rather than using a less sophisticated procedure of manually solving the problem by counting-all/on using their fingers. Collectively these issues highlight the reliance of procedural skill on factual and conceptual competencies. However, despite interdependence, difficulties across the components can occur independently leading to the proposition that they depend on differential cognitive processes (Geary, 2004; Dowker, 2005; 2012).

1.4.1.2 Domain-general factors

According to the domain-general account, maths difficulties are mainly driven by cognitive processes that are non-specific to maths performance (Dowker, 2005; Knops et al., 2017; Passolunghi & Lanfranchi, 2012). The Multi Component Pathways Model (LeFerve et al., 2010) holds that early maths acquisition depends on both domain-specific numerical and domain-general cognitive processes. In formulating this model, LeFevre and colleagues examined 4-6-year olds' early linguistic and non-linguistic numeracy skills, as well as their performance on cognitive assessments of (1) linguistic ability (vocabulary and phonological awareness), (2) quantitative ability (quantity discrimination), and (3) visuospatial attention (spatial span). They found that early linguistic skills uniquely predicted children's number naming performance two years later, but not non-linguistic arithmetic performance. Contrary to this, quantitative ability uniquely predicted only non-linguistic numerical magnitude processing performance, suggesting that the two pathways are distinct. Notably, spatial attention predicted unique variance in both linguistic and non-linguistic numeracy performance, leading the authors to suggest that the attentional pathway is a chief candidate in maths difficulties in children with ADHD.

Similarly, Geary 's hierarchical model (2004; Geary & Hoard 2005) holds that maths competency relies on the successful comprehension of numerical concepts and the procedural knowledge involved during problem solving. Within this framework, conceptual and procedural domain-specific factors exploit broader domain general cognitive skills, and particularly the central executive, responsible for attentional and inhibitory regulation of information processing. This information is likely to be represented in a verbal format (e.g., number words, verbal counting) or visuospatial format (e.g., number magnitudes and the 'mental number line'). Thus, MLD may manifest as difficulties in the conceptual or procedural components, arising because of difficulties in attentional processes or information representation/manipulation difficulties.

Performance across the different maths components is linked to a variety of cognitive processes implicated in ADHD (Cragg et al., 2017; Geary et al., 2017; Rhodes et al., 2005; 2012). For example, inhibitory control is proposed to help control interference from competing arithmetic facts and specific features that these share due to their common dependence on semantic memory networks (Ashcraft, 1987; Bellon et al., 2016; Cragg et al., 2017). LeFevre and colleagues (2013) found that executive attention performance (largely dependent on inhibitory processes) predicted children's arithmetic fact fluency growth between Grade 2 and Grade 4. To illustrate, when asked to compute 5 + 3 =? interference control would be crucial for suppressing nearby and competing but incorrect association such as 5 + 2 = 7, 5 + 4 = 9, 4 + 3 = 7 and 3 + 3 = 6 (De Visscher & Noël, 2014). In this sense, inhibitory control helps establish strong links between problems and answers, whilst also minimizing erroneous associations during retrieval (Geary et al., 2012; LeFevre et al., 2013). Inhibitory control could also be important for overcoming dominant but less efficient conceptually based strategies (Geary, 2004; Gilmore et al., 2018). For example, longer sums such as 7 + 18-18 =? can be quickly solved using the conceptually based inversion shortcut (i.e., eliminating the 18's and arriving at the answer 7) instead of using a less efficient/more familiar strategy which involves solving the sum from left to right (Robinson & Dubé, 2013). Lastly, inhibitory control is necessary for minimizing irrelevant information from contaminating the WM system during procedural calculations by selecting and employing the most appropriate strategy and suppressing less efficient but well-rehearsed ones (Lemaire & Lecacheur, 2011).

Cognitive flexibility can help shift between different conceptual rules of mathematical notations (e.g., + and -) as well as their procedural underpinnings (Cragg & Gilmore, 2014). Although set-shifting performance has been linked with general maths achievement, evidence of its association with conceptual understanding in children is mixed (Andersson 2010; Bull & Lee,2014; Cragg et al., 2017; Gilmore et al., 2018). Lemaire and Lecacheur (2011) found that children who scored lower on inhibitory control and cognitive flexibility were less likely to select the most efficient strategy for estimating answers to two-digit addition problems, resulting in poorer arithmetic performance. Cognitive flexibility can help the child shift between different numerical strategies required for different types of problems (Andersson, 2010, Clark et al., 2010). Research shows that children with reduced performance on tasks measuring inhibitory control and set shifting are more likely to make procedural errors (Andersson, 2010; Clark et al., 2010; Cragg et al., 2017; Gilmore et al., 2015). Finally, cognitive flexibility can help mentally rearrange problems into different formats in order to identify conceptual relationships, particularly during initial learning (Siegler & Araya 2005; Cragg et al., 2017).

WM is documented as one of the strongest predictors of maths achievement in children, although the relative importance of visuospatial and verbal WM processes is contested (Cragg et al., 2017; Geary 2004, Gilmore et al., 2018; Li & Geary, 2013;

Szucs et al., 2013). In a neurotypical population, Cragg and colleagues (2017) found that WM was the only domain-general process which directly influenced maths achievement, as well as indirectly via the factual, conceptual, and procedural components. Further, inhibitory control was only uniquely related to factual and procedural skill, which in turn affected broader attainment. Another study by Szucs and colleagues (2013) found that children with MLD predominantly showed visuospatial WM deficits but not verbal WM difficulties, implicating visuospatial WM processing as particularly important to maths. Moreover, Li and Geary (2013) found that central executive task performance predicted 7-year-old's performance on numerical operations, whilst visuospatial STM did not. However, central executive performance was indexed using backward digit recall tasks involving numbers, which could have been confounded by the numerical stimuli. Interestingly, children showing higher visuospatial STM gains from age 7 to 11 had the higher levels of attainment in maths by age 11. Cragg and colleagues (2017) suggested that this discrepancy in visuospatial versus phonological contribution reflects age-related changes in WM domain contributions to maths performance. During earlier years children predominantly rely upon verbal memory processes required for basic arithmetic learning such as rehearsal of number facts, whereas visuospatial memory processes are mobilised by more complex maths reasoning in older children (Cragg et al., 2017).

Factual knowledge is largely dependent on retrieval of arithmetic facts from memory (De Visscher & Noël, 2014; Geary, 2007; 1993). For example, when solving a sum such as 2 + 3 =? it would be more efficient for the child to derive the answer from memory than to count using their fingers. This is because finger counting strategies tax WM resources and take longer to implement when compared with direct retrieval, which relies on automatic processing (Geary et al., 2004; Geary, 2007).

Children with memory difficulties struggle to encode taught information due to a fast decay of the items in WM (Cragg et al., 2017; Campbell et al., 2011; Gremillion and Martel, 2012). Although WM is associated with maths fact retrieval from long term memory, more passive verbal and visuospatial STM subcomponents account for unique variance in arithmetic fact retrieval performance, parallel to their role in governing semantic and spatial rehearsal of verbal and numerical representations (Dehaene & Cohen, 1995; Cragg et al., 2017). Memory retrieval deficits may also arise due to difficulties in strategically scanning long term memory for previously learned knowledge that help interpret and solve a sum. For example, having mastered the concept of commutativity (i.e., a + b = b + a), children can quickly reason that if 21 + 43 = 64, then 43 + 21 = 64 without explicit procedural calculations. Gilmore and colleagues (2018) found that WM was the strongest contributor to conceptual maths performance in 8-10-year-olds; its' predictive value reduced when a domain specific skill of number-line estimation performance was considered. Nonetheless, WM has also been found to predict number-line estimation performance, rendering it as an important contributor to both lower level and advanced maths skills (Gilmore et al., 2018; Xenidou-Dervou et al., 2015).

WM is also closely linked with procedural skill (Bull et al.,2008; Fuchs et al., 2010). The central executive is likely to be engaged during more advanced arithmetic operations by (1) selecting more efficient/appropriate strategies (e.g., carrying, borrowing and columnar trading), and (2) allocating attentional resources for strategy execution (Ashcraft, 1992; Geary et al.,1993; Meyer et al., 2010). In line with this, Andersson (2008) found that performance on three tasks tapping into the central executive accounted for unique variance in written multi-digit addition and subtraction problems efficiency in 9-10-year-olds after accounting for IQ, reading, and age.

Although evidence suggests that it is mainly the central executive which drives procedural deficits, evidence relating to significant contributions of the visuospatial sketchpad and phonological loop is equally robust (Andersson, 2008; Cragg et al., 2017). These specialized subsystems are necessary for encoding and maintaining modality-specific information in memory. One study found that whilst counting recall significantly predicted word problem solving in children aged 7-8 years, performance on the backward digit span did not (Meyer et al.,2010). The researchers suggested that this reflects an impairment in numerical information retrieval from long term memory into WM, rather than a deficit in concurrent retrieval and manipulation of information in the backward digit span task. WM also predicts conceptual knowledge, although findings relating to the comparative role of verbal and visuospatial WM processes are mixed (Andersson, 2010; Cowan et al., 2011; Jordan et al., 2013; Cragg et al., 2014; Gilmore et al., 2018).

Research into the role of planning in maths performance is relatively scarce (Cai et al., 2016). Planning is an important component of general problem-solving abilities and particularly in managing a sequence of operations (Davidson et al., 1994). Arguably, planning would be crucial for successful procedural computations requiring children to organise solution steps (Rourke, 1993). Tasks that tap into planning abilities require the child to (1) devise a schema, (2) select moves and sequences of moves, and (3) maintain the schema and individual moves in visuospatial WM (Levin et al., 1994). Arguably, children with planning difficulties may find it difficult to plan and keep track of the necessary steps for successful problem solving, and likely struggle to attend to and store the necessary steps/ solutions in a correct sequence (Dowker, 2005). Planning has been linked to broader maths achievement in children and adolescents (Best et al., 2011). There is also some evidence to suggest that children with arithmetic difficulties have difficulties with the Tower of London planning task (Sikora et al., 2002). In a study of Chinese primary school children, Cai and colleagues (2016) found that planning skills accounted for unique variance in maths performance of second graders. Specifically, operational planning (strategic and tactical approach to solving a problem in line with task-imposed constraints) was found to be a significant predictor of math fluency, reasoning, and problem-solving abilities independent of WM capacity.

1.5 Maths in children with ADHD

Evidence for maths difficulties in ADHD comes from high rates of co-occurrence with MLD, lower performance scores on standardized maths tests, and below average math grades at school (Daley & Birchwood, 2010; DuPaul et al., 2013; Tosto et al., 2015). Some children with ADHD struggle with basic arithmetic processes such as digit estimation (Sella et al., 2018) and number magnitude comparisons (Kaufmann & Nuerk, 2008), as well as more complex processes such as word problem solving (Re et al., 2016). A systematic review by Tosto and colleagues (2015) found that 76% of studies found evidence for a significant negative association between ADHD symptoms and maths ability even after controlling for a range of confounding factors. Antonini and colleagues (2016) found that children aged 7-11 years with ADHD had significantly lower numerical operations scores than neurotypical controls. Moreover, maths errors were mediated by children’s visuospatial memory (n-back) performance, but not by parent-rated inattention symptoms. In a similar study, Gremillion and Martel (2012) found that, jointly, semantic language and verbal WM mediated the relationship between children’s ADHD symptoms and standardised maths reasoning achievement scores. A recent study found that maths impairment was most strongly associated with visuospatial WM processes in both children with ADHD and children with learning difficulties but without ADHD diagnosis, implicating a common cognitive pathway as driving maths difficulties (Gathercole et al., 2018). Collectively, these findings suggest that cognitive processes, rather than behavioural symptoms, could be key in modulating children's maths abilities.

Previous studies on maths in ADHD use broad assessments of maths attainment levels. Although standardized achievement tests are useful tools for identifying broad maths strengths and weaknesses, they can mask profile variations in specific math component skills (Cragg & Gilmore, 2014; Cragg et al., 2017). For example, Numerical Operations subtest on the Wechsler Individual Achievement Test (WIAT) comprises untimed written calculation problems (addition, subtraction, multiplication, and division). This task draws on various maths skills such as the child's ability to: (1) access number facts (e.g., knowing from memory that 2 + 5 = 7), (2) draw on basic arithmetic concepts (e.g., addition is the opposite of subtraction), and (3) apply correct procedures (e.g., carry when adding above 10). Thus, a low score on the Numerical Operations subtest indicative of impairment lacks the qualitative information required to ascertain which specific aspect of mathematical skill (factual, conceptual, or procedural) is steering the low attainment score. As such, assessing specific maths components is more desirable exploring pathways of impairment (Cragg et al., 2017).

Another issue relates to studies failing to screen for other co-occurring disorders. Up until 2013, the 4th edition of the DSM (DSM-IV) did not allow for concurrent diagnoses (APA, 200; Harris et al., 2015; Leitner, 2014). This means that much of our understanding of educational difficulties in ADHD are limited to research that frequently excludes children with co-occurring developmental disorders. Yet, ADHD seldom occurs in isolation and co-occurrences with other disorders is the rule rather than the exception (Larson et al., 2011). Despite this many studies exploring maths in ADHD fail to screen for co-occurring symptom constellations or opt to exclude children with other neurodevelopmental disorders from participating. This makes it difficult to characterise maths difficulties in children with ADHD in a way that reflects diagnostic complexities.

1.6 Statement of the problem

As evidenced above, children with ADHD are at increased risk for maths difficulties. Previous studies focus on behavioural ADHD symptoms and their relationship to maths performance in this population (Tosto et al., 2015). However, aetiological models of ADHD suggest that cognitive vulnerabilities, such as EF and memory difficulties, give rise to conventional manifestations of behavioural symptoms of this disorder (Castellanos & Tannock, 2002; Coghill et al., 2005). Further, research in children with ADHD, as well as neurotypical populations, has linked maths attainment to cognitive task performance (e.g., Anonini et al., 2016; Cragg et al., 2017). As such, cognitive constructs offer a more compelling target for researching causal mechanisms of maths difficulties in ADHD than behavioural symptoms. The current literature would therefore benefit from a comprehensive investigation of the relationship between a wide range of cognitive processes and maths performance in this population.

Furthermore, models of numerical cognition suggest that there are several domain-specific numerical skills that draw on domain-general cognitive processes for successful maths performance (Geary, 2004; LeFevre et al., 2010). This includes factual knowledge, conceptual understanding, and procedural skill. Despite inter-correlations, difficulties across the components can occur independently implying dependence on differential cognitive processes (Dowker, 2001; 2005). The pattern of associations between domain-specific maths skills and domain-general cognitive domains implicated in ADHD is yet to be elucidated.

Previous research has predominantly relied on standardised measures of attainment when assessing maths in ADHD. These assessments are useful for obtaining age-normed achievement scores that show how a child is performing in broad maths domains (e.g., numeracy or problem-solving skills), when compared to their neurotypical age-matched peers. However, the generic nature of these tests fails to pinpoint the mechanisms that give rise to broader maths underachievement. Research in neurotypical children and children with dyscalculia have identified two interrelated tribes of factors as contributing to mathematical achievement: (1) domain-general cognitive processes, and (2) domain-specific numerical abilities (Cragg et al., 2017; Szucs et al., 2013; Träff et al., 2017). The association of these factors with broader achievement in children with ADHD is yet to be established. Understanding the nature of this relationship will be crucial for informing predictive models and generating effective intervention strategies.

ADHD is a heterogeneous disorder characterised by a diverse range of difficulties in neurocognitive functioning. ADHD also carries an increased risk for adverse educational outcomes, although research has focused largely on broad attainment levels, rather than specific maths skills. Furthermore, although, as a group, children with ADHD frequently underperform on measures of maths and cognition, research documents substantial intra-group heterogeneity. Thus, administering a generic intervention to a diverse group of ‘underachievers’ may produce incompatibility between the underlying deficits and intervention-targeted processes, resulting in wasted resources and thwarting potential for long lasting improvements (Kadosh et al., 2013; Rapport et al., 2013). It is therefore important to identify differential patterns of cognitive performance in ADHD and their relationship to more specific maths skills.

Despite overwhelming evidence for heterogeneity much of the research continues to overlook its importance. Studies often rely on samples with ‘pure’ ADHD and fail to screen for other frequently co-occurring disorders such as ASD, DCD, and/or behavioural difficulties (Antonini et al., 2016; DuPaul et al., 2016; Kofler et al., 2019; Simone et al., 2017; Sturm et al., 2018; Semrud-Clikeman et al., 2010). This approach is limited in that it fails to capture the complexities of real-life diagnoses of neurodevelopmental disorders and this challenges the external validity and generalisability of findings (Astle et al., 2019; Kofler et al., 2019).

Furthermore, the difference between receiving an ADHD diagnosis versus falling just below the threshold for meeting diagnostic criteria may reflect a purely quantitative difference rather than a qualitative one (Sonuga-Barke & Halperin, 2010; Taylor et al., 2019). This has led researchers to advocate a shift away from categorical conceptualisations of ADHD that bind neurodevelopmental disorders to diagnostic categories. A more favourable approach is a dimensional characterisation of disorders in which ADHD is regarded as an arbitrary cut-off point on a continuous behavioural dimension (Angold & Costello, 2009; Haslam et al., 2006; Gathercole et al., 2018). Thus, it is as equally compelling to explore children who do not meet criteria for ADHD but, nonetheless, show a certain degree of diminished functioning.

Another methodological concern within the literature relates to inclusion of children with ADHD that are on medication (Biederman et al., 1999; Efron et al., 2014) or had recently been taking medication (Barry et al., 2002). There is evidence to show that psychostimulant treatment improves neuropsychological and academic functioning (Powers et al., 2008; Vaidya et al., 1998). A drug-naïve sample will therefore be more favourable for identifying disorder-specific causal associations with functional outcomes. Additionally, not all parents opt for pharmacological intervention and so it is important to establish basal disorder-associated profiles which can in turn inform a variety of intervention modalities.

1.7 Aims of this thesis

The current literature requires a comprehensive investigation of the relationship between cognitive and maths performance in a heterogeneous ADHD sample. The broad aim of this thesis was to provide an in-depth examination of cognitive and maths performance in a clinical ADHD sample. This is achieved using the following chapters

(1) Chapter 2 includes a systematic review of previously published literature on the association between cognition and maths in clinical ADHD samples, highlighting some of the key issues that must be considered in the thesis.

(2) Chapter 3 includes a comprehensive overview of the general methodology used for the remaining experimental study chapters including participant inclusion, characteristics, and sample size, as well as the materials and procedures employed.

(3) This is followed by Chapter 4, which explores cognitive correlates of maths attainment and more specific maths skills in children referred for ADHD assessment to CAMHS.

(4) Chapter 5 examines the effects of co-occurrence between ADHD and motor difficulties, by comparing cognitive and math performances profiles of those children with and without co-occurring motor difficulties.

(5) Lastly, Chapter 6 employs a data-driven approach to explore maths performance in different cognitive cluster groups and compare this approach to a categorical diagnostic method.

Please note that the study chapters are presented as papers which are under review/revisions. As such, there may be some duplication of information throughout.

2 Chapter 2: Cognitive and maths performance in children with attention deficit hyperactivity disorder (ADHD): A systematic review

As demonstrated in the General Introduction, cognitive processes play an important role in children's maths learning. Difficulties in cognitive functioning are a core feature of ADHD, who also tend to show lower levels of maths attainment than their neurotypical peers. This chapter offers a detailed review of existing findings from studies assessing the relationship between cognitive processes and maths performance in children with a clinical ADHD diagnosis. This systematic review includes an evaluation of risk of bias within the studies to highlight some of the key areas and methodological considerations that can be addressed by future research in this area. Please note that while this chapter is placed before the General Methodology Chapter 3, the systematic review was conducted after methodological decisions which were made for the experimental study chapters.

The protocol for this review can be found on PROSPERO (registration number: CRD42020169708). The chapter includes a publication under revision:

Kanevski, M., Booth, J.N., McDougal E., Stewart, T.M., McGeown, S., Rhodes, S.M. (2021). The relationship between cognition and maths in children with Attention-Deficit/Hyperactivity Disorder: a systematic review. *Child Neuropsychology* (under revision).

2.1 Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is one of the most common neurodevelopmental disorders with global prevalence rates of around 5% (Polanczyk et al., 2007; 2014). Although ADHD was previously regarded as a childhood disorder, it is now recognised as a lifespan disorder with difficulties persisting well into adulthood (Biederman et al., 2010; Döpfner et al., 2015; Faraone et al., 2006; Harpin, 2005). Long-term functional adversities are documented across behavioural, socioemotional, educational, and occupational domains (Taylor et al., 2019; Klein et al., 2012; Kuriyan et al., 2013). Educational risks are of particular concern given their inherent contribution to future life success (Duncan et al., 2007; Klein et al., 2012). Core ADHD symptoms of inattention, impulsivity, and hyperactivity can have negative effects on children's academic functioning, increasing their susceptibility to a myriad of educational difficulties (Arnold et al., 2020; Daley & Birchwood, 2010; Loe, & Feldman, 2007). Previous research indicates an ADHD diagnosis can have especially negative consequences on children's level of maths achievement (Mayes et al., 2020; Silva et al., 2020), although the precise mechanisms behind maths difficulties remain contested.

2.1.1 ADHD symptoms and maths

A previous review found that over 70% of studies identified a negative association between behavioural ADHD symptoms and maths ability, even after controlling for a range of attenuating factors such as age, socioeconomic status, IQ, and psychostimulant medication (Tosto et al., 2015). Notably, symptoms of inattention showed more substantial associations with maths than hyperactivity-impulsivity, implicating attentional processes as particularly important to maths. According to the clinical symptom model, difficulties with sustaining attention impede upon processes that promote successful learning and academic functioning such as focusing on classroom activities, following instructions, and completing homework (Calub et al., 2019). This is supported by research linking diminished attention with lower maths performance as indexed by teacher ratings and standardised achievement tests (Breslau et al., 2009; Calub et al., 2019; Duncan et al., 2007; Garner et al., 2014). Nonetheless, pharmacological treatment aimed at alleviating clinical ADHD symptoms leads to marginal and short-lived improvements in maths attainment, suggesting that factors other than inattention symptoms could be involved (Baweja et al., 2015; DuPaul et al., 2016; Kortekaas-Rijlaarsdam et al., 2019; Molina et al., 2008).

Others suggest that maths underachievement in ADHD may be due to generally lower levels of intellectual functioning (Calub et al., 2019; Duckworth et al., 2012; Frazier et al., 2004; Mayes et al., 2009). However, significant associations between IQ and maths performance could be propelled by the large overlap between conventional IQ tests and higher order cognitive processes on which many children with ADHD struggle with (Antonini et al., 2016; Coghill et al., 2014; Dennis et al., 2009). Thus, another plausible explanation is that higher order cognitive processes, responsible for regulating attention, modulate maths performance (Friedman et al., 2018; Rapport et al., 2008; Thorell, 2007).

2.1.2 The role of cognition in maths

Cognitive impairments in ADHD are frequently found on tasks assessing Executive Functions (EF), memory, processing speed, temporal processing, delay aversion, and motor control (Coghill et al., 2014; Rhodes et al., 2004; 2005; 2006; Sonuga-Barke et al., 2010). Of these, EF, memory, and processing speed have been implicated in children’s maths performance (Bellon et al., 2016; Bull & Lee, 2014; Cai et al., 2016; Cragg et al., 2017; Formoso et al., 2018; Geary 2004; Gilmore et al., 2015; LeFevre et al., 2013; Sturm et al., 2018; Szucs et al., 2013; Verguts & Wim, 2005). Particular focus has been given to EF mechanisms due to their strong affiliations with attention regulation (Barkley, 1997; see reviews by Bull & Lee, 2014; Gilmore et al., 2018). EF are a set of higher-order cognitive processes responsible for managing goal-oriented behaviours and, typically, these include response inhibition, cognitive flexibility, working memory (WM), and planning (Diamond, 2013; Miyake et al., 2000).

In the context of maths, inhibition can help suppress retrieval of related but incorrect solutions from memory (e.g., inhibit 8 when being asked to 4 × 4 =? De Visscher & Noël, 2014) and curb automatically activated solution strategies in favour of more efficient ones (Lemaire & Lecacheur, 2011; Robinson & Dube, 2013). Cognitive flexibility can facilitate effortless shifting between different problem steps, operations (e.g., addition and subtraction), and notations (e.g., verbally presented digits and written Arabic symbols; Robinson & Dube, 2013; Siegeler & Araya, 2005), although the evidence for its role is mixed (Bull & Scerif, 2001; Clarket al., 2010; Cragg et al., 2017). WM consistently emerges as one of the strongest predictors of maths performance (Cragg et al., 2017; Lee et al., 2012; Monette et al., 2011). WM supports encoding and retrieval of arithmetic facts in the long-term memory store through repeated practice (Cragg et al., 2017; Gremillion & Martel 2012) and helps regulate, manipulate, and update verbally/spatially presented numerical information 'online' (Cragg et al., 2017). The domain of planning has also been associated with children's maths ability (Best et al., 2011; Lai et al., 2019; Sikora et al., 2002). Planning skills help organise knowledge and promote correct execution of a sequence of steps on more complex computations and its unique contribution has been demonstrated above and beyond WM capacity (Cai et al., 2016; Davidson et al., 1994; Dowker, 2005; Rourke, 1993).

Considerable evidence suggests that EF task performance is compromised in children with ADHD when compared to their neurotypical peers (Coghill et al., 2014; Kofler et al., 2018; Nigg et al., 2005; Willcutt et al., 2005). Moreover, ADHD-associated decrements in EF task performance are often accompanied by substantial group differences in maths attainment (Antonini et al., 2016; Biederman et al., 2004; Friedman et al., 2018; Holmes et al., 2014). However, in attempting to explore the cognitive mechanisms by which such group differences arise, studies focus on a select one or two EF components (e.g., Antonini et al., 2016). A global account of the contribution of the constituent domains is therefore necessary to help ascertain the relative principality of EF processes.

Cognitive correlates of maths have also been extended to cognitive processes without substantial executive processing. This includes modality specific verbal and visuospatial storage systems responsible for encoding and retrieval of information in short-term memory (STM) in the absence of concurrent processing (Baddeley & Hitch, 1974). Disruptions to visuospatial and linguistic information representation mechanisms hinders long term memory storage and retrieval of basic number facts (Cragg et al., 2017; Geary, 2004). Indeed, STM, impaired in some children with ADHD (Rapport et al., 2008; Rhodes et al., 2005; 2012), is crucial for establishing networks for learned facts and retrieving these from long term memory via linguistic and visuospatial codes (Dehaene & Cohen, 1995; Holmes & Adams, 2006). STM has been identified as an important predictor of maths performance, although studies yield mixed results on the relative contributions of phonological and visuospatial storage domains (Bull et al., 2008; Gathercole et al.,2006; Passolunghi et al., 2014; Swanson & Kim, 2007). Phonological memory storage appears to be crucial for encoding and processing of verbal codes for numbers, fundamental to elementary aspects of maths learning such as counting and arithmetic fact retrieval from long term memory (Andresson, 2010; Geary et al., 2008).Furthermore, visuospatial memory tends to become more important with age as it taxes visualisation and representation of quantities that support more advanced aspects of maths problem solving (Cragg et al., 2017; Holmes & Adams, 2006; Li and Geary, 2013). Thus, age and the type of maths assessment used can impact the relative engagement of phonological versus visuo-spatial storage domains.

Another important cognitive construct is processing speed – the efficiency with which relatively simple and automated cognitive tasks are executed (Shanahan et al., 2006). Children with ADHD generally show slower processing speed than their neurotypical peers, although studies yield mixed results (Calhoun & Mayer, 2005; Goth-Owens et al., 2010; Jacobson et al., 2011; Nikolas & Nigg, 2013). This variability is proposed to stem from the broad range of measures used to index processing speed, including reaction time, perceptual speed, psychomotor speed, and decision speed (Kibby et al., 2019; Salthouse, 2000). There is evidence to suggest that processing speed affects maths achievement indirectly through its effects on EF (Cassidy et al., 2017; Rose et al., 2011). Processing speed facilitates the fluency with which children compute solutions during simple arithmetic by minimising decay in WM and by creating stronger associations for these in long term memory (Bull & Johnson, 1997; Cirino, et al., 2015; Fuchs et al., 2006; 2008; 2010). Nonetheless, the role of processing speed may vary as a function of the maths domain being assessed with research showing direct associations when assessing basic arithmetic, and indirectly during more complex maths problem solving tasks (Fuchs et al., 2006; 2008; 2010; Rose et al., 2011).

2.1.3 Methodological considerations

Exploring cognitive and maths performance in children with ADHD warrants consideration of various methodological issues. One issue relates to inclusion of children receiving medication at the time of assessment (e.g., DuPaul et al., 2004; Efron et al., 2014). Medication treatment is a confounding factor in ADHD research which can underestimate the relationship between EF and maths due to documented benefits on neurocognitive and academic performance (e.g., Hawk et al., 2018; Kortekaas-Rijlaarsdam et al., 2019; Leo & Cohen, 2003; Powers et al., 2008). As such, the literature would benefit from a comprehensive assessment of these associations in the absence of active stimulant treatment. In doing so the current review can help inform possible targets for intervention free from pharmacological effects and inform alternative methods of intervention.

A range of approaches have been employed to assess maths performance including both individual and combined indices of arithmetic fluency, word problems, reasoning, and numerical operations (e.g., Antonini et al., 2016; Capodieci & Martinussen, 2017; Friedman et al., 2018; Holmes et al., 2014; Sabagh-Sabbagh & Pineda, 2010). The type of maths assessment used could influence the pattern/strength of association with certain cognitive constructs as well as the conclusions that are drawn regarding their suitability as targets for intervention (Allen, et al., 2019). As such, any review should consider more intricate aspects of numerical abilities, as well as broad attainment scores.

Lastly, children with ADHD present with highly heterogeneous cognitive profiles (Coghill et al., 2014; Luo et al., 2019; Nigg et al., 2005; Willcutt et al., 2005), and not all children with ADHD struggle with maths (Czamara et al., 2013; Mayes et al.,2020;

Capano et al., 2008; Shalev et al.,1995). High rates of co-occurrences with other neurodevelopmental disorders such as Oppositional Defiant Disorder (ODD), Conduct Disorder (CD), Autism Spectrum Disorder (ASD), Developmental Coordination Disorder (DCD), and learning difficulties pose a myriad of additional difficulties that may exacerbate difficulties in maths performance (Liu et al., 2017; Capano et al., 2008; Czamara et al., 2013; Rasmussen & Gillberg, 2000; Zajic et al.,2018). It is therefore important to review the inclusion of these co-occurrences within the current literature to establish whether these affect children's maths performance.

2.1.4 Objectives

A previous review explored the association between ADHD symptoms of inattention, hyperactivity, and impulsivity, and maths performance (Tosto et al., 2015). However, cognitive mechanisms, rather than behavioural symptoms appear to be important to children's maths performance. To date, there has been no systematic exploration of the association between cognition and maths in children with ADHD. The aim of this review was to examine existing literature addressing the relationship between key cognitive processes and maths performance in clinical ADHD population. Specifically, this review examines correlation between objectively assessed performance on cognitive tasks and children's maths performance. Specifically, previously implicated cognitive domains in ADHD were included: inhibitory control, cognitive flexibility, visuospatial and verbal working memory, planning, processing speed, as well as short- and long-term memory. Furthermore, this review was interested in both standardised attainment scores, as well as non-standardised indices of numerical skills. The key outcomes of interest were the correlations between cognitive and maths scores. In doing so, the current review will help conceptualise the cognitive correlates of maths performance in children with ADHD and highlight potential avenues for early interventions aimed at improving maths skills. From an applied perspective, establishing the cognitive mechanisms which correlate with maths performance in ADHD can act as a steppingstone in formulating predictive models and help in educational developments of instructional design and practice.

2.2 Method

The protocol for this review was registered with the International Prospective Register of Systematic Reviews PROSPERO; registration number CRD42020169708 available from http://www.crd.york.ac.uk/prospero/. To ensure clarity and transparency of search strategy and procedures reporting, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) checklist was used (Appendix A; Moher et al., 2015).

2.2.1 Eligibility criteria

The PICOTS (Population, Intervention/Assessment, Comparison, Outcomes, Timeframe, and Study Design) framework was used to devise a study screening criterion. This review focused on papers published between 1992-2020 in peer-reviewed journals written in English for which full text was available.

Population: Aligning with UK-wide primary school years, studies with children aged between 4 and 12 years recruited through clinical, community, or population-based studies were included. Recommended guidelines for ADHD assessment and treatment typically begin at age four (Wolraich et al., 2019). Children aged over 12 were excluded as this review focuses on primary school years during which basic numerical skills are mastered. Studies where the data from different age groups was aggregated in a way in which data for those aged 4-12 could not be extracted, were excluded. Studies had to report a clinical diagnosis of ADHD or hyperkinetic disorder using the DSM-IV/5 or ICD-10/11 which constitute the most widely established mental health classification systems (Stein et al., 2013). Studies using other diagnostic criteria were excluded. A clinical diagnosis of ADHD had to be reported by a parent or identified using ADHD-validated parent rating scales or parent interviews. Additionally, diagnosis had to be corroborated via teacher verification (e.g., questionnaire or interview). Studies failing to mention teacher verification were excluded under the assumption that there was no multi-setting corroboration of difficulties – a crucial aspect of obtaining an accurate ADHD diagnosis (APA, 2013). The only exception for this was where no teacher corroboration was present, but another source of confirmation was present, such as confirmation of a diagnosis by a psychiatrist or use of ADHD-medication, to which teacher corroboration is inherent.

Participants had to either (1) be drug-naïve, or (2) be asked to abstain taking medication ahead of their participation in the study. Studies where participants were actively on medication during testing were excluded due to confounding effects of pharmacological treatment on cognition and academic productivity (e.g., see Hawk et al., 2018; Kortekaas-Rijlaarsdam et al., 2006; Leo & Cohen, 2003; Powers et al., 2008). Where authors failed to report medication status, a contact attempt was made to clarify medication status and if there was no response from the author the study was excluded under the assumption that some/all participants were not subject to wash-out requirements. Participants with ADHD and other co-occurring neurodevelopmental disorder and learning difficulties were included to accommodate for well-documented co-occurrences (Elia et al., 2008; Lange, 2018; Reale et al., 2017). Studies with individuals with parent-reported epilepsy, Down syndrome, brain injury, or chromosomal conditions were excluded due to their specific effects on neurocognitive functioning (Ekstein et al., 2011; Lee et al., 2016; Lo-Castro et al.,2011). Studies including children with IQ < 70 or intellectual disability were also excluded.

Intervention: Studies were included where either of the following maths assessments were administered: (1) standardised tests (e.g., Wechsler Objective Numerical Dimensions; WOND), (2) non-standardised tests (e.g., number fact fluency), and/or (3) state-wide or nation-wide school based standardised tests. Studies using school-specific achievement tests or grades were excluded due to potential discrepancies in curriculum across schools (Tosto et al., 2015). Studies were only included if at least one of the cognitive domains of interest was objectively assessed. Studies relying on parent/teacher ratings of cognitive function (e.g., Behaviour Rating Inventory of Executive Function) were excluded due to their subjectivity and small-modest associations with objective performance-based tests (Toplak et al., 2013).

Comparison: Studies comparing children with ADHD to any other group were included, so long as the authors reported on the relationship between cognition and maths in the ADHD group.

Outcomes: The main outcome of interest was the examination of correlations between maths and cognitive scores. Studies were included where effect sizes between mathematic and cognition for the ADHD group were reported (e.g., correlation coefficient, beta coefficients, p-values). In studies using multiple tasks to measure a single construct, all eligible effect sizes were included. Determination of effect sizes using conversion to a common metric (*r*) was explored (e.g., Allen et al., 2019). Following extensive examination of the literature, it became apparent that calculating an effect size (e.g., Cohen’s *d* or Hedge’s *g*) from the same group (i.e., single ADHD group) using two different variables measured at a single time point (i.e., cognition and maths) would not be possible without access to the raw data from each of the studies, which was beyond the scope of the present review (Borenstein et al., 2021; Field, 2001; Higgins et al., 2019).

Timeframe: The start point for the search was set at 1994 for DSM-IV based diagnoses and 1992 for ICD-10 based diagnoses. Studies published before 1992 (for ICD-10 research) and 1994 (for DSM-IV research) were excluded. For DSM-IV, 1994 marks the important reconceptualization from a previously regarded unitary disorder to ADHD as we know it today, with the specification of three subtypes endorsed by factor analytic research (Biederman et al., 1997; Lahey et al., 1994). For ICD, 1992 marks the publication of the critical update from the more outdated ICD-9 (published in 1976) to ICD-10 aimed at integrating more recent research and thereby providing greater accuracy of diagnoses (Taylor & Hemsley 1995).

Study Design: Any quantitative research where data for the association between cognition and maths in children with ADHD was available, including: (1) case-control studies comparing children with ADHD and any other group, (2) cross sectional studies examining cognition and maths in ADHD, (3) longitudinal/cohort studies that follow up children with ADHD and children are aged 12 or younger at the end of the follow up, or where baseline data is available for children aged 12 or younger that are followed up longitudinally, and (4) intervention/experimental studies aimed at improving maths or cognitive performance with available baseline (i.e., pre-intervention) data. Studies solely using qualitative research methods were excluded (e.g., ethnography, action research, social observation, focus groups, case study research). Systematic reviews, conference proceedings and protocols were excluded.

2.2.2 Search strategy

2.2.2.1 Search methods for study identification

Searches were conducted between March and August 2020. The following electronic data bases were searched: PsycINFO, PubMed, SCOPUS, EMBASE, ERIC, and Web of Science. The search strategy was first defined by identifying three key terms from the research question: “cognition”, “maths” and “attention deficit hyperactivity disorder”. Common terms for these key items were extracted or adapted from previous reviews on ADHD (e.g., Tosto et al., 2015; Willcutt et al., 2012) and maths in children (e.g., Simms et al., 2019), as well as previously implicated cognitive domains of interest to ADHD (e.g., Coghill et al., 2018; Kofler et al., 2018; Willcutt et al., 2005) and those which have previously been suggested as important for maths learning (e.g., Cragg et al., 2017; Gilmore et al., 2018). The final search string terms and search strategy combinations are summarised in Table 2.1. Following completion of the search strategy in each of the specified databases, citations were retrieved and uploaded onto Endnote where any duplicates were removed. The list of references of included studies were also screened to identify any additional papers that may have been missed. Additionally, the reference list from a previous review of maths and ADHD symptoms (Tosto et al., 2015) was also screened.

Table 2.1 Search strategy key words and combinations

S1	"Attention deficit hyperactivity disorder" OR "attention deficit disorder" OR ADHD OR "hyperkinetic disorder" OR "hyperkinetic syndrome" OR "attention deficit" OR "attention disorder" OR "hyperactivity disorder"
S2	Maths OR math* OR arithmetic* OR numer* OR number*
S3	Cogniti* OR attention* OR "executive function" OR EF OR "selective attention" OR "executive control" OR "response inhibition" OR inhibition OR "interference control" OR "cognitive flexibility" OR "set shifting" OR shifting OR "working memory" OR WM OR planning OR "problem solving" OR organisation OR memory "processing speed"
S4	S1 AND S2 AND S3

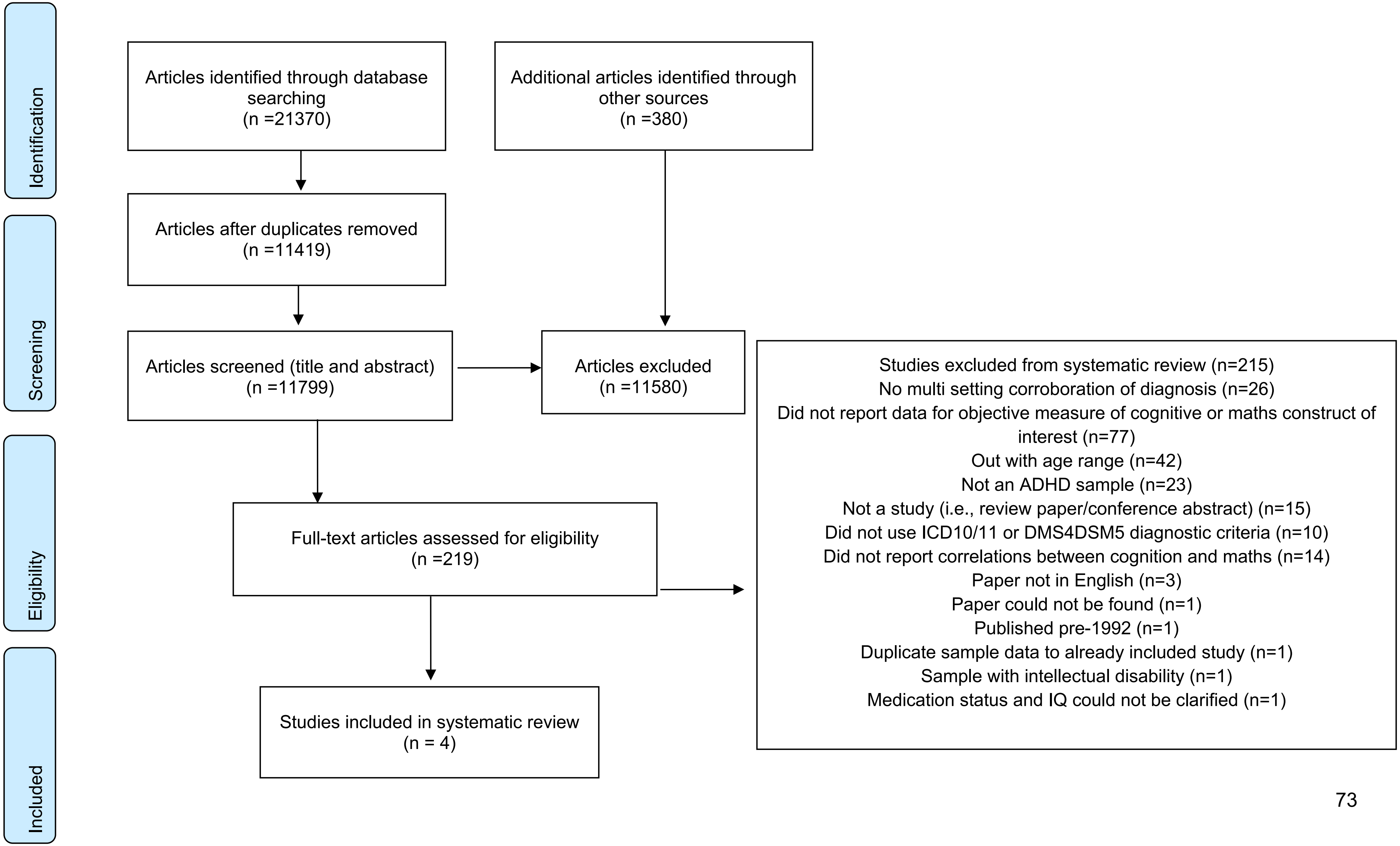
2.2.2.2 Screening for inclusion

Searches generated a pool of studies to be screened. In the first step, these articles were screened one of the reviewers (MK) by title and abstract using a pre-defined screening checklist (Appendix B; adapted from Polanin et al., 2019). A 20% sample was then screened by a second reviewer (JO) with an interrater agreement rate of 97% which is deemed as acceptable (Belur et al.,2018; Schlosser, 2007). Any conflicts were initially resolved through discussion. During the second step, papers were scrutinised for eligibility (MK) by applying full text review screening criteria (adapted from Shvedko et al., 2018). A 20% sample from these was screened by an independent reviewer (JO), resulting in 100% agreement. Following full text review, four studies were deemed as eligible for inclusion.

2.2.2.3 Study selection

In total, 21370 were generated from the electronic database and 380 additional studies were identified through screening references lists. Following duplicate removal 11799 articles were screened by title and abstract. From these, 219 met eligibility criteria for full text screening. These were carefully sifted and key reasons for exclusion were provided. In total, four papers qualified to be included in the present review. A flow diagram detailing the study selection process is provided in Figure 2.1 (Moher et al., 2009).

Figure 2.1 Flow diagram of study selection process



2.2.3 Data extraction

Data from the final articles included was independently and blindly extracted by two reviewers (MK & either EMC or JO) and any discrepancies were resolved through discussion. Data extraction items included information on (1) source of study (authors, publication year, country of study), (2) methods and population characteristics (study design, diagnostic criteria used, ADHD subtype, sample size, age range, mean age and SD, sex, IQ range and mean, medication status, ethnicity, SES, co-occurrences, drop outs/non completers), (3) outcome measures (maths assessment and domain, cognitive assessment and domain), and (4) results (*r* value and accountability for confounding factors). A correlation coefficients and confidence intervals were either directly extracted from each study or calculated using a freely available calculator (Lenhard & Lenhard, 2016; https://www.psychometrica.de/effect_size.html). For any data clarifications or missing data, corresponding authors were contacted by email and a follow-up email was sent after 4 weeks from initial contact date[1]. Any finalised missing information is specified as "not reported" (NR).

2.2.4 Risk of bias

Risk of bias (RoB) was assessed using the Newcastle Ottawa Scale (NOS; Wells et al., 2012). The NOS is one of the most widely used tools for assessing the quality of observational research (Luchini et al., 2017). The NOS has been used extensively in previous systematic reviews including in ADHD populations (e.g., Cortese et al., 2016; Donzelli et al., 2020; Ruiz-Goikoetxea, et al., 2017). Although the NOS was developed for quality assessment of case-control and cohort studies, it has previously

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[1] One of the studies (Dahlin, 2013) was excluded as it did not report on children's medication status (a key inclusion criteria) and attempts to clarify medication status with author via email correspondence were unsuccessful.

been adapted for cross-sectional design studies (e.g., Stewart et al., 2017; Wang et al., 2017). In line with the Cochrane Handbook for Systematic Reviews of Interventions (Higgins & Green, 2011), the criteria for items in the NOS were tailored to the present review by consolidating previous reviews (Donzelli et al., 2020; Stewart et al., 2017) and agreed upon by three of the reviewers (MK, SR & SMC). For case-control and cohort studies (max = 9 points) a score of ≥7 stars rendered low risk of bias, 4-6 stars qualified as medium risk of bias, and studies scoring ≤4 stars were high risk of bias. Cross-sectional studies (max = 7 points) scoring ≥5 stars were deemed as low risk of bias, 3-4 stars qualified as medium risk of bias, and studies scoring ≤3 stars were high risk of bias. Studies were not excluded based on a high RoB. Rather, this assessment was used to highlight important points for future research considerations. The RoB was completed by two independent reviewers (MK & EMC) with any discrepancies resolved through discussion.

2.2.5 Synthesis

The main aim of the present review was to examine the correlations between maths and cognitive scores in children with an ADHD diagnosis. The magnitudes of effect sizes were interpreted according to Cohen (1988) as small (r = .10), medium (r = .30) or large (r = .50). The protocol set out to quantitatively synthesise the relationship between maths and cognition. However, only four of the included studies (Alloway, 2011; Friedman et al., 2018; Kim et al., 2020; Miranda- Casas et al., 2012) reported a statistic for the association between cognition and maths from which a common effect size could either be extracted or calculated. These studies assessed a wide range of cognitive constructs and maths domains – none of which could be combined according to meaningful commonalities in the measured characteristics. In line with previous arguments, it was decided that quantitatively synthesising few studies with largely heterogeneous characteristics was unwarranted (Valentine et al., 2010). Thus, a narrative synthesis was provided.

2.3 Results

2.3.1 Study characteristics

Descriptive data relating to source, methods, and participants from included articles is summarised in Table 2.2[2]. Across the four studies, there were 334 participants in total with sample sizes ranging between 24-224 children. Overall, 15% were girls, and participants' ages ranged between 6-12 years (Age $_{\text{Median}}$ = 8.36 years). There were three case-control studies and one cross-sectional study. Further, three of the included studies included less than 50 participants. Included studies were also heterogeneous in terms of location comprising one study each from Spain, South Korea, UK, and USA.

All but one of the studies (Miranda-Casas et a., 2012) used standardised assessments of maths achievement. The descriptions of these assessments are provided in Table 2.3. Each assessment description was mapped onto one of three broad domains. The numerical operations domain included tasks that required children to conduct direct simple or complex arithmetic computations (Manon, 2010; Mazzocco et al., 2008). The numerical concepts domain included tasks that capitalised on children's acquisition of basic numerical concepts such as counting digits or objects, reading numbers, and quantity judgements (Butterworth, 2005; Gelman, 1990; Gelman & Gallister, 1992). Lastly, applied problem solving required children to solve

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[2] Data includes information that was confirmed via email correspondence with the author.

word problems orally and apply knowledge to real-life contexts (e.g., time, money, graphs; Zheng et al., 2011; Swanson et al., 2013). The nature of applied problem-solving tasks is such that performance inherently requires children draw on a range of specific maths skills including numerical concepts and mental numerical operations. In terms of cognition, included studies assessed verbal and spatial aspects of STM and WM, inhibitory control, and processing speed. A detailed description of the tasks used to assess cognitive constructs can be found in Table 2.4.

Table 2.2 Source, methods, and population characteristics

Study	Design	Country	Subtype	N (F)	Age (Mean, SD)	IQ Mean (SD)	Medication washout	Ethnicity	SES	Co-occurrences	Non-completers	RoB
Alloway, 2011	Case-control	UK	ADHD-C	50 (7)	8-11 (9.75, 1.00)	WASI Vocab 81.54 (17.82) Block Design 95.42 (14.51)	24hr	NR	NR	NR	NR	Medium
Friedman et al., 2018	Case-control	USA	ADHD-C	36 (0)	8-12 (9.45, 1.18)	WISC FSIQ 104.33 (9.92)	Drug naïve; 24hr (N = 16)	NR*	HFFISS = 48.67	ODD 22%	NR	Medium
Kim et al., 2020	Case-control	South Korea	ADHD-C 42.4% ADHD-I 47.8% ADHD-H 4% NOS 5.8%	224 (42)	6-12 (8.2, 2.1)	WISC FSIQ 95.4 (15.00)	Drug naïve	NR	NR	ODD 11.2% MDD 1.3% Anxiety 5.8% Enuresis 0.9% Tic 9.4%	60 w/o complete data	Low
Miranda-Casas et al., 2012	Cross-sectional	Spain	ADHD-C	24 (1)	6-10 (7.96, 1.08)	WISC-R NOS 103.54 (12.86)	48hr	NR	NR	NR	NR	Medium

ADHD-I Inattentive Subtype; *ADHD-H* Hyperactive-Impulsive Subtype; *ADHD-C* Combined Subtype; *DSM* Diagnostic and Statistical Manual; *HFFISS* Hollingshead Four Factor Index of Social Status*; MDD* Major Depressive Disorder*; ODD* Oppositional Defiant Disorder*; NR* Not reported; *NOS* Not otherwise specified; *RoB* Risk of Bias; *UK* United Kingdom; *USA* United States of America; *WASI* Wechsler Abbreviated Scale of Intelligence; *WISC* Wechsler Intelligence Scale for Children; *FSIQ* full scale IQ

* Ethnic breakdown provided for full sample; included African American, Bi- or multi-racial, Caucasian, and Hispanic English speakin

Table 2.3 Description of maths assessments

Assessment	Study	Description	Domain
WOND (Wechsler, 1996)	Alloway, 2011	Standardised assessment of numeracy skills in children aged 6 to 16 years. Numerical operations subtest assesses written arithmetic computation skills in addition, subtraction, multiplication, and division. Maths reasoning examines applied problem solving, numeration and number concepts, graphs, and statistics and measurement. Together these subtests provide a composite maths score.	APS Numerical concepts Numerical operations
KTEA-I/II (Kaufman & Kaufman 1998; 2004)	Friedman et al., 2018	Standardised assessment of academic skill in ages 4 to 25 years. The Maths Applications (1st edition) and Maths Concepts & Applications (2nd edition) requires children to solve orally presented problems requiring application of maths principles in real life situations (e.g., pictures, tables, graphs). On the Maths Computation subtest (1st & 2nd edition) children are asked to solve written math calculation problems.	APS Numerical concepts Numerical operations
K-WISC-IV Arithmetic (Koh et al., 2015)	Kim et al., 2020	Standardised assessment of intellectual ability in children aged 6-16 years. The arithmetic subtest assesses children's ability to mental solve orally presented problems under timed conditions, with and without images.	APS Numerical concepts Numerical operations
EPA (DeClerq et al., 2000)	Miranda et al., 2012	Computerized assessment of children's maths skills. The problem-solving scale evaluates verbal comprehension and mental representation of problems. The numerical knowledge scale assesses reading units and tens, operation symbol comprehension, numerical and serial production, and comprehension. The calculation scale examines arithmetic procedures and mental calculation.	APS Numerical concepts Numerical operations

WOND Wechsler Objective Numerical Dimensions; KTEA-I/II Kaufman Test of Educational Achievement 1st/ 2nd edition; *K-WISC* Korean–Wechsler Intelligence Scale for Children; *EPA* Evaluation and Prediction Assessment; *APS* applied problem solving

Table 2.4 Description of cognitive assessments

Assessment	Study	Description	Domain
AWMA (Alloway, 2007)	Alloway, 2011	The verbal STM tasks assessed children's ability to recall sequences of words, non-words, and digits. The verbal WM tasks assessed listening recall, backward digit recall, and counting recall. On assessments of visuospatial STM children recalled sequences of dot matrices and block locations, and reproduced paths. Visuospatial WM assessments included recalling increasing sets of sequences of odd-one-out shapes and spatial locations of rotated stimuli.	Verbal STM Verbal WM Visuospatial STM Visuospatial WM
TSRT (Dubois et al., 1995)		Computerised task assessing children's memory of sequences of colour changing blocks	Visuospatial WM
Visuospatial WM task (Rapport et al., 2008)	Friedman et al., 2018	Children were presented with squares on a screen and a black dot sequentially appeared in each of the squares. All dots were black with the exception of a red dot. Children were required to indicate the sequence position of the black dots by pressing on the corresponding squares and indicate the position of the red dot last.	Visuospatial WM*
Phonological WM task (Rapport et al., 2008)	Friedman et al., 2018	Children were presented with a mixture of numbers and a capital letter on a screen and were then asked to recall the numbers from smallest to largest and specify the letter last.	Verbal WM*
ATA (Shin et al., 2000)	Kim et al., 2020	Computerised CPT assessing children's responses to target and non-target auditory (beeps) and visual (shapes) stimuli. Commission errors (inhibition) and response times (processing speed) are measured.	Inhibitory control Processing speed
CPT (Ávila & Parcet, 2001)	Miranda et al., 2012	Computerised task during which children are presented with letters. Children are asked to respond as quickly as possible when the letter X is preceded by an A. Commission errors (inhibition) and response times (processing speed) are measured.	Inhibitory control Processing speed
WISC-R Digit span (Wechsler, 1980)	Miranda et al., 2012	Children repeat orally presented sequences of numbers in forward (verbal STM) and backward (verbal WM) order.	Verbal STM Verbal WM

AWMA Automated Working Memory Assessment; *WISC* Wechsler Intelligence Scale for Children Revised; *TSRT* Temporo Spatial Retrieval Task*;* *ATA* Advanced Test of Attention; *CPT* Continuous performance test; *WM* working memory; *STM* short term memory

* Different WM components (i.e., verbal STM, spatial STM, and central executive) were calculated by regressing common variance across the tasks.

2.3.2 Risk of bias

The RoB ratings of each study according to the NOS quality assessment tool is summarised in Table 2.2. It is important to note that the inclusion criteria used in the present review was such that these studies can be generally considered as high-quality studies. Indeed, all the studies scored either low or medium RoB across selection, comparability, and outcomes domains.

Selection

Three of the studies scored high RoB on the item relating to representativeness of the ADHD sample (Friedman et al. 2018; Kim et al., 2020; Miranda-Casas et al., 2012). This was mainly due to studies failing to report the socio-economic background of participants (Kim et al., 2020; Miranda-Casas et al., 2012) and the country in which the study was conducted (Friedman et al., 2018; Miranda-Casas et al., 2012). Three of the studies excluded children with a co-occurring ASD diagnosis (Alloway, 2011; Friedman et al. 2018; Miranda-Casas et al., 2012), whilst another study specified excluding children showing a pervasive developmental disorder (Kim et al., 2020). Studies also screened the ADHD group for at least one other frequently co-occurring developmental disorders including DCD (Alloway, 2011) and ODD (Friedman et al. 2018; Kim et al., 2020). In relation to the definition of ADHD item, only one of the studies (Alloway, 2011) scored high RoB as it failed to report whether the ADHD diagnosis was corroborated by a teacher[3]. It is also important to note that none of the

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[3] Diagnosis was conducted according to DSM-IV criteria by a paediatric psychiatrist/community paediatrician and all children were on ADHD medication. For purposes of inclusion, teacher corroboration was assumed due to its fundamental role in receiving a clinical diagnosis.

studies reported inclusion of children with a reading disorder, and only one of the studies (Friedman et al., 2018) included children with a maths learning difficulty.

Comparability

A maximum of two points could be awarded to this item. For the first point, age and medication treatment were selected as the most important factors that, where relevant, should have been accounted for either in the design or addressed in the analysis. To obtain a second point, studies could control for any additional confounding factor (e.g., sex, IQ[4]). All studies accounted for differences in age in either the design or analysis. However, in two studies (Friedman et al., 2018; Miranda-Casas et al., 2012) some children in the ADHD groups were subject to a 24-48hr medication which was not controlled for in the analysis. Nonetheless, these studies accounted for at least one other important factor in either the design or the analysis including IQ (Friedman et al., 2018; Miranda-Casas et al., 2012), sex (Friedman et al., 2018), and SES (Friedman et al., 2018). The study scoring low RoB on this comparability domain accounted for IQ and sex (Kim et al., 2020).

Outcome

Three studies scored a high RoB on the assessment of outcome item (Alloway, 2011; Kim et al., 2020; Friedman et al., 2018). Although all studies used objective and validated measures of both cognitive and maths performance, they failed to specify whether tasks were administered by a qualified clinician (i.e., clinical psychologist, psychiatrist) or a trained psychologist/researcher. In relation to the appropriateness of

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[4] Based on previous arguments against using IQ as a covariate in assessments of neurocognitive function (Dennis et al., 2009), IQ was included here as an additional, rather than critical, confounding factor.

statistical test, two of the studies scored a high RoB due to failure to provide sufficient information in relation to all appropriate values (Miranda-Casas et al., 2012)[5] and for not carrying out correction for multiple testing in their correlational analysis (Alloway, 2011). Additionally, three of the studies (Alloway, 2011; Friedman et al., 2018; Miranda-Casas et al., 2012) failed to report on how many children were initially recruited to the study and the proportion for whom data was available, thereby failing to acknowledge issues around missing or incomplete data.

2.3.3 Narrative synthesis

All studies reported a positive association between children's cognitive and maths performance, albeit with different magnitudes of effect sizes and significance levels. Studies indexed children's maths performance in a variety of ways. One of the studies presented maths achievement scores as composites combining various subtests together (Alloway, 2011), while others opted for providing individual composite scores for subtests (Friedman et al., 2018; Kim et al., 2020). Another study (Miranda-Casas et al., 2012) did not use a standardised achievement test and instead used tasks that reflected more specific aspects of maths skills. Cognitive domains assessed included: verbal STM, verbal WM, visuospatial STM, visuospatial WM, inhibitory control, WM central executive, and processing speed. Studies mainly included children with the ADHD-C subtype, except for one study (Kim et al., 2020) which, in addition to this, included children with the ADHD-I and ADHD-H subtypes.

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[5] Means and SD's included were provided by Miranda-Casas et al., 2012 via email correspondence.

Verbal STM

Three studies assessed the association between verbal STM and maths in children with ADHD-C. Alloway (2011) found a statistically significant, medium-sized, correlation between a standardised composite score of verbal STM on the AWMA and children's composite WOND scores mapping on to numerical operations and applied problem solving (*r* = .45, 95% CI 0.20 to 0.65, *p* < .01). However, this association was no longer significant once age and IQ were considered (*r* = .200, 95% CI -0.08 to 0.45, *p* > .05). Friedman and colleagues (2018) did not control for age and IQ but nonetheless found no significant association between a verbal STM factor and KTEA-I/II applied problem-solving performance (*r* = .285, 95% CI -0.05 to 0.56, *p* = .093) nor numerical operations (*r* =.270, 95% CI -0.06 to 0.55, *p* = .112). Using a stepwise multiple linear regression, with IQ introduced in the first block, Miranda-Casas and colleagues (2012) did not find verbal STM performance to be a statistically significant predictor of any of the maths tasks that mapped onto numerical concepts, operations, nor applied problem solving.

Verbal WM

Two studies addressed the relationship between maths and verbal WM (Alloway, 2011; Miranda-Casas et al., 2012). Alloway (2011) found a statistically significant, large correlation between verbal WM composite on the AWMA and WOND composite score (*r* = .55, 95% CI 0.32 to 0.72, *p* < .01). However, this association was no longer significant once age and IQ were partialled out (*r* = .22, 95% CI -0.06 to 0.47, *p* > .05). Introducing IQ in the first block of the regression analysis, Miranda-Casas and colleagues (2012) found that verbal WM performance was a statistically significant predictor of children's calculation procedures (*Beta* = .496 *p* = .014, calculated *r* = .546, 95% CI 0.18 to 0.79) and general calculation scale (*Beta*=.495 *p* =.014, calculated *r* = .545, 95% CI 0.11 to 0.75). The relationship between verbal WM and all remaining maths task performance was not significant.

Visuospatial STM

Two studies reported on the relationship between visuospatial STM and maths (Alloway, 2011; Friedman et al., 2018). Alloway (2011) found a statistically significant large association between the visuospatial WM composite on the AWMA and WOND composite score (*r* = .510, 95% CI 0.27 to 0.69, *p* < .01). This association remained significant even after age and IQ were controlled for (*r* = .28, 95% CI 0.002 to 0.52, *p* < .05). Friedman and colleagues (2018) justified not accounting for IQ due to substantial overlap with WM. Nonetheless, they did not find a strong association between a visuospatial STM factor and KTEA-I/II applied problem-solving performance (*r* = .151*,* 95% CI -0.19 to 0.46], *p* = .380), nor numerical calculations (*r* =.220, 95% CI -0.12 to 0.51, *p* =.196).

Visuospatial WM

Two studies reported on the relationship between maths and visuospatial WM (Alloway, 2011; Miranda-Casas et al., 2012). Alloway (2011) found a statistically significant, large association between the visuospatial WM composite on the AWMA and the WOND composite maths scores (*r* = .59, 95% CI 0.37 to 0.75, *p* < .01). This association was no longer significant once age and IQ were accounted for (*r* = .25, 95% CI -0.03 to 0.49, *p* > .05). Introducing IQ in the first block of the regression analysis, Miranda-Casas and colleagues (2012) did not find that visuospatial WM performance significantly predicted children’s performance on a range of maths tasks, with the exception of numerical comprehension and production which was one of four tasks that mapped onto numerical concepts (*Beta* = .448, *p* = .028, calculated *r* =.498, 95% CI 0.12 to 0.75).

Central Executive

One study (Friedman et al., 2018) partialled out common variance between children's performance on a verbal WM and visuospatial WM tasks to index a central executive performance factor. Results showed a moderate-sized correlation between the central executive and KTEA-I/II applied problem-solving performance (*r* = .405, 95% CI 0.09 to 0.65, *p* = .014) as well as children's calculation achievement scores (*r* =.446, 95% CI 0.14 to 0.68, *p* =.006). Given the inherent role of numerical calculation skills in tasks which assess applied problem-solving abilities, it is difficult to derive conclusions on whether the central executive's role extends to children's numerical concepts.

Inhibitory control

Two studies assessed the association between inhibitory control and maths (Kim et al., 2020; Miranda-Casas et al., 2012). Controlling for sex and IQ, Kim and colleagues (2020) found a significant association between WISC Arithmetic (applied problem solving) and commission errors on the auditory ATA task (*r* = -.25, 95% CI -0.37 to -0.12, *p* < 0.001), but not the visual variant of attention task (*r* = .02, 95% CI -0.15 to 0.11 *p* > .05). Miranda-Casas and colleagues (2012) only used a visual variant of the CPT task and found that commission errors significantly predicted children's ability to read units and tens (*Beta* = -.460, *p* = .024, calculated *r* =-.510, 95% CI -0.76 to -0.13) – one of four tasks that mapped onto numerical concepts domain. Other maths outcome measures including numerical calculation, concepts, and broader applied problem-solving skills, were not significantly predicted by the visual inhibitory control index.

Processing speed

Controlling for sex and IQ, Kim and colleagues (2020), reported a weak, non-significant, correlation between WISC Arithmetic and response times on the auditory ($r = .08$, $p > .05$, 95% CI -0.05 to 0.21) and visual ($r = .03$, 95% CI -0.10 to 0.16, $p > .05$) variants of the ATA task.

2.4 Discussion

2.4.1 Summary of evidence

This review aimed to summarise findings on the associations between cognitive processes and maths performance in children diagnosed with ADHD. Broadly, cognition was positively related to children's maths performance whereby better cognitive performance was correlated with higher maths scores. Evidently, very few studies considered the relationship between cognition and maths in children with ADHD and, as such, implications of the present review should be interpreted with caution. A previous systematic review demonstrated a positive association between ADHD and maths ability across various age groups (Tosto et al., 2015). The current review extends this idea by highlighting cognitive mechanisms, frequently found to be impaired in children with ADHD, as potentially important targets for exploration in children's maths performance. The present review also complements a shift in the conceptualisation of learning difficulties in children by exploring these within the context of cognitive processes instead of diagnostic categories (Astle et al., 2019).

Generally, verbal STM did not show significant associations with maths performance, and where it did, this relationship was no longer significant once IQ and age were considered. A previous study in a neurotypical population suggests that verbal STM is particularly important for older children's solution of easier mental arithmetic sums, possibly due to proficiency of symbolic-linguistic processes or employment of more advanced strategies employing retrieval of verbal codes (Holmes & Adams, 2006). Based on the current review, the potential role of verbal STM cannot be ruled out.

Findings in relation to visuospatial STM were mixed. In one of the studies visuospatial STM maintained its large associations with achievement composite scores even after IQ and age were considered, whilst another study did not find evidence for the importance of this memory domain even in the absence of accountability for IQ scores in the statistical model. One possibility for these discrepant findings could be the differences in approach used to assess visuospatial STM performance. Whilst Alloway (2011) used three different tasks to index composite visuospatial STM performance, Friedman and colleagues (2018) utilised a regression-based strategy to segregate this domain from WM tasks.

Both verbal WM and visuospatial WM performance correlated with children's composite achievements scores. However, this association weakened once age and IQ were considered. One of studies also addressed the role of the central executive component of WM in children's maths aptitude. Regressing common variance between components of WM highlighted the central executive as the key component most closely associated to children's maths attainment. This echoes previous findings in neurotypical populations (Cragg et al., 2014) and may reflect associations between updating requirements of the central executive with that of intelligence tests (Friedman et al., 2018). In such a case, the findings across the studies uphold the importance of WM, and in particularly updating, to maths attainment (Cragg et al., 2014).

Importantly, when more specific calculation procedures were considered, verbal WM showed a substantial association even after accounting for IQ, whilst visuospatial WM emerged as important for children's numerical comprehension. Collectively, these findings imply that whilst verbal WM is related to numerical calculation skills, visuospatial WM could be especially related with children's conceptual understanding, Furthermore, this highlights challenges of indexing maths performance using composite achievement scores, which can obscure the relationship between cognitive processes and more specific maths skills which contribute to broader underachievement (Cragg et al., 2014). Future research exploring maths in ADHD would therefore benefit from differentiating between conceptual and procedural performance when exploring cognitive signatures of maths performance.

The strength of association between inhibitory control and maths varied depending on the format of stimuli presentation. Inhibition of auditory information was associated with applied problem-solving skills, whilst inhibition of visually presented stimuli was related to a very specific conceptual skill of reading units and tens. These findings suggest that inhibition of irrelevant visual stimuli is related to a very specific aspect of children's numerical concept comprehension (i.e., the ability to read units and tens). Contrary to this, suppression of irrelevant auditory stimuli is related to a broader range of numerical skills which standardised applied problem-solving subtests tap in to. This further highlights the importance of disentangling broad achievement scores by exploring performance on more specific maths abilities. Doing so can help identify more informative pathways of impairment that would otherwise be concealed by standardised composites. Notably, the studies assessing inhibitory control diverge in the subtypes of ADHD that children were diagnosed with. Kim and colleagues (2020) included children with all three ADHD subtypes, Miranda-Casas and colleagues (2012) focused only on children with ADHD-C, a discrepancy which may have further contributed to the differences in findings.

Lastly, processing speed, addressed by one of the studies, showed a weak correlation with applied problem-solving performance. However, no conclusions can be made in relation to more specific numerical skills that such assessments tap into. It is important to note that other processes previously implicated in children's maths performance, such as cognitive flexibility, planning, and delayed aspects of memory were not assessed (Bull & Lee, 2014; Cai et al., 2016; Cragg et al., 2017; Geary 2004; LeFevre et al., 2013; Szucs et al., 2013). These domains have previously been identified as impaired in many children with ADHD, and thus their role in maths performance warrants an important target for further exploration.

All studies either excluded children with a co-occurring ASD diagnosis and/or failed to screen for frequently co-occurring disorder symptoms. Although isolating ADHD from other diagnoses is useful for identifying difficulties specific to this population, ADHD seldom occurs in isolation. Rather, children with ADHD frequently meet criteria for at least one additional disorder. For example, while between 11-22% of children in the studies met diagnosis for ODD in two of the studies (Friedman et al., 2018, Kim et al., 2020), the other two studies failed to report on co-occurrences (Alloway, 2011; Miranda et al., 2012). This is particularly problematic for development and administration of interventions to a diverse group of children where underlying cognitive difficulties are incompatible with the targeted processes, thwarting potential for long lasting improvements (Kadosh et al., 2013; Rapport et al., 2013). Addressing issues surrounding cognitive heterogeneity and co-occurrences will be crucial for navigating decisions around educational interventions. More recent research urges a shift towards a dimensional characterisation of disorders which are generally considered to be distinct (Gathercole et al., 2018; Sonuga-Barke & Coghill, 2014). Arguably, such an approach would be more compatible in reflecting the complex realities of cognitive and educational difficulties experienced by children with ADHD.

It is important to note that while some studies controlled for IQ in their statistical models (Alloway, 2011; Miranda Casas et al., 2012; Kim et al., 2020) others did not (Friedman et al., 2018). IQ scores are linked to both maths and cognitive performance in children with ADHD, with some studies rendering IQ as the best single predictor of academic achievement (Mahone et al., 2002; Mayes & Calhoun, 2007). As a result, researchers may be inclined to use IQ scores as a covariate when assessing cognitive and/or educational outcomes in ADHD. However, others argue against using IQ as a covariate in assessments of cognitive functioning ADHD (De Zeeuw et al., 2012; Dennis et al., 2009; O'Brien et al., 2010). Assessments of IQ frequently examine multiple intercorrelated cognitive abilities, and so controlling for IQ scores when assessing maths outcomes removes important variance that can be attributed to underlying cognitive processes affected in ADHD (Frazier et al., 2004). A previous meta-analysis found that medicated children with ADHD showed an average increase of 6-7 IQ points when compared to drug naive children (Jepsen et al., 2009). This implies that lower IQ scores could reflect difficulties in EF processes related to focusing/maintaining attention or difficulties in test taking behaviour, rather than diminished intellectual functioning. In other words, IQ tests seldom represent independent aptitude abilities from other aspects of cognition that are impaired in ADHD – an important statistical pre-requisite in the use of covariates (Dennis et al., 2009). Future work should therefore carefully consider whether or not it is appropriate to control for IQ scores in their study design (see Dennis set al., 2009 for a comprehensive overview of this issue).

2.4.2 Limitations

Due to the wide range of cognitive processes assessed, and the different approaches used to measure and report maths performance scores, a quantitative synthesis was not possible. Additionally, the small number of studies that were identified for inclusion limits the conclusions that can be drawn with regards to the relationship between specific cognitive processes and maths performance in ADHD. Nonetheless, the small number of studies coupled with their relatively recent dates of publication likely reflects the inception of research in this area and echoes a similar novelty found in neurotypical populations (Allen et al., 2019).

Another potential limitation relates to strict inclusion criteria of children with a clinically confirmed ADHD diagnosis according to stringent diagnostic criteria. Teacher corroboration of difficulties was one of the predetermined key inclusion criteria for this review. A diagnosis of ADHD requires that functional impairments are present in two contexts, typically at home and at school (Alder et al., 2015). Thus, the gold-standard to diagnosing ADHD occurs via parent reports of the child’s behaviour at home combined by teacher reports of the child’s behaviour at school. Notably, community-oriented approaches using parent or teacher questionnaires are linked to high false positives of ADHD and may therefore not be representative of the clinical realities of ADHD (Coghill & Seth, 2015; Sayal et al., 2008). Nonetheless, research shows that even children with high ADHD symptoms in the absence of a clinical diagnosis struggle with maths, implying that even subthreshold symptoms can put children at higher risk for maths difficulties (Czamara et al., 2013). Plausibly, exclusion of studies with children scoring high on ADHD symptoms may have resulted in loss of informative data on the association between cognitive and maths performance. Despite this, the present review was able to assemble findings of high-quality studies in which participants were truly representative of the diagnosed population in question.

Another limitation relates to the limited representation of different ADHD subtypes. Studies in the present review predominantly included children with the ADHD-Combined subtype, except for one study (Kim et al., 2020) that, in addition to this, included children with the ADHD-Inattentive and ADHD-Hyperactive/Impulsive subtypes. Thus, the findings of the present review are limited in their generalisability to all ADHD subtypes. Lastly, the present review only included peer reviewed studies that were published in English. As such, it is possible that important findings in other languages, or studies which had not been published, may have been missed.

Lastly, the current review used a 20% subsample for title/abstract and full text screening by an independent researcher, consistent with other reviews (e.g., Stewart et al., 2017). A dual blind review of a 20% subsample for title/abstract screening is in line with previous recommendations for conducting systematic reviews (Nevis et al., 2015). To mitigate the possibility that important studies would be missed, the references list of included papers was also screened for inclusion. Furthermore, due to limited resources, it was only possible to apply 20% dual screening at full text review and a reason for exclusion at full-test screening was provided for each excluded study to decrease the possibility that a study would be missed.

2.4.3 Conclusions and future directions

This review explored available research on the association between cognition and maths in children with ADHD. This review highlighted the importance of assessing the relationship between cognitive domains and maths in ADHD. However, the few studies available coupled by small sample sizes and substantial methodological heterogeneity makes it difficult to draw solid conclusions. Overall, however, studies reviewed showed that better cognitive performance was associated with higher maths performance. This review highlights a strong need for further research on the identification of specific cognitive correlates of maths skill in children with ADHD. In particular, such research would benefit from dissecting specific numerical skills, rather than broad attainment scores which risk masking the specific areas children with ADHD struggle with. Future research should also carefully consider whether or not it is appropriate to control for IQ when examining cognitive functioning and its relationship to maths in ADHD, as issues around shared variance may understate their association.

3 Chapter 3: General methodology

This chapter provides a detailed overview of broad methodological decisions employed for the remaining experimental study chapters. First, considerations relating to participant inclusion within the thesis will be outlined, followed by an exploration of participant characteristics and sample size. Lastly, materials used for the data collection will be described. The rationale behind each of these will be addressed.

3.1 Participants

The participants described in each of the experimental chapters are the same. The description of participants below therefore relates to considerations that are relevant to all remaining chapters.

3.1.1 Participant inclusion

Participants were recruited from the referral waiting list for ADHD assessment at NHS Lothian Child and Adolescent Mental Health Service (CAMHS) – a clinical service for children and young people with challenges in behavioural and emotional wellbeing. In line with arguments for the dimensional approach to ADHD (Marcus & Barry, 2011), all children on the referral waiting list were invited to participate in the study, meaning that some children did not end up receing a formal ADHD diagnosis. Referral to CAMHS typically arises via health or education practitioners as a result of significant concerns about the child’s cognitive functioning, learning, and/or behaviour that are negatively affecting the child at home and at school. Referrals are assessed by the NHS CAMHS team for waiting list placement on the basis of moderate severe or complex difficulties. Thereafter, a comprehensive investigation of the child’s difficulties is conducted by a clinical assessment comprising: (1) interviews regarding difficulties and developmental history with child and family, with concurrent liaison with the child's school as well as any other professionals involved with the child, (2) observation of child within a clinical and scholastic setting, and (3) completion of standardised cognitive assessments and parent questionnaires. Following full assessment by CAMHS information about the ADHD status was shared with the research team.

Exclusion criteria was determined prior to data collection. Exclusion criteria were shared with the CAMHS team as part of the recruitment process and were confirmed with the family at the initial phone call. To take part, participants had to be between the ages of 6 years 0 months and 12 years 11 months. Children typically receive a diagnosis of ADHD between the ages of 6-12 years, with an average age of diagnosis of 7 and 10 years (Holden et al, 2013; Visser et al, 2014). This age group aligns with children's integration into the school setting, with increasing EF demands of impulse control, instruction adherence, task-specific attentional focus, and alternation between multiple classroom tasks (Barr et al., 2010; Pellicano et al., 2017). Furthermore, this age group was selected in line with early scholastic skill acquisition of basic maths processes and concepts, such as mental calculation, appropriate use of notations, and number relationships, which provide a foundation for mastery of more advanced mathematical skills (The Scottish Government, 2016; Geary, 2004; 2006).

To be included children had to score above the threshold (T score ≥60) for atypical scores on either of the Conners Parent DSM-5 ADHD subscales. Children with typical range scores on both the ADHD-Inattention and ADHD-Hyperactivity/Impulsivity subscales were excluded as they did not present with functionally impairing ADHD difficulties which are the focus of this thesis.

Children had to have English as their primary language. English is the only language for which all tests are available for on the CANTAB battery (CANTAB, 2018). Moreover, other measures used within the study were all standardised on a UK national sample (Dunn & Dunn, 2009; Weschsler, 2017; 2016;2011). Limited English language proficiency may put children at a disadvantage when completing educational and cognitive assessments and thereby fail to provide an accurate representation of their cognitive and academic potential.

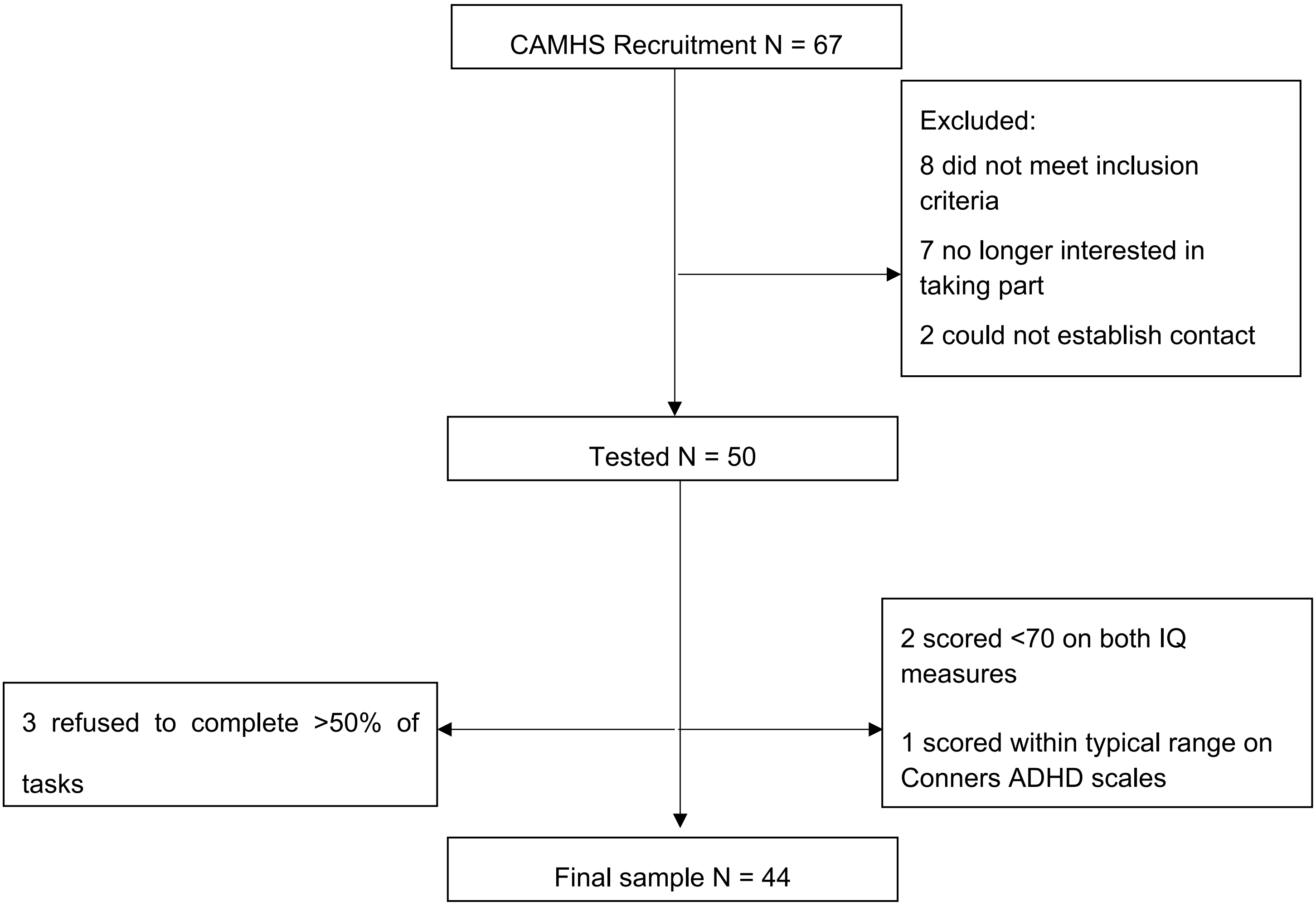
Participants all had to be drug naïve. Previous research includes at least some children that were on ADHD medication at testing time (e.g., Gathercole et al., 2018; Efron et al., 2014) or had recently been taking medication (Barry et al., 2002; Friedman et al., 2018; Holmes et al., 2014). There is some evidence to show that medication improves academic and cognitive performance, even under 24-48hr washout periods (Hawk et al., 2018; Kortekaas-Rijlaarsdam et al., 2006 Leo & Cohen, 2003; Powers et al., 2008). To provide a more accurate characterisation of disorder-related difficulties w/o pharmacological treatment, the present thesis recruited drug-naïve children free from current or previous medication treatment. Recruiting children from the clinical waiting list was thus beneficial as all children were drug naïve and could be tested prior to confounds of medication (DuPaul et al., 2004; Efron et al., 2014).

Studies with individuals with chromosomal conditions were excluded due to their specific effects on neurocognitive functioning (Ekstein et al., 2011; Lo-Castro et al., 2011). Similarly, children with suspected intellectual disability (i.e., IQ scores ≤ 70 on both IQ measures) were excluded (Danielsson et al., 2012; Shree & Shukla, 2016).

3.1.2 Sample size

A total of 67 children were recruited. From these, 15 (22%) were subsequently excluded as they either failed to meet inclusion criteria (N = 8), were no longer interested in taking part (N = 7) or the researcher could not re-establish contact to arrange testing (N = 2). One child was rated by their parent within the typical range for both Parent Conners DSM-5 ADHD subscales and was therefore excluded from the analyses. Furthermore, three children refused to engage in a testing session in its' entirety (i.e., ≥50% of tasks were incomplete) and were removed from the analysis. A further two participants scored below cut-off (IQ ≤70) and were excluded due to suspected intellectual disability. The final sample for statistical analysis included 44 children. A flow chart depicting reasons for exclusion from analysis is provided in Figure 3.1.

Figure 3.1 Recruitment and analysis exclusion flow chart



Worldwide estimates of ADHD prevalence in childhood range between 3% to 5% (Polanczyk et al., 2007). Rates of ADHD diagnosis in the UK tend to be lower, ranging between 0.5-0.9%, than that of screening-oriented prevalence estimates (Holden et al., 2013; McCarthy et al., 2012; Services over Scotland, 2012). The present sample size is in line with previous research recruitment of ADHD samples via clinic referrals (e.g., Calub et al., 2019 (N = 28); Friedman et al., 2018 (N = 39); Jacobson et al., 2010 (N = 41)). Small samples are common in clinical neurodevelopmental research (e.g., Bonafina et al., 2000; Takács et al., 2014; Vanbinst et al., 2015). Although larger samples have been cited in the literature, these tend to be drawn from community-based school recruitment (e.g., Antonini et al., 2013; Gremillion & Martel, 2012) which, arguably, fall short of the clinically debilitating difficulties that constitute referral to clinics.

3.1.3 Sociodemographic characteristics

Children's age ranged between 6 to 12 years (*M* = 101.34 months, *SD* = 19.39). Of those tested, 30 were in Primary 2 to Primary 4 (*M* = 90.47 months, *SD* = 10.25) and 14 were in Primary 5 to Primary 7 (*M* = 124.64 months, *SD* = 12.33). The majority of participants were male (N = 31, 70%) and right-handed (N = 40, 91%). The proportion of children from each Scottish Index of Multiple Deprivation (SIMD) quintile were as follows: Quintile 1 = 22.7%, Quintile 2 = 22.7%, Quintile 3=9.1%, Quintile 4=11.4%, and Quintile 5=34.1%. Thus, children's socio-economic background was generally well spread with comparable proportions of children from the most deprived (45.4%) and least deprived (45.5%) areas in Scotland.

3.1.4 Clinical characteristics

Following full assessment by CAMHS, diagnostic confirmation was sought from the clinical team. Clinical data was also collected as part of this thesis – four questionnaires were completed by parents regarding the child's day to day behaviour: Conners Parent questionnaire, Strengths and Difficulties Questionnaire (SDQ), Movement ABC Checklist, and the short Autism Quotient (AQ-10). Clinical characteristics of the sample are summarised in Table 3.1. Over half of the participants recruited ended up receiving a clinical ADHD diagnosis. Around a third of the sample did not meet criteria for clinical diagnosis. These children can be referred to as subclinical ADHD as although they did not meet criteria for ADHD, they (1) raised enough clinical suspicion to be placed on the waiting list, and (2) scored high on at least one of the Parent Conners DSM-5 ADHD subscales reflecting a certain degree of ADHD difficulties. Five children were still awaiting full evaluation for ADHD at the clinic at the time of data analysis. Information regarding children's natal complications was obtained from parents at the first visit with the researcher: three children had low birthweight (< 2500g), four were born preterm (< 37 weeks) and one child was born very preterm (< 32 weeks; Anderson et al., 2011; Franz et al., 2018). The CAMHS team also provided information regarding children's ASD status: five children had a clinical ASD diagnosis and an additional seven were referred for further ASD evaluation following their assessment.

Table 3.1 Clinical characteristics of included participants

	Total sample (N = 44)
Parent-rated ADHD symptoms	
Conners ADHD Inattention T-Score, Mean (SD)	81.41 (10.43)
Conners ADHD Hyp/Imp T-Score, Mean (SD)	84.66 (9.01)
CAMHS diagnosis	
Clinical ADHD diagnosis *n* (%)	24(55%)
No ADHD diagnosis *n* (%)	15 (34%)
Awaiting ADHD evaluation *n* (%)	5 (11%)
Clinical ASD diagnosis *n* (%)	5 (11%)
Awaiting ASD evaluation	7 (16%)
Co-occurring symptoms n (%) *with high difficulties*	
Conners Oppositional Defiant Disorder	35 (80%)
Conners Conduct Disorder	33 (75%)
Strengths and Difficulties Questionnaire	36 (82%)
Movement ABC Checklist	25 (57%)
Autism Quotient-10	12 (27%)
Perinatal complications n (%)	
Low Birthweight < 2500g	3 (7%)
Preterm Birth < 37 weeks	4 (9%)

ADHD symptoms were assessed using elevated T-scores (≥60) on the Conners Parent DSM-5 ADHD ADHD-Inattentive and/or ADHD-Hyperactive/Impulsive subscales (Czamara et al., 2013; Loe & Feldman, 2007). The majority of children (N = 41) scored high on both ADHD-Inattention and ADHD-Hyperactivity/Impulsivity subscales, one child scored high only on the ADHD-Inattention subscale and two children had elevated scores only on the ADHD- Hyperactivity/Impulsivity subscales.

Given that ADHD frequently co-occurs with other neurodevelopmental disorders, co-existing symptoms were screened for using parent questionnaires. As indicated by the Conners Parent DSM-5 subscales, a large proportion of children showed co-occurring externalising behavioural difficulties of ODD (80%) and CD (75%). The Conners Parent questionnaire also showed that many children scored above the cut off recommended for further investigation for anxiety (95%) and depression (86%). However, please note that the anxiety and depression screener items were limited to 3 items, and thus these are only mentioned for descriptive purposes. Around a third of children also showed high ASD symptoms (27%) on the AQ-10 and over half (57%) scored high on the Movement-ABC Checklist. Most of the sample (82%) had emotional and behavioural difficulties as indexed by the SDQ.

3.2 Materials

All clinical and assessment data available to the researcher relates exclusively to the materials described below. This data was collected by the researcher and is independent from any clinical assessments conducted by CAMHS clinicians. The only clinical information available directly from CAMHS was the diagnostic outcome for each participant.

3.2.1 Socioeconomic background

Children’s socioeconomic backgrounds were indexed by the Scottish Index of Multiple Deprivation (SIMD; Scottish Government, 2016). The SIMD identifies areas of deprivation in Scotland and was created as part of the government’s efforts to target policies and funding sources at tackling socioeconomic deprivation within geographical units. The SIMD calculates levels of deprivation using a residential postcode which comprises 38 indicator data across seven domains: income, employment, heath, education, housing, access to services, and crime. The SIMD was calculated by inserting the family’s residential postcode into the SIMD tool (SIMD, 2016). SIMD was ranked using quintiles that split the zones into 5 groups, each containing 20% of Scotland’s data zones (1 = most deprived and 5 = least deprived). The SIMD has previously been used in child populations in areas exploring the relationship between socioeconomic adversity and academic attainment (Perry et al., 2018) and behaviour difficulties (Carson et al., 2015). It has also previously been used as an index of socioeconomic status of children with ADHD (Coghill et al., 2014).

3.2.2 Parent questionnaires

Four questionnaires were completed by parents regarding the child’s day to day behaviour. Albeit not diagnostic these questionnaires helped assess ADHD and frequently co-occurring symptoms of other developmental disorders which could affect children’s cognitive and/or academic performance (May et al., 2013; Rassmussen & Gillberg, 2000; Sayal et al., 2015).

The Conners 3-Parent (Conners, 2008) is 110 item questionnaires used to provide a dimensional assessment of ADHD and related difficulties in children and adolescents. The Conners has previously been used to assess ADHD symptoms in children (Gathercole et al., 2018; Patros et al., 2018). The Conners has good internal consistency (*α* = 0.97) and test re-test reliability (*r* = .98) and is used routinely in clinical settings (Conners, 2008). Parents were presented with 108 statements and asked to circle the number that maps onto how well each item described their child in the past month. Response scores ranged between 0 = ’Not true at all’, 1 = ‘Just a little true’, 2 = ’Pretty much true’, and 3 = ’Very much true’. Questions 109 and 110 provided qualitative responses regarding parents’ concerns about the child and any strengths/weaknesses that their child might have. These were not used for the current thesis but were relayed to the CAMHS team via clinical reports. The Conners features content scales that assess ADHD-related concerns in specific domains: Inattention, Hyperactivity/Impulsivity, Learning Problems, Executive Functioning, Defiance/Aggression, and Peer/Family Relations. Furthermore, the Conners benefits from the added component of symptom counts that map on to DSM-5 ADHD symptom-level information scales ADHD-Inattentive and ADHD-Hyperactive/Impulsive as well as co-occurring externalising disorders CD and ODD. The Conners 3 Parent DSM-5 Symptom Scales provide good internal consistency (*α* = .90), test-retest reliability (*r* = 0.89) and interrater reliability (r = .84; Kao & Thomas, 2010). These reliability estimates are slightly higher than that of the Content scales. Furthermore, the use of the DSM-5 Symptom Scales is recommended by the manual for this tool and were thus used in the present thesis as indices of ADHD (Conners, 2008). Using normative data, a raw score on each DSM-5 subscale was converted into a standardised T-score. A T-score ≥60 reflected atypical levels of disorder symptoms than is typical for the child’s age.

The SDQ (Goodman, 2001) is a brief behavioural and emotional screening tool used to identify mental health problems in children aged 4-17 years old. The SDQ is a promising tool for identifying ADHD cases in community and clinical samples with good test-retest reliability (*r* = 0.70) and internal consistency (*α* = 0.73; Algorta et al., 2016; Goodman and Goodman, 2009; Stone et al., 2010). The SDQ consists of 25 items measuring five broad constructs: emotional problems, conduct problems, hyperactivity, peer problems and prosocial behaviour. Parents were asked to think about their child's behaviour over the last six months and, for each item, tick the box which represents whether the statement was 'Not True', 'Somewhat True' or 'Certainly True'. Responses were scored on a three-point scale of 0, 1 or 2, using the SDQ Scoring Aid. A response of 'Somewhat True' always received a score of 1, whereas 'Not True' and 'Certainly True' were scored either 0 or 2, depending on the item. A total difficulty score was generated by summing scores from all of the scale excluding the prosocial scale (a total of 20 items). A total difficulty score reflected higher difficulties with a score of ≥17 as a cut off point for 'Abnormal' level of emotional and behavioural difficulties.

The child version of the AQ-10 (Allison et al., 2012) was used to flag potential autism traits. This 10-item questionnaire is a quick referral guide to identify potential autism characteristics in children aged 4-11 years in primary care settings. The AQ-10 was adapted from the original 50-item AQ for the purposes of identifying "red-flags" in primary care settings and is reported to have good internal consistency (*α*= 0.85; Allison et al., 2012). Parents were asked to read ten statements and indicate the extent to which they agreed or disagreed with the statement, with four response options: 'Definitely Agree', 'Slightly Agree', 'Slightly Disagree' or 'Definitely Disagree'. Each question could receive 1 point. Questions 1, 5, 7, and 10 received 1 point for 'Definitely Agree' or 'Slightly Agree' and questions 2, 3, 4, 6, 8, and 9 received 1 point for Slightly Disagree' or 'Definitely Disagree' responses. A score > 6 was used as a cut off for considering referral for a specialist diagnostic assessment for autism (sensitivity 0.95, specificity 0.97; Allison et al., 2012).

The Movement ABC-2 Checklist (Schulz et al., 2011) was used to flag movement difficulties indicative of high DCD symptoms. The Movement ABC-2 Checklist measures functional motor performance in children aged 5-12 years and has been reported to have good internal consistency ($\alpha = 0.94$; Schoemaker et al., 2012). This questionnaire can be completed by parents as they observe the child in a wide variety of contexts. If the behaviour at question were not observed, parents were asked to estimate the level of performance based on how the child manages similar activities. Parents were presented with 30 items half of which asked about the child's movement in a static/predictable environment (Section A), and the other half in a dynamic/unpredictable environment (Section B). Each section is made up of three sub-sections containing 5 items (Section A: self-care skills, classroom skills, and physical education/recreational skills; Section B: self-care/recreational skills, ball skills, and physical education/recreational skills). Response scales ranged between 0 = 'Very Well', 1 = 'Just OK', 2 = 'Almost', and 3 = 'Not Close'. A total movement difficulty score was derived by adding the scores for Section A and Section B. Scores were mapped onto a traffic light system to establish whether the child falls into age-expected range. Children were scored as having either a definite and significant motor functioning difficulty (red; ≥ 95th percentile), at risk for having a motor difficulty (amber; 85th – 94th percentile) or no motor difficulty detected (green; < 85th percentile). Children scoring in the red zone were deemed as scoring high on DCD difficulties.

3.2.3 IQ tasks

Intelligence was assessed using the Wechsler Abbreviated Scale of Intelligence (WASI-II; Wechsler, 2011) and the British Picture Vocabulary Scale (BPVS-III; Dunn & Dunn, 2009). Children receiving a score of < 70 on both subtests were excluded from analyses due to suspected intellectual disability.

The WASI is a standardised IQ test which takes around 45 minutes to complete. The WASI has been used extensively as a test of intelligence in clinical child populations and shows high correlations with its' more comprehensive equivalent the Wechsler Intelligence Scale for Children (WISC; Astle et al., 2019; McCrimmon & Smith, 2013; Raggio et al., 2010; Raiford et al., 2016; Scott et al., 2007). Four subtests were administered in a sequential order: Block Design, Vocabulary, Matrix Reasoning, and Similarities. A raw score was calculated for each subtest and converted to a T score using age-standardised norms, with a score of < 70 implying intellectual disability. Together, the Vocabulary and Similarities subtest T-Scores provided the Verbal Comprehension Index (VCI; r = .94) while the Block Design and Matrix Reasoning T-Scores together provided the Perceptual Reasoning Index (PRI; r = .92). Furthermore, a Full-Scale IQ (FSIQ; r = .96) score was generated from all four subtests.

Although the WASI-II provides a good index of expressive vocabulary it does not generate a measure of receptive vocabulary. Given the high co-occurrences rates between ADHD and ASD it was expected that some children may struggle with providing verbal response in the WASI. As such, the British Picture Vocabulary Scale (BPVS-III; Dunn & Dunn, 2009) was used to provide an index of receptive vocabulary IQ. During this task children listen to words said out loud by the experimenter and respond by pointing to a picture from four options that best represents that word's meaning. Raw scores were converted into an age-standardised scores with a score of < 70 deemed to be within an atypical range. The BPVS ($r = 0.91$) is also a standardised measure which has been used to assess verbal ability in neurotypical children and children with neurodevelopmental disorders (Hannant et al., 2016; Rhodes et al., 2011; Rhodes et al., 2016). Furthermore, the BPVS has been argued to be less affected by confounding effects of other cognitive functions (Coghill et al., 2014).

3.2.4 Cognitive tasks

Participants completed eight tasks from the new version of the Cambridge Neuropsychological Test Automated Battery (CANTAB, 2018[6]) and one assessment from the WISC-V using a touch screen iPad (10.5-inch screen). The selection of cognitive tasks was largely informed by the comprehensive literature reviews (Chapters 1 and 2). Specifically, this was achieved by identifying domains that are frequently implicated in ADHD (Coghill et al., 2014; Kofler et al., 2019; Nigg et al., 2005; Rhodes et al., 2012; Rhodes et al., 2005; Rhodes et al., 2006; Willcutt et al., 2005) and, concurrently, those which have been shown to be important to children''s maths performance (Anonini et al., 2016; Andersson, 2010; Clark et al., 2010; Cowan et al., 2011; Cragg et al., 2017; Gilmore et al., 2015; Gremillion and Martel, 2012).

The CANTAB battery has been used extensively to examine neuropsychological functioning in neurotypical children and in children with developmental disorders such as ADHD (e.g., Lawson & Farah, 2017; Rhodes et al., 2016; 2012; Coghill et al., 2018; 2014; Seyedtabaei et al., 2018). It benefits from

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[6] Permission was granted by CANTAB to use images of task examples (i.e., Figures 3.2-3.8). These are subject to © Copyright 2018 Cambridge Cognition Limited. All rights reserved.

nonverbal task stimuli and requires minimal linguistic proficiency during administration (Luciana, 2003). This liberty from verbal responses is particularly important as language difficulties have been documented in children with ADHD (Helland et al., 2016; Geurts & Embrechts, 2008). Another advantage of the CANTAB is that administration was identical for every participant and so minimizes administration variability (Fried et al., 2015). The researcher was always present in case the child was unsure about the task instructions. Another advantage is the CANTAB's appealing digital testing format which can help maintain interest and motivation in children than non-computerised cognitive tests (Luciana & Nelson, 2002; Luciana 2003). The cognitive tasks, and their respective outcome measures and domains are summarised in Table 3.2.

Table 3.2 Cognitive tasks and domains

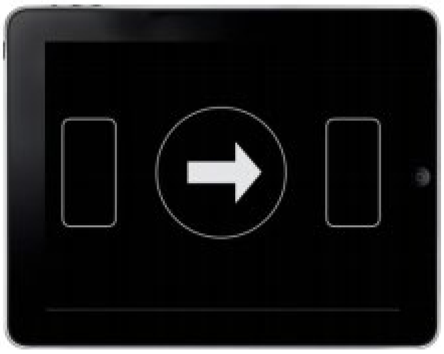
Task	Outcome measure	Domain
Stop Signal Task	Stop signal RT	Inhibitory control
	Stop signal median RT	Processing speed
Intra-Extra Dimensional Set Shift	Intra-Extra dimensional errors	Cognitive flexibility/set shifting
Stockings of Cambridge	Problems solved in minimum moves	Planning
Spatial WM	Between Search Errors	Visuospatial WM updating
	Strategy (6-8 boxes)	Visuospatial WM strategy
Delayed Matching to Sample	% Correct responses on 12s delay trials	Delayed short term recognition memory
Spatial Span	Spatial span forwards length	Visuospatial STM
	Spatial span reverse length	Visuospatial WM
Verbal Recognition Memory*	Immediate recognition accuracy	Immediate verbal recognition memory
	Delayed recognition accuracy	Delayed verbal recognition memory
Letters Numbers Sequencing	Maximum letter number sequence accurately recalled	Verbal WM updating

*This task was administered only to those aged 8 years and over

Inhibitory control. The Stop Signal Task assessed response inhibition - the ability to overcome impulses and inhibit pre-potent motor responses. Participants were presented with a white arrow at the centre of the screen pointing either left or right (Figure 3.2). The initial learning phase required participants to press a corresponding button depending on the direction in which the arrow pointed. Thereafter, participants were introduced to an auditory signal (a beep) that signals them to withhold the response. The delay between arrow presentation and audio signal (stop-signal delay) varies to avoid predictability of action cancellation timeframe. The Go/Stop trial ratio was 3:1. The outcome measure was the Stop Signal Reaction Time.

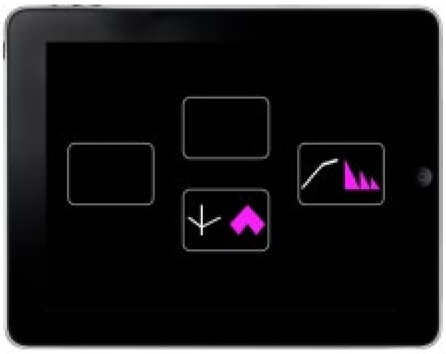
Processing speed. Children's processing speed was also indexed using the Stop Signal Task. The median RT (ms) on all Go trials in the task was the key outcome measure (Stop Signal Task Median RT All Go Trials).

Figure 3.2 Example from a trial on the Stop Signal Task



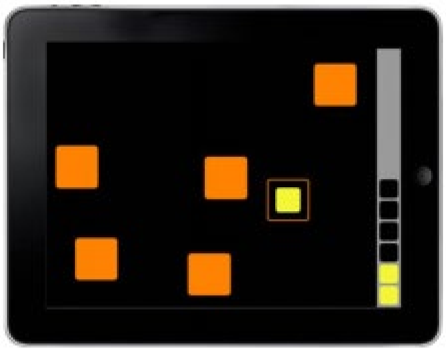
Cognitive flexibility. The Intra-Extra Dimensional Set Shift task measured children's cognitive flexibility – the ability to flexibly switch attention between different stimuli characteristics. Participants were presented with two abstract shapes and prompted to learn which one is correct by selecting a shape and receiving feedback on whether their response was correct/incorrect. After six correct responses the rules changed, and participants were now required to shift attention to a previously trivial stimulus attribute. Initially the task involves simple stimuli comprising one of the dimensions (intra-dimensional stage, e.g., two pink block shapes differing in form). As the task progresses new compound stimuli are introduced (extra-dimensional stage e.g., white lines; Figure 3.3). Participants had to shift between a set criterion of learning at each of the nine experimental stages: (1) simple shape discrimination, (2) simple shape reversal, (3) compound discrimination 1, (4) compound discrimination 2, (5) compound reversal, (6) intra-dimensional shift, (7) inter-dimensional reversal, (8) extradimensional shift, and (9) extradimensional reversal. Once the participant provided 6 consecutive correct responses the task progressed onto the next stage. The key outcome measure was the total number of times that an incorrect stimulus was selected, adjusted for every stage that was not reached (Intra-Extra Dimensional Errors).

Figure 3.3 Example of compound discrimination trial on the Intra-Extra Dimensional task.



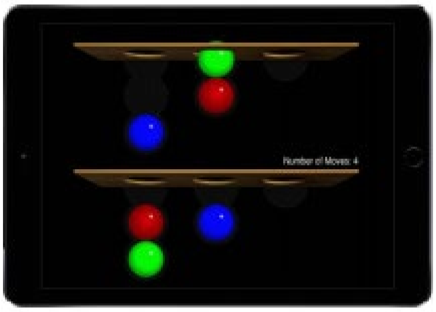
Visuospatial WM updating and strategy. The Spatial WM task examined visuospatial WM updating. Participants were presented with coloured boxes distributed on the screen and were asked to touch each box until they find a concealed token. Once the child located a token, they must move it to a column on the right-hand side of the screen. Children were instructed that once a token was found inside a box, that box would remain empty for the rest of the trial. The number of boxes increased across the trials from 3, 4, 6 and 8 items (Figure 3.4). The key outcome measure is the number of times a participant incorrectly revisits a box in which a token was previously found (Spatial WM Between Search Errors across all assessed four, six and eight token trials). This task relies heavily on EF domains as, although participants need to remember previous token locations, the main focus is on updating and manipulating visuospatial information. The second outcome measure is number of times a child started a new search pattern from the same box they started with previously (Spatial WM Strategy), which also reflects EF requirements. If the child always begins a search from the same starting point, then it is inferred that a planned strategy is employed for finding the tokens (strategy score across trials with 6 tokens or more; 1 = they always begin the search from the same box and higher scores indicate that they are beginning their searches using a variety of different boxes).

Figure 3.4 Example of a 6-token trial on the Spatial WM task



Planning. The Stockings of Cambridge task assessed children's ability to monitor, evaluate and update a sequence of planned moves. Participants were presented with two displays containing 3 stacked coloured balls. Participants were instructed to move one ball at a time in the lower display to copy the pattern shown in the upper display in a specified number of moves (Solve Phase; Figure 3.5). Children were told to make as few moves as possible to match the two patterns, whilst adhering to the following rules: (1) a ball cannot be moved if there is another ball on top of it, and (2) balls cannot hang in mid-air. In the Follow Phase, participants were asked to copy the moves made by the iPad that mimicked their Solve Phase responses. This allowed for the movement time to be discounted from measures of thinking time. The first blocks of trials comprised an initial Solve Phase of six practice trials and six experimental trials, followed by Follow Phase of two practice trials and six experimental trials. The second block of trials comprised an initial Solve Phase with two practice trials and six experimental trials, followed by two practice trials and six experimental trials. The key outcome measure was the total number of problems solved in the minimum possible number of moves (Stockings of Cambridge Problems Solved; higher is better).

Figure 3.5 Example from a four-move trial on the Stockings of Cambridge task

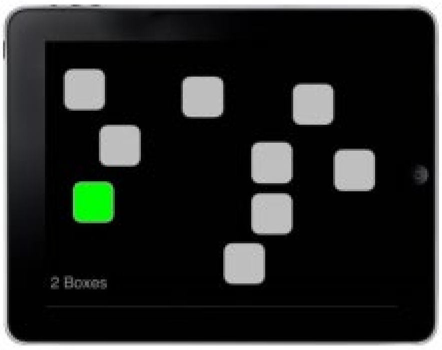


Delayed short term recognition memory. The Delayed Matching to Sample task was used to assess children's delayed short term recognition memory for visuospatial information. On each trial participants were presented with an abstract pattern and asked to select the pattern which exactly matched this sample from four possible options. On some trials the sample and the choice patterns were shown simultaneously (Figure 3.6), in others there was a delay before the four choices appear (0, 4 and 12s). In total there were four practice trials (simultaneous, 0-, 4-, and 12-seconds delays) followed by twenty experimental trials (five per delay type). The key outcome measure was the percentage of correct responses on 12s delay trials.

Figure 3.6 Example from simultaneous pattern presentation trial on the Delayed Matching to Sample task

Visuospatial STM and WM. The Spatial Span task examined visuospatial STM (forwards variant) and visuospatial WM (reverse variant). Participants were presented with white squares on the screen that changed colour sequentially for 3000ms (with a 500ms delay between each colour change). Following a 1000ms delay, participants were asked to reproduce the sequence by selecting the boxes in the order in which they changed colour (Spatial Span Forwards) and, in a second version of the task, the reverse order in which they changed colour (Spatial Span Reverse). For each task version there were two 2-box sequence practice trials (Figure 3.7) followed by eight experimental trials comprising 2- to 9-box sequence length. Children had three attempts for any given level of sequences and progressed onto next sequence length upon successful completion of preceding sequence. Performance outcomes were defined as the maximum correct sequence length for the forward and reverse variants.

Figure 3.7 Example from a 2-box trial on the Spatial Span task



Verbal recognition memory. The Verbal Recognition Memory task examined immediate and delayed memory for verbal information in children aged 8 years and older. Participants were presented with 18 words appearing in sequence on a screen, with each stimuli word presented for 1000ms (Figure 3.8). Participants were asked to indicate previously presented words from a list of 24 words. Following a 20-minute delay, children were once again invited to select previously presented words from a list of 24 words. Outcome measures were the total number of distinct words participant correctly recalled immediately after presentation (Immediate Verbal Recognition Memory; higher is better), and (2) following a 20-minute delay (Delayed Verbal Recognition Memory; higher is better). This task required children to be able to read words and, in line with CANTAB manual guidelines, was only administered to children aged over 8 years.

Figure 3.8 Example from recognition trial on the Verbal Recognition Memory

Verbal WM updating. The Letters Numbers Sequencing from the WISC-V measured verbal WM updating. Participants listen to a randomly ordered series of letters and numbers (e.g., B-1-2-T) and are asked to first repeat the numbers in ascending order then the letters in alphabetical order (e.g., 1-2-B-T). The task is divided into ten testing items each composed of three trials. The task begins with 2 numbers and letters and gets progressively more difficult, with 8 items as the most difficult level. One point is awarded for each correctly recited trial (max = 30 points).

The Maximum Letter Number Sequencing Total Raw Score is then transformed into a scaled score as the key outcome measure.

3.2.5 *Maths tasks*

All tasks relating to the assessment of children's maths competencies are summarised in Table 3.3.

Table 3.3 Maths tasks and domains

Task	Outcome measure	Domain
Wechsler Individual Attainment Test (WIAT)		
Mathematics Problem Solving	Total accuracy	Maths problem solving
Numeracy	Total accuracy	Numerical operations
Maths Fluency (addition, subtraction, and multiplication*)	Total accuracy	Arithmetic fluency
Maths component skills		
Factual knowledge	Total accuracy	Knowledge of addition and subtraction facts
Conceptual understanding	Total accuracy	Understanding and applying conceptual principles
Procedural skill task	Total accuracy	Procedural computations accuracy
	Mean RT for accurate trials	Procedural computations efficiency

*This task was administered only to those aged 8 years and over

3.2.5.1 Maths achievement

Children completed the Wechsler Individual Achievement Test - Third Edition (WIAT-III) – a standardised assessment of maths achievement. The WIAT-III, and similar alternatives, are widely used to index broad attainment scores in ADHD

(Alloway, 2011; Antonini et al., 2016; Friedman et al., 2018; Gremillion and Martell, 2012; Holmes et al., 2014). In order to provide a comprehensive indication of children’s achievement levels, all three maths subtests from WIAT-III were used: Mathematics Problem Solving, Numeracy, and Maths Fluency. All tasks were administered following standard procedures described in the manual. Total raw scores on each subtest were converted into a standardised score using age-appropriate normative data. These were then combined to index composite standard scores for each of the subtest combinations to index performance.

Mathematics Problem Solving. The Mathematics Problem Solving subtest (untimed) required children to solve orally presented word problems comprising items relating to time, money, measurement, geometry, probability, or reading graphs. Starting from the age-appropriate starting point, children were asked to listen to problems read out loud by the researcher, look at the corresponding visual stimuli, and provide an oral or pointing response.

Numeracy. The Numeracy subtest (untimed) measured written maths calculation skills including basic skills, basic operations with integers, geometry, algebra, and calculus. Children were directed to an age-appropriate starting point and asked to solve problems in written form. Together, Mathematics Problem Solving and Numeracy mapped on to a composite Maths score.

Maths Fluency. The Maths Fluency subtests measured written maths calculation fluency under timed conditions across addition (all ages), subtraction (all ages), and multiplication sums (ages 8 + years). Children were presented with written sums and asked to write down answers to as many sums as they could in one minute (timed using a stopwatch). Maths Fluency Addition, Subtraction, and Multiplication were combined to provide a composite standard Maths Fluency score.

3.2.5.2 Maths component skills

Previous investigations almost exclusively rely on a unidimensional approach to maths. Standardised achievement tests provide useful methods for generating an attainment index for children compared to others their age. However, such approaches assume that maths is a unitary process and risk masking more specific components requiring intervention (Cragg et al., 2017; Dowker, 2005; Furlong, et al., 2015). The selection of tasks to assess maths component skills was guided predominantly by Geary's (2004) hierarchical model (discussed in Chapter 1) according to which maths attainment is underpinned by more specific maths skills, namely: factual knowledge, conceptual understanding, and procedural skills components. The tasks used to assess these components contained different content for children in the different school year groups Primary 2-4 and Primary 5-7. Children's raw scores were transformed into *z*-scores based on scores from others in their year group.

Factual knowledge. The factual knowledge task assessed knowledge of number facts (adapted from Cowan et al., 2011 and Simms et al., 2015). Children were presented with single digit addition problems on a computer screen and were asked to quickly retrieve the answer to each sum. Children were told that most people know the answer to the problem without having to work it out so once a sum appears, they should provide an answer out loud as fast as they can. If the child could not recall an answer, they were asked to respond with "I don't know". Children were presented with 2 practice trials and 12 experimental trials during which the experimenter read each sum out loud to the child. On each trial the sum was on the screen for a total of 4 seconds and correct responses provided before a blank screen appeared were scored 1 point. A score of 0 was awarded for an incorrect response or no response within the specified time frame. To eliminate potential floor or ceiling effects a different set of items were presented depending on the year in which the child is at school. Children in Primary 2 to Primary 4 received single digit addition sums that did not exceed answer of 10 (e.g., 3 + 5 =?). Children in Primary 5 to Primary 7 were administered addition problems that exceeded an answer of 10 but were below 20 (e.g., 7 + 7 =?). The outcome measure was the total number of correct responses (max = 12).

Conceptual understanding. The conceptual understanding task (adapted from Cowan et al., 2011 and Simms et al., 2015) assessed children's understanding and application of conceptual principles. First, participants were presented with a double-digit addition or subtraction problem on the screen with its answer (e.g., 31 + 45 = 76). The experimenter read each sum out loud as it appeared. After 6 seconds, another related sum appeared below it but this time without an answer (e.g., 76-45 =?). Participants were instructed to use the first sum to help them solve the second sum. There were 4 practice trials, one for each conceptual principle (double plus one, commutativity, inversion, and identical). Children received 12 experimental trials, three for each conceptual principle: double plus one (e.g., 42 + 42 = 84, 42 + 43 =?), related by commutativity (e.g., 48 + 21 = 69, 21 + 48 =?), related by inversion (e.g., 79-17 = 62, 62 + 17 =?) and identical (e.g., 56-27 =29, 56-27 =?). Children had 6 seconds to provide an answer. Correct responses provided before a blank screen appeared scored 1 point. A score of 0 was awarded for an incorrect response or no response within the specified time frame. The problems were designed in a way that children were unlikely to be able to solve them within the time limit unless they relied on conceptual insight. Different sums were used depending on child's stage at school.

Children in Primary 2 to Primary 4 were presented with double digit solution sums, while those in Primary 5 to Primary 7 were presented with a mixture of double-digit and three-digit numbers. The outcome measure was the total number of correct responses (max = 12).

Procedural Skill. The procedural skill task (Cragg et al., 2017) examined children's ability to execute maths procedures accurately and efficiently. Children were shown pictures depicting different strategies and told that any of these strategies, or others, were acceptable: counting in head, counting on fingers, decomposition, and retrieval. This ensured that younger participants understood that any strategy could be used for the task. Participants were given 4 practice trials and 10 experimental trials containing addition and subtraction operations using single and double-digit number. On each trial children were presented with a math problem on a screen and asked to solve this using any preferred method. Participants were required to provide their answer verbally at which point the experimenter pressed a key and inserted the answer. The outcome measure was the total correct responses (accuracy) and the mean reaction time (efficiency RT; seconds) for correctly answered trials.

3.3 Ethics

Favourable ethical opinion was granted from the North West Haydock Research Ethics Committee (Reference: 17/NW/0642). This study was reviewed and given management approval by NHS Lothian, co-sponsored by University of Edinburgh and NHS Lothian. Informed assent was carefully managed at all stages of the project. All children were given an opportunity to provide verbal (ages 6-8 years) or written (ages 9-12 years) assent at the first visit. The assent of children was managed by provision of age-appropriate (ages 9-12) information sheets in the information pack sent out to their home. Information about the study was also provided to children aged 6-8 years in developmentally appropriate language at the first visit to ensure that younger children understood the study and their involvement. Parent consent was managed by provision of a separate information sheet in the information pack. Information sheets described details of the research in easily intelligible language. Fully informed assent was obtained by meeting with the child and parent in their home during the first visit, where the study was explained and opportunity for questions was provided. The researcher gauged for both verbal and nonverbal cues that the child was happy to continue at various points during the testing sessions. Parents of children provided full informed written consent for their child's participation, as well as their own participation for completing the questionnaires about their child's behaviour. Additionally, parents of children granted permission for the researcher to contact the child's school to schedule and conduct future visits.

3.3.1 Data processing

Raw data collected was stored in a locked filing cabinet drawer within the research centre grounds, accessible by key to members of the research team. To maintain confidentiality, contact consent forms and participation consent forms were stored in a separate designated locked filing cabinet. No identifying information (e.g., names, ages, and sex) were included on any of the raw data paper forms. All participants were given a unique code and only this participant code was noted on paper forms. Data was initially coded and processed onto SPSS by either the PhD researcher (MK) and then double coded independently by a fully trained masters student (CS or JO). Any electronic data and analytical data files were stored on a secure university drive, on a password protected VPN.

3.4 Procedures

3.4.1 Participant recruitment

All children were recruited from the waiting list for ADHD assessment in NHS Lothian CAMHS clinics in Scotland. These children were referred by a specialist ADHD nurse and awaiting full clinical assessment. Information packs were created and handed to the CAMHS clinical team[7]. These contained a letter of invitation for parents/guardians, an information sheet for parents/guardians and an information sheet for young persons aged 9-12 years, a contact consent form, as well as a pre-paid envelope for return of contact consent form. Information packs were either posted out by the clinical team or handed out to parents at initial assessment appointment with the CAMHS psychiatric nurse at the clinic. All participating families received a £30 Amazon voucher at the first visit in recognition of time spent taking part in the research.

3.4.2 Data collection

Participants took part in a wider project on academic learning and cognition. Data used in this thesis was collected from two visits totalling to around 3hours of testing per child. Where necessary, the researcher returned for additional visits. All participants were assessed on the same measures. The first visit always took place at the participants' home except for one child who was tested in a community hall. The first visit always required the presence of a parent to complete consent/assent procedures and the questionnaires meaning it typically took place after school hours. Following explanation of the study and consent/assent procedures, parents were asked about their child's handedness, as well as their birthweight and gestational age

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[7] It was not possible to calculate the approximate recruitment rate as the number of information packs distributed by CAMHS to families were not monitored.

(N = 13 parents provided this latter information directly from the child's red book). Parents were also asked to provide details of their child's school to book subsequent visits.

Thereafter, children completed the cognitive tasks assessing memory and attention on an iPad under the supervision of a researcher. The order of the CANTAB tasks was counterbalanced across participants, such that the first twenty-five participants performed the tasks in the following order: Spatial WM, Delayed Matching to Sample, Stockings of Cambridge, Verbal Recognition Memory-Immediate, Intra-Extra Dimensional, Spatial Span Forward, Spatial Span Reverse, Verbal Recognition Memory Delayed, Stop Signal Task. The rest of the participants received the tasks in the reverse order. During this session, a second attending researcher explained the questionnaires to the parent. All parents were given the option of either completing the questionnaires independently or with the help of a researcher reading the questionnaires out loud to them. This was done to support parents who may themselves have ADHD-like traits such as inability to concentrate on text or difficulties reading (Laasonenet al., 2010; Yoshimasu et al., 2018). Having a second co-attending researcher also allowed parents the opportunity to ask about anything they were unsure of and promoted complete data coverage to all items.

The second visit was typically conducted at the child's school in a quiet room, on average 15 days after the first visit. The number of days between the first and second visit ranged between 1 day and 53 days. In some cases (N = 11), due to either parent preferences or school holidays, the second visit was conducted at home. During the second visit all children were provided with the opportunity to give verbal assent to continue participation. During the second session children completed the following tasks: WASI, BPVS, WIAT Maths, maths component assessments and the WISC Letter Number Sequencing task.

Children who failed to complete any of the tasks across the two visits were re-scheduled for an additional session to complete any unfinished assessments where possible. The designation of tasks for each of the visits was guided by the expectation that children would prefer to engage with a digital game-like iPad tasks assigned to visit one after school, over that of school-like educational tasks assigned to the second session. Observational data was also collected during all visits, noting the child's behaviour, attitude, and engagement with the testing (Appendix C). Furthermore, some of the data collected as part of this thesis (i.e., observational data, maths attainment, and IQ) was used towards the formulation of a clinical report for each individual child by the wider research team. The clinical report was sent to the lead psychiatrist of the CAMHS team to help with a more detailed profile of the child's functioning.

3.4.3 Data preparation

3.4.3.1 Missing data

Non-completers in child and adolescent mental health clinic setting are characterised by substantially higher functional impairments and psychiatric symptoms (Pellerin et al., 2010). Attrition, where unaddressed, limits the validity of studies. Dong and Peng (2013) emphasize the importance of addressing the proportion and mechanisms of missing data prior to making decisions on how to address it. The magnitude and mechanisms of missingness of the data were addressed using missing data analysis, complemented by the observational notes completed during the sessions (Appendix C).

Proportion. Missing data analysis on the cognitive and maths assessments revealed that 11.9% of data values were missing from the dataset, with 25 children (56.8% of sample) having at least one missing value. The missing data here was above the 5% recommended inconsequential rate and just above 10% cut-off as potentially biasing for analysis (Bennet, 2001; Schafer, 1999). However, the Verbal Recognition Memory task was only administered to those aged 8 years and over as it required that children are able to read. Once the Verbal Recognition Memory outcome measures were excluded from the missing data analysis, 8.01% of the values were missing with 18 children (40.9% of sample) having at least one missing value.

Mechanisms. The causes behind missing data and the pattern of the missingness are argued to be more important criterions than the amount of missing data (Tabachnick & Fidell, 2007). To identify the mechanisms by which data was missing completers and non-completers were compared using a series of *t* tests and the Little's Missing Completely at Random (MCAR).

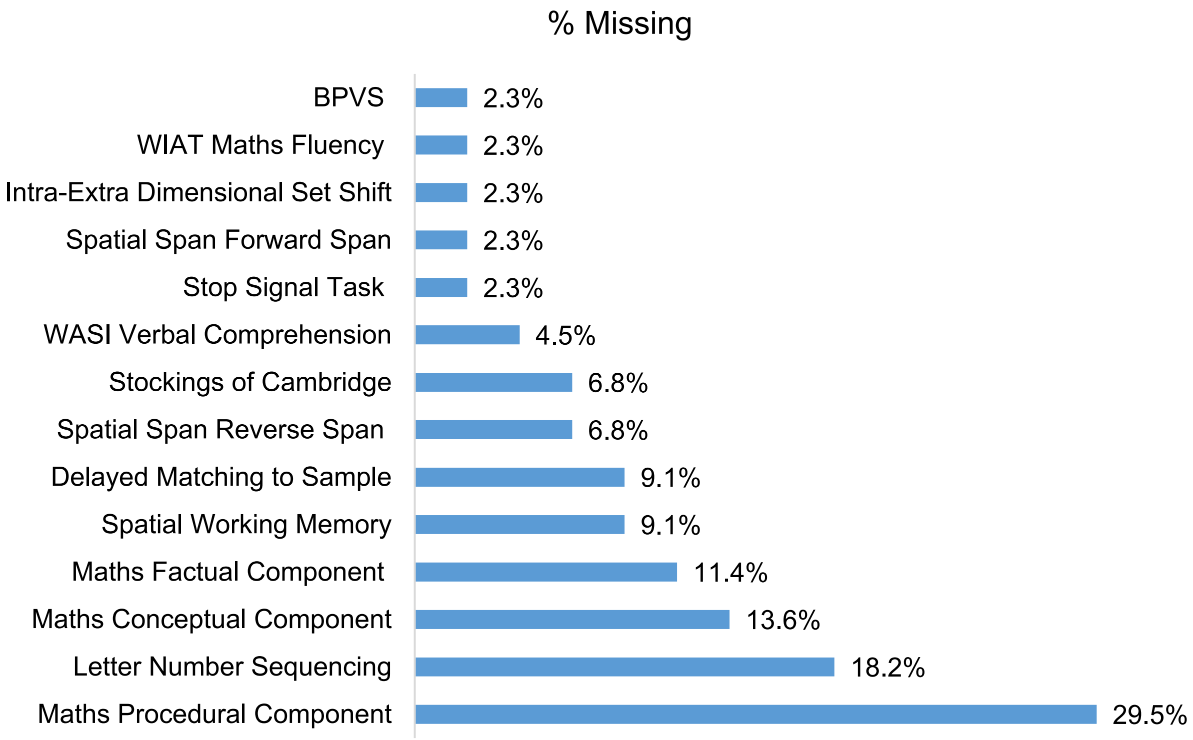
Thirteen children had missing data on at least one of the maths outcomes measures. Participants with missing observations on maths assessments differed in age, such that younger children [*t* (42) = -4.56, *p* = .000] were less likely to complete maths tasks. Completers and non-completers did not differ on their cognitive scores, IQ, nor on any of the parent rated symptoms of ADHD-Inattention, ADHD-Hyperactivity/Impulsivity, ODD, CD, ASD or movement difficulties (all *p*'s > .05).

In relation to the cognitive outcomes measures, 14 children had missing data on at least one of the cognitive tasks (excl. VRM). Participants with missing observations on cognitive assessments differed in age [*t* (42) = -3.02, *p* = .004] and in their parent reported birthweight [*t* (42) = -3.20, *p* = .003] such that younger participants, and those with lower birthweight were less likely to complete a cognitive task. Non-completers on the cognitive assessments also differed in their SDQ scores [*t* (37.33) = -2.39, *p* = .022] and ODD scores [*t* (18.41) = -2.38, *p* = .028], with children scoring lower (i.e., less difficulties) on these parent questionnaires as more likely to complete assessments. Lastly, children with incomplete cognitive data scored lower on the accuracy [*t* (29) = -2.17, *p* = .039], and efficiency RT scores [*t* (29) =-3.37, *p* = .002] on the procedural skill task than those with complete data.

Little's MCAR test was also considered, which generated $\chi2(198) = 199.83$, *p* = .450 suggesting that the data was MCAR. However, to be considered MCAR missingness cannot be related to any variables in the data set (Enders, 2013). The aforementioned differences between completers and non-completers imply that data could not be MCAR. The qualitative observation notes made during data collection indicated that children disengaged due to visible frustration, which could have been due to underlying difficulties in the domains tested by the tasks. In such a case data can be deemed as missing not at random (MNAR). Data MNAR refers to missing values on a variable as related to the underlying values of that variable itself (Peugh & Enders, 2004). In such cases the missingness is systematically related to the unobserved values. An example of this would be where a child with poor numerical skills refuse to complete a maths assessment due to underlying difficulties on those tasks. MNAR data cannot be recovered using statistical algorithms such as multiple imputation (Jakobsen et al., 2017; Rhemtulla & Little, 2012). As such, pairwise deletion was selected as the method for treating missing values in the analyses. Furthermore, differences between completers and non-completers were reported in each of the experimental study chapters (i.e., Chapters 4-6). This approach has previously been employed in similar work (e.g., Antonini et al., 2016).The author recognises that whilst the current approach of pairwise deletion limits the validity of the findings, it nonetheless reflects an improvement from previous studies which fail to address completion rates and/or identify factors contributing to non-completion (e.g., Alloway, 2011; Friedman et al., 2018; Holmes & Adams, 2014; Kaufmann & Nuerk, 2008; Kim et al., 2020; Miranda et al., 2005; Passolunghi et al., 2005).

The percentage of participants for whom data was missing across maths assessments and cognitive tasks is depicted in Figure 3.9. Below is a narrative synthesis of the reasons behind the missing data for all variables to promote transparency.

Figure 3.9 Percentage of missing data for key outcome measures



Session 1. Data on the neurocognitive CANTAB tasks was missing due to children's refusal to engage with one or more of the tasks. In such cases, the task was

terminated to avoid causing any emotional distress to the child. The format of the CANTAB administration follows a pre-specified rigid order, such that failure to complete a task early in the sequence meant that the child could not progress to later tasks. This was the case for 4 children who disengaged at variable sequential points: Stockings of Cambridge task (N = 2), Delayed Matching to Sample (N = 1) and Intra-Extra Dimensional (N = 1)[8]. Additionally, two children completed all tasks apart from the Stop Signal Task[9]. The Stop Signal Task was the longest task to complete lasting approximately 20 minutes and featured auditory signals (i.e., loud beeps). Both participants for whom the data was missing on this outcome measure had a maximum score on the AQ-10. One of the children had a pre-existing ASD diagnosis whilst the other was referred for further investigation for ASD. Another participant who received the tasks in the reverse presentation (i.e., Stop Signal Task first) disengaged from the outset, and also had a co-occurring ASD diagnosis. It may be plausible to suggest children's sensitivity to auditory tones often documented in ASD (Wiggins et al., 2009) affected their ability to complete the Stop Signal Task. On the Spatial Span Forwards and Reverse task variants, failure to complete the easiest 2-box practice stage resulted in termination of the task and thus missing values for the span length.

Session 2. The maths and IQ assessments were predominantly missing due to children's refusal to engage. Two children refused to provide verbal responses on the WASI Verbal Comprehension subscales – one child had a clinical ASD diagnosis, and the second child was referred for further ASD evaluation. This implies that expressive

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[8] All children to whom this applied received the CANTAB in the reverse order: Stop Signal Task Verbal Recognition Memory-Immediate…. Spatial WM.

[9] These children received the CANTAB in the forwards order: Spatial WM, Delayed Matching to Sample….Stop Signal Task.

language difficulties found in some children with ASD may have resulted in missing values on the tasks (Bal et al., 2019). This also highlights the benefits of administering the BPVS as a measure of verbal IQ via nonverbal pointing responses, as this was successfully completed by all participants. Only one child had a missing score on the BPVS as their raw score was too low for age-standardisation. The Letter Number Sequencing task was typically administered at the very end of the second session. Early termination of the session due to general disengagement (N = 5), difficulty providing oral responses on verbal tasks (N = 2), and non-availability of trained researcher in administering this task (N = 2) resulted in missing data on this measure. Refusal to engage in the maths tasks specifically, resulted in missing values on the factual (N = 4), conceptual (N = 5) and procedural (N = 2) components, as well as WIAT Math Fluency Subtraction (N = 2) and Addition (N = 2) Subtests. Additionally, maths components tasks were not administered for two participants due to lead researcher trained in administration of these tasks not being available in these cases (all other data for these participants was available).

3.4.3.2 Age standardisation

Due to wide age-range of participants in the sample it was important to account any age differences within the analyses. Any assessments that were not previously standardised according to normative data within administration manuals were standardised prior to analyses. The maths component tasks contained different content for children in P2-P4 and those in P5-P7 to avoid floor or ceiling effects. As such, children's raw scores were transformed into *z*-scores based on each individual year group for further analyses[10]. Raw scores on the CANTAB assessments were transformed into *z*-scores for further analyses based on age. Paediatric normative data for the CANTAB version used in this study was not available at the time of analysis. The following variables comprising measures were reverse scored so that higher scores indicated better performance: Stop Signal Task Stop Signal RT, Stop Signal Task Median RT All Go Trials, Intra-Extra Dimensional Errors, Spatial WM Errors, Spatial WM Strategy, and Procedural Correct RT.

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[10] There was only one child in Primary 6 and, as such was, included with the Primary 7-year group standardisation

4 Chapter 4: Cognitive correlates of maths performance of children referred for ADHD evaluation

Chapter 2 highlighted the scarcity of research on the association between cognition and maths in ADHD. The current evidence mainly addresses visuospatial and verbal WM processes, but other important cognitive processes have not been comprehensively addressed. It also outlined some methodological considerations that would benefit from being addressed. This includes moving away from broad attainment tests towards exploring more specific aspects of maths skills that underlie general achievement levels. Also highlighted in the General Introduction and Chapter 2 is the need to screen for other frequently co-occurring diagnoses. The purpose of the current chapter is to provide comprehensive investigation of a range of cognitive processes and their relationship to maths performance in a drug naïve and well characterised sample of children referred for clinical ADHD evaluation.

4.1 Introduction

Attention Deficit Hyperactivity Disorder (ADHD) affects around 1-2 % of school-aged children in the UK (Russell et al., 2014). It is characterized by clinically significant symptoms of hyperactivity, impulsivity, and inattention that impact social, behavioural, cognitive, and/or academic functioning (APA, 2013). Children with ADHD are particularly susceptible to difficulties in maths, albeit the precise mechanisms behind these remain ambiguous (Lucangeli & Cabrele, 2006; Sturm et al., 2018; Tosto et al., 2015). Early maths acquisition is a crucial prerequisite to more advanced learning throughout school and is an important predictor of outcomes later in life including education progression, job quality, salary earnings, and mental health (Bynner, 2002; Duncan et al., 2007; Emerson & Hatton, 2007; Parsons & Bynner, 2005; Ritchie &

Bates, 2013). Despite this, research into the relationship between ADHD and maths performance is scarce rendering it a compelling target for further exploration.

Previous research consistently indicates that children with ADHD struggle with maths, as demonstrated by lower scores on standardised achievement tests (Barry et al., 2002; Capodieci & Martinussen, 2017; Frazier et al., 2007), and below average maths grades (Daley & Birchwood, 2010; Molina et al., 2009). Around a third of children with ADHD show a specific learning disability in maths (Del'Homme et al., 2007; DuPaul et al., 2013), typically defined as a 1.5-2 standard deviation discrepancy between intellectual ability (IQ) and achievement (APA, 2013; Gathercole et al., 2018). Notably, children with high ADHD symptoms that fall short of a clinical diagnosis also show difficulties in maths (Loe & Feldman, 2007).

Children with predominantly inattentive (ADHD- I) and combined (i.e., inattentive + hyperactive/impulsive; ADHD-Combined) symptom presentations tend to struggle academically more so than their hyperactive-impulsive (ADHD-H) peers (Willcutt et al., 2012). A review by Tosto and colleagues (2015) found that 76% of reviewed studies showed a significant negative association between core ADHD symptoms and maths achievement, even after controlling for a range of attenuating. Notably, inattention yielded more substantial associations with maths difficulties than hyperactivity-impulsivity. Although some research shows that ADHD symptoms uniquely predict maths underachievement, cognitive factors tend to mediate this association (Antonini et al., 2016; Barry et al., 2002; Gremillion & Martel, 2012; Greven et al., 2014; Hart et al., 2010; Mayes et al., 2020; Rogers et al., 2011). This suggests that the relationship between ADHD symptoms and maths could be an artefact of underlying cognitive operations.

Executive Functions (EF) have received particular attention due to their close affiliations with attentional control and well-documented difficulties in ADHD (Brocki et al., 2010; Gau & Shang, 2010; Pennington & Ozonoff, 1996). Conceptualisations of EF during primary school typically comprise inhibitory control, cognitive flexibility/set shifting, working memory (WM) and planning (Diamond, 2013; Miyake et al., 2000). Previous work supports the importance of these EF domains to children's maths attainment (Alloway 2011; Antonini et al., 2016; Gremilllion & Martel, 2012; Friedman et al., 2018; Gathercole et al., 2018; Holmes & Adams 2014). For example, Antonini and colleagues (2016) found that although inhibitory control performance showed substantial associations with maths achievement in children with ADHD, only n-back (1-back) performance (a paradigm frequently used to assess WM capacity) remained a unique predictor when both were considered together. Notably, maths achievement was mediated by children's n-back performance but not by parent-rated symptoms of inattention. Another study by Gremillion and Martel (2012) found that verbal WM only partially mediated the relationship between 6-12-year-olds' ADHD symptoms and mathematics attainment. However, both studies used a community-based sample limiting the generalisability of findings to children who experience clinically debilitating difficulties. Furthermore, other EF domains (e.g., set shifting and planning), were not examined making it difficult to ascertain the relative association of each domain to maths achievement.

In a comprehensive investigation of both EF and memory in children with ADHD and learning difficulties, Gathercole and colleagues (2018) found that maths attainment yielded the strongest associations with visuospatial cognition, including higher order EF tasks of switching, planning, and visuo-spatial WM as well as storage. In addition to this, verbal STM also showed unique associations with children's maths score. However, it is important to note the aforementioned studies relied on reverse span tasks which have been criticised to load on to short-term memory (STM) storage and recognition processes, rather than more complex updating requirements linked to higher order EF processing (Jaeggi et al., 2010). Thus, sequence reversal is arguably insufficient for tapping into the updating domain of WM (Conway et al., 2005; Engle et al., 1999; Wells et al., 2018).

According to the prominent model by Baddeley and Hitch (1974) the capacity-limited central executive of the WM system uses attentional processing for actively regulating, manipulating, and updating information 'online'. Meanwhile, the phonological loop and visuospatial sketchpad are responsible for storing modality-specific information in STM in the absence of concurrent processing (Baddeley & Hitch, 1974; Cowan, 2008). *Worki*ng memory refers to a more complex cognitive process of actively manipulating and updating information in STM constituting: (1) serial reordering of information, (2) updating information by actively adding and deleting information from memory, and (3) dual processing by working with the information while concurrently storing it (Nee et al., 2013; Wager & Smith, 2003; Wells et al., 2018). Although reverse span tasks are frequently used to index WM, it has been argued that sequence reversal is insufficient for tapping into updating and dual processing subdomains of *working* memory (Conway et al., 2005; Swanson & Kim, 2007; Wells et al., 2018).

Although ADHD is predominantly conceptualised as a single disorder, children present with heterogeneous cognitive profiles (Coghill et al., 2014; Nigg et al., 2005; Willcutt et al., 2005) that can catalogue differential patterns of academic vulnerabilities (Astle et al., 2019; Roberts et al., 2017). Some research points to lower-level verbal and visuospatial memory storage difficulties as core characteristics of ADHD (Rapport et al., 2008; Rhodes et al., 2012; Tillman et al., 2011). Modality-specific memory storage components are also implicated in maths achievement (Cragg et al., 2017; Gathercole et al., 2018; Holmes & Adams 2006). Thus, it is important to address the relative association of WM capacity with and without updating requirements. Research suggests that while executive WM processes are employed by more complex Mathematics Problem Solving tasks such as those found in achievement tests, domain-specific storage of the phonological loop and visuospatial sketchpad is particularly important for elementary maths skills, such as rehearsal of visuospatial (e.g., 2 + 2 = 4) , and phonological codes (e.g., *two plus two equals four*) for basic arithmetic facts (Bull et al., 2008; Cragg et al., 2017; Friedman et al., 2018; Holmes & Adams, 2006). Given the foundational role of early arithmetic skills to more advanced maths acquisition, memory in the absence of active processing represents an imperative construct for further investigation.

Another lower-level cognitive construct identified as vulnerable in ADHD (Nikolas & Nigg, 2013) and associated with maths achievement (Gathercole et al., 2018) is processing speed. Processing speed facilitates cognitive efficiency by increasing the amount of information that can be processed within a given timeframe and reduces decay of information in memory (Clark et al., 2014). Processing speed has previously been linked to children's basic arithmetic fluency, and indirectly to more advanced problem solving (Fuchs et al., 2006; 2008; 2010; Rose et al., 2011). Although some studies show that children's processing speed is a viable predictor of maths achievement independent of WM, some of these associations may be exaggerated due to measures of processing speed containing maths-related stimuli such as numbers (e.g., Bull & Johnson, 1997; Geary, 2011; Mayes & Calhoun, 2006;

Sturm et al., 2018). Exploring processing speed performance using tasks without maths-related stimuli is therefore more favourable in identifying whether its' associations are domain general or not.

Evidently, maths performance is associated with a diverse set of cognitive processes. However, the generalisability of previous findings to the wider ADHD population is limited due to several methodological constraints. Previous investigations either exclude and/or provide insufficient screening for frequently co-occurring disorder symptoms. This includes movement difficulties akin to Developmental Coordination Disorder (DCD), Autism Spectrum Disorder (ASD), as well as clinically significant externalising behavioural problems, such as Opposition Defiant Disorder (ODD) and Conduct Disorder (CD; Friedman et al., 2018; Gathercole et al., 2018; Holmes et al., 2014; Sturm et al., 2018). Estimates of co-occurrences range between 40%-80%, rendering co-existence with other disorders in ADHD as the rule rather than the exception (Elia et al., 2008; Lange, 2018; Reale et al., 2017). However, many studies either fail to screen for co-occurring symptom constellations or exclude children with co-occurrences from participation.

Another methodological issue relates to inclusion of children that had been prescribed psychostimulant medication (e.g., Gathercole et al., 2018) or underwent a 24-hour washout period (e.g., Friedman et al., 2018; Holmes et al., 2014). Medication treatment improves parent ratings of behavioural symptoms (Posey et al., 2007) as well as cognitive (Vaidya et al., 1998; Rhodes et al., 2006) and academic functioning in ADHD (Powers et al., 2008). Moreover, even under 24-hour wash out requirements, children with a history of stimulant treatment perform better on some academic, behavioural, and cognitive domains than their non-medicated ADHD peers (Semrud-

Clikeman et al., 2008). Thus, children with previous history of medication treatment may preserve related advantages even when off medication. Assessment of a drug naïve sample is necessary for identifying possible targets for psychoeducational interventions in the absence of the confounding effects of medication.

Previous investigations almost exclusively employ a unidimensional approach to maths skills, and this can arguably further contribute to inconsistent findings. Standardised achievement tests provide useful methods for identifying broad maths strengths and weaknesses by averaging performance across multiple domains to generate an attainment index. However, such approaches assume that maths is a unitary process and risk masking more specific components requiring intervention (Dowker, 2005; Furlong et al., 2015). For example, a low attainment score on a standardised test could by driven primarily by (1) difficulties retrieving previously learned arithmetic facts from memory known as *factual knowledge*, (2) problems understanding and identifying conceptually based relationships among numbers and operations, also referred to as *conceptual understanding*, and/or (3) difficulties applying computational procedures accurately and efficiently, also known as *procedural skill* (Dowker, 2005; Geary, 2004; Hiebert & Lefevre, 1987). Global attainment scores obscure which of these specific component process (i.e., factual, conceptual, or procedural) is steering underachievement. Given the consistent associations between ADHD and broad maths achievement scores, these must be decomposed further in exploring cognitive pathways of vulnerabilities (Sturm et al., 2018). Such an approach will be more desirable in informing formulation of interventions tailored to children’s needs (Cragg et al., 2017; Kadosh et al., 2013).

Indeed, hierarchical models of maths hold that broad achievement relies on children's domain-specific factual, conceptual, and procedural skills that in turn employ domain general cognitive mechanisms such as memory and EF (Geary, 2004; Cragg & Gilmore, 2014; Cragg et al., 2017). Although performance on the three components is inter-correlated, disruptions can occur independently suggesting that the underlying cognitive processes that support these skills may also differ (Dowker, 2005; Gilmore & Papadatou-Pastou, 2009; Wilson & Dehaene, 2007). In neurotypical children, inhibitory control is proposed to help suppress interfering items during factual retrieval (e.g., inhibit 8 when asked to do 4 × 4 =?), and for impeding upon well-learned but incompatible procedural operations (e.g., adding when being asked to subtract; Bull & Lee, 2014; De Visscher & Noël, 2014; Robinson & Dube, 2013; Lemaire & Lecacheur, 2011). Moreover, cognitive flexibility has been linked to children's ability to shift between operations (e.g., + /-), notations (e.g., between verbally presented digits and written Arabic symbols), as well as multiple problem steps and strategies during tasks assessing conceptual and procedural components (Andersson, 2010; Bull & Lee, 2014; Clark et al., 2010). However, some research suggests that the roles of inhibition and cognitive flexibility exist predominantly on tasks using numerically oriented stimuli, rather than domain general measures of these processes (Cragg et al., 2017). Further research is necessary to determine whether more profound difficulties on non-numerical inhibitory control and cognitive flexibility, characteristic of ADHD, are related to componential maths performance. Planning may underlie more complex multistep maths computations by facilitating organisation of knowledge and accurate execution of step-by-step sequences (Cai et al., 2016; Davidson et al., 1994; Dowker, 2005; Rourke,1993). To date, the role of planning has seldom been investigated in the context of maths.

WM tends to emerge as the strongest predictor of math component skills in neurotypical samples. Cragg and colleagues (2017) found that although both verbal and visuospatial WM accounted for unique variance in factual fluency and procedural strategies, only verbal WM predicted conceptual understanding. This suggests that conceptual comprehension relies on phonological codes whilst factual knowledge and procedural skill draw on both phonological and visuospatial processing of numerical information. Indeed, WM is important for modality specific manipulation and updating of verbal and visuospatial information during solutions, particularly in multi-step procedural computations (e.g., 6 + 7 =?) that require maintenance of current solutions 'online' (i.e., 6 + 6 = 12) simultaneous performance of other parts of the problem (i.e., 12 + 1 = 13), and updating old solutions with new ones (e.g., updating 12 with 13) (Robinson & Dube, 2013; Andersson, 2008). Notably, WM predicted broader achievement both directly and indirectly via these components (Cragg et al., 2017), echoing previous findings in ADHD regarding the central executive's mediation of more complex problem solving via elementary numerical skills (Friedman et al., 2018). Given that WM is important for maths in children, and that difficulties in WM are documented in many children with ADHD, it is important to investigate associations between WM and the factual, conceptual, and procedural components in this population.

Evidence derived from neurotypical populations also supports the role of cognitive processes without strong executive elements in some maths components Cragg and colleagues (2017) found that although both verbal STM and visuospatial STM accounted for unique variance in factual knowledge, visuospatial STM also predicted procedural skill. This suggests that phonological rehearsal is particularly important for learning and retrieving basic arithmetic facts, whilst spatial span is critical for factual retrieval and more complex maths computations. STM uses linguistic and spatial codes to cultivate networks for learned information in memory, such as basic arithmetic facts (e.g., 1 + 2 = 3), operational strategies (e.g., -/ +), and solution procedures (e.g., borrowing/carrying), which should eventually become well embedded in long term memory and automatized upon utilisation (Dehaene & Cohen, 1995; Geary, 2004). Lastly, visuospatial processing speed was found to account for unique variance in factual fluency and concept comprehension, but not procedural skill, further suggesting that this construct may be more important for basic numerical processes than more advanced computations (Fuchs et al., 2006).

The present study

Evidently, difficulties in specific cognitive processes can lead to differential patterns of strengths and weaknesses across the factual, conceptual, and procedural components. However, their relationship to cognition in the context of ADHD remains unknown. This study sought to provide a comprehensive investigation of cognitive and behavioural correlates of maths skills in ADHD. Although correlation does not necessarily mean causation, it is a crucial pre-requisite to identifying pathways of impairment and for informing predictive models (Kofler et al., 2020). The current study provides a holistic examination of the relationship between behaviour, maths, and cognition in a drug naïve, clinically referred, sample of children with high ADHD symptoms. Specifically, prospective correlates of (1) maths attainment, and (2) the factual, conceptual, and procedural maths components, were examined. These included previously implicated cognitive constructs of EF, memory, and processing speed. Additionally, due to evidence surrounding the role of ADHD symptoms in maths achievement (for review see Tosto et al., 2015), coupled with the novelty of the componential nature of maths being assessed here, the associations between inattention and hyperactivity/impulsivity with all maths outcome measures were also explored. Identifying the differential associations between ADHD symptoms, cognition and maths components can help illuminate more specific difficulties experienced by children with ADHD that are otherwise masked by broad achievement tests. This will be imperative in informing practitioner decision making and in the selection of tailored intervention options to remedy maths difficulties. The present study sought to address the following hypotheses:

1. Given the previously marked associations between inattention and maths, it was expected that maths outcome measures would yield stronger associations with symptoms of inattention than hyperactivity impulsivity (Tosto et al., 2015).
2. Based on existing literature it was predicted that maths attainment and maths components would strongly correlate with EF, memory, and processing speed (Cragg et al., 2017; Gathercole et al., 2018; Holmes et al., 2014). Due to the lack of research on maths components in ADHD, mixed findings in neurotypical children, coupled with the disorder-general approach used here, no specific predictions were made for differential association between individual cognitive and maths outcome measures.

4.2 Method

4.2.1 Participants

The sample consisted of forty-four drug naïve children on the ADHD referral waiting list at the Child and Adolescent Mental Health Services (CAMHS) in NHS Lothian. Participants (31 male) were aged 6 to 12 years (M = 101.34 months, SD = 19.39). Of these, thirty children were in Primary 2 to Primary 4 at school (M = 90.47

months, SD = 10.25), and fourteen were in Primary 5 to Primary 7 (M = 124.64 months, SD = 12.33). Children came from a variety of socioeconomic backgrounds with equal proportions of children (45%) from the two most deprived and two least deprived areas as per the Scottish Index for Multiple Deprivation (SIMD) quintiles.

ADHD symptoms were based on parent ratings on the Conners Parent DSM-5 ADHD subscales (Conners, 2008). Forty-one children scored high on both ADHD-Inattention and ADHD-Hyperactivity/Impulsivity scales, whilst one child score high only on the ADHD-Inattention scale and two children had elevated scores only on the ADHD- Hyperactivity/Impulsivity scales. As indicated by the Conners, a substantial proportion of children showed co-occurring externalising disorder symptoms of ODD (79%) and CD (75%). Around a third of children also showed high co-occurring ASD (27%) traits as per the AQ-10, and approximately half showed high movement difficulties (56%) as measured by the Movement-ABC Checklist. Most of the sample (81%) were also rated as having high emotional and behavioural difficulties on the SDQ. Children were excluded if they had (1) a primary language other than English, (2) current or previous stimulant medication use, (3) a known chromosomal condition, (4) an IQ score ≤ 70 on both IQ measures, or (5) a score within the typical range (< 60) on both Connrs Parent DSM-5 ADHD subscales. All parents and children provided consent/assent before participating. Favourable ethical opinion was obtained prior to data collection from the North West Haydock Research Ethics Committee.

4.2.2 Materials

4.2.2.1 Parent questionnaires

Parents/carers of children completed the Conners 3 Parent (Conners, 2008) as a measure of ADHD, ODD, and CD. Parents were presented with 108 statements and asked to rate how well each item described their child's behaviour in the past month (0 = Not true at all, 3 = Very much true). Scores comprised four DSM-5 Symptom scales for ADHD-Inattention, ADHD-Hyperactivity/Impulsivity, CD, and ODD. A T-score ≥60 reflected an atypical level of symptoms and was used as a cut-off for more symptoms of the disorder than is typical for the child's age.

The AQ-10 was used to index autistic traits in the sample (Allison et al., 2012). Parents/carers indicated the extent to which they agreed or disagreed with ten statements in relation to their child's behaviour. A score > 6 was used as a cut off for considering referral for a specialist diagnostic assessment for autism.

The Movement ABC-2 Checklist (Schulz et al., 2011) was used to obtain parents'/carers' views about children's movement in day-to-day settings. Children were scored as having either a serious movement difficulty (≥ 95th percentile), at risk for having a movement difficulty (85th – 94th percentile) or no movement difficulty (< 85th percentile).

The SDQ (Goodman, 2001) was used as a brief behavioural and emotional screening tool for assessing emotional and behavioural difficulties in participants. Parents/carers rated how relevant each statement was to their child's behaviour over the past six months. A score of ≥17 e reflected higher emotional and behavioural difficulties (Goodman, 2001).

4.2.2.2 IQ

The Wechsler Abbreviated Scale of Intelligence-II (WASI; Wechsler, 2011) was used as a measure of general intellectual functioning via four subtests: Block Design, Vocabulary (expressive), Matrix Reasoning, and Similarities. A FSIQ score was generated from all four subtests as an index of general IQ. The British Picture Vocabulary Scale (BPVS; Dunn & Dunn, 2009) was used to provide an index of receptive vocabulary IQ (Dunn & Dunn, 2009). Children with a BPVS and WASI-II Full-Scale IQ score ≤ 70 were deemed as potentially having an intellectual disability and were thus excluded from the study. All scores were age standardised.

4.2.2.3 Cognitive tasks

Participants completed eight tasks from the Cambridge Neuropsychological Test Automated Battery (CANTAB®, 2018) on a touch screen iPad and one assessment from the Wechsler Intelligence Scale for Children – Fifth UK Edition (WISC-V). All outcome measures from the CANTAB were selected based on “key variables” identified by the software providers’ manual and consolidation of previous literature in ADHD (e.g., Coghill et al., 2018; Fried, et al., 2015; Gau & Shang, 2010). The cognitive tasks, as well as their respective outcome measures and domains, are summarised in Table 4.1.

Table 4.1 Cognitive tasks and domains

Task	Outcome measure	Domain
Stop Signal Task	Stop signal RT	Inhibitory control
	Stop signal median RT	Processing speed
Intra-Extra Dimensional Set Shift	Intra-Extra dimensional errors	Cognitive flexibility/set shifting
Stockings of Cambridge	Problems solved in minimum moves	Planning
Spatial WM	Between Search Errors	Visuospatial WM updating
	Strategy (6-8 boxes)	Visuospatial WM strategy
Delayed Matching to Sample	% Correct responses on 12s delay trials	Delayed short term recognition memory
Spatial Span	Spatial span forwards length	Visuospatial STM
	Spatial span reverse length	Visuospatial WM
Verbal Recognition Memory*	Immediate recognition accuracy	Immediate verbal recognition memory
	Delayed recognition accuracy	Delayed verbal recognition memory
Letters Numbers Sequencing	Maximum letter number sequence accurately recalled	Verbal WM updating

*This task was administered only to those aged 8 years and over

Inhibitory control. The Stop Signal Task was used to assess children's response inhibition. Participants responded to an arrow pointing in either left or right direction by pressing corresponding buttons. Responses had to be withheld if an auditory signal is heard. The key outcome measure was the stop signal reaction time (SSRT) in milliseconds (ms) – the length of time between go stimulus and stop stimulus at which the children successfully withheld their response on 50% of trials (lower is better).

Cognitive flexibility. The Intra-Extra Dimensional task measured attentional set-shifting – the ability to flexibly switch attention between different stimuli characteristics. Participants selected abstract shapes and were prompted to learn rules regarding their choices via audio feedback. Once a rule was learned, the stimuli and/or rules are changed, and participants had to shift attention to previously trivial stimulus attributes. The key outcome measure was the total number of times that an incorrect stimulus was selected, adjusted for every stage that was not reached (Intra-Extra Dimensional Errors; lower is better).

Visuospatial WM updating and strategy. The Spatial WM task examined visuospatial WM with updating. Participants were shown square 'boxes' and were asked to find a concealed token by looking in each box, with the caveat that once found, a token will not be hidden in the same box twice. The number of boxes increases from 4, 6, and 8 items. Key outcome variables were (1) number of times participant incorrectly revisited a box in which a token was previously found (Spatial WM Between Search Errors; lower is better), and (2) number of times participant began a new search pattern from the same box previously started with on 6-8 box trials, whereby the same starting point indicates a planned strategy for finding the tokens (Spatial WM Strategy; a low score indicates high strategy use).

Verbal WM updating. Letter Number Sequencing (WISC-V) measured verbal WM updating. Participants listened to randomly presented letters and numbers and had to recite the numbers in ascending numerical order and the letters in alphabetical order. The total number of items increased from 2 to 8. The key outcome variable was children’s scaled score for the total number of trials (max = 30) for which the letters numbers sequence was correctly recited.

Planning. The Stockings of Cambridge task assessed children's ability to monitor, evaluate, and update a sequence of planned moves. Participants copied a model pattern of three stacked coloured balls using a prespecified minimum number of moves ranging from 2, 3, 4 and 5. The key outcome measure was the total number of problems solved in the minimum possible number of moves (Stockings of Cambridge Problems Solved; higher is better).

Visuospatial STM and WM. The Spatial Span task indexed visuospatial STM storage and visuospatial WM. Participants reproduced the order in which boxes change colour in a forward sequence (Spatial Span Forwards; visuospatial STM) and in reverse sequence (Spatial Span Reverse; visuospatial WM). The number of boxes increased from two to nine items, depending on the child's progress. The outcome measure was the maximum correct span length (higher is better).

Delayed short term recognition memory. The Delayed Matching to Sample assessed delayed short-term visual recognition memory. Participants selected a previously presented pattern from a choice of four patterns shown either simultaneously or at 0, 4, and 12 second delays. The outcome measure was percentage of trials on which participants correctly responded upon first attempt on 12s delays (Delayed Matching to Sample % Correct 12s where higher is better).

Verbal recognition memory. The Verbal Recognition Memory task assessed immediate and delayed memory for verbal information. Participants were shown 12 words sequentially and were asked to indicate previously presented words from a list of 24 words. Following a 20-minute delay, children were once again invited to select previously presented words from a list of 24 words. Outcome measures were the total number of distinct words participant correctly recalled immediately after presentation

(Immediate Verbal Recognition Memory higher is better), and (2) following a 20-minute delay (Delayed Verbal Recognition Memory; higher is better). This task required children to be able to read words and, as such, was only administered to children aged over 8 years.

Processing speed. Children's processing speed was indexed using Stop Signal task (described above). The median RT (ms) on all Go trials in the task was the key outcome measure (Stop Signal Task Median RT All Go Trials; lower is better).

4.2.2.4 Maths tasks

All tasks relating to the assessment of children's maths competencies are presented in Table 4.2.

4.2.2.4.1 Maths achievement

Maths achievement was assessed using the Wechsler Individual Achievement Test (WIAT®-III; Wechsler, 2017) subtests: Mathematics Problem Solving, Numeracy, and Maths Fluency. The Mathematics Problem Solving subtest required children to solve orally presented word problems comprising items relating to time, money, measurement, geometry, probability or reading graphs. The Numeracy subtest measured written maths calculation across basic skills, basic operations with integers, geometry, algebra, and calculus. The Maths Fluency subtests measured written maths calculation fluency under timed conditions across addition, subtraction, and multiplication sums. The three fluency subtests were combined provide a composite standard Maths Fluency score. Standardised scores for Mathematics Problem Solving, Numeracy, and Maths Fluency were used as the key outcome measures of achievement.

Table 4.2 Maths tasks and domains

Task	Outcome measure	Domain
Wechsler Individual Attainment Test (WIAT)		
Mathematics Problem Solving	Total accuracy	Maths problem solving
Numeracy	Total accuracy	Numerical operations
Maths Fluency (addition, subtraction, and multiplication*)	Total accuracy	Arithmetic fluency
Maths component skills		
Factual knowledge	Total accuracy	Knowledge of addition and subtraction facts
Conceptual understanding	Total accuracy	Understanding and applying conceptual principles
Procedural skill task	Total accuracy	Procedural computations accuracy
	Mean RT for accurate trials	Procedural computations efficiency

*This task was administered only to those aged 8 years and over

4.2.2.4.2 Maths components

Factual knowledge. The factual knowledge task (adapted from Cowan et al., 2011 and Simms et al., 2015) assessed knowledge of arithmetic facts. Children were asked to quickly solve single digit addition sums, each presented on the screen for four seconds. To eliminate potential floor or ceiling effects items of varying difficulty were presented depending on the child’s year at school, such that they were easy enough to solve for their expected level. Children in Primary two to Primary 4 (ages 6 to 9 years) received single digit addition sums with answers below 10 (e.g., 3 + 5 =?). Children in Primary 5 to Primary 7 (ages 9 to 12 years) received addition problems that exceeded an answer of 10 but were below 20 (e.g., 7 + 7 =?). The outcome measure was the total number of correct responses provided within the four seconds limit (max = 12).

Conceptual understanding. The conceptual understanding task (adapted from Cowan et al., 2011 and Simms et al., 2014) assessed children's understanding and application of maths concepts. Participants were presented with double-digit addition and subtraction sums on the screen with its answer (e.g., 31 + 45 = 76). After 6 seconds, another related sum appeared below it but this time without an answer (e.g., 76-45 =?). Children were asked to use the first sum to help solve the second sum. Children were presented with 12 experimental trials in total, three for each conceptual principle: double plus one (e.g., 42 + 42 = 84, 42 + 43 =?), related by commutativity (e.g., 48 + 21 = 69, 21 + 48 =?), related by inversion (e.g., 79-17 = 62, 62 + 17 =?) and identical (e.g., 56-27 =29, 56-27 =?). Children had 6 seconds to provide an answer for the second sum. The problems were designed in a way that children were unlikely to be able to solve the sum within this time limit unless they relied on conceptual insight. Children in Primary 2 to Primary 4 were presented with double digit sums, while those in Primary 5 to Primary 7 were presented with a mixture of double-digit and three-digit numbers. The outcome measure was the total number of correct responses provided within the time limit (max = 12).

Procedural Skill. The procedural skills task (Cragg et al., 2017) assessed children's ability to execute maths procedures accurately and efficiently. Children received 10 experimental trials comprising school level-appropriate addition and subtraction operations using single and double-digit numbers. Children were instructed to provide their answer as quickly as they can. Children in Primary 2 to Primary 4 were presented with addition and subtraction sums with solutions below 20 (e.g., 8 + 9 =? 14-8 =?), while those in Primary 5 to Primary 7 were presented with more difficult sums exceeding solutions of 15 (e.g., 8 + 26 =?; 45-24 = ?) The outcome measures were the total correct responses (i.e., accuracy max = 10) and the mean RT in seconds for correctly answered trials (i.e., efficiency). The mean RT scores were reverse scored so that higher score indicated better performance.

4.2.3 Procedure

Testing was conducted across two or more sessions depending on individual child's needs, with a total testing duration of approximately 3 hours. The second visit was typically conducted at the child's school in a quiet room, on average 15 days after the first visit. The number of days between the first and second visit ranged between 1 day and 53 days. Regular breaks were provided to minimise fatigue and maintain compliance. Testing typically took place either at the child's home (first session) or at school (second session). During the first session children completed the eight game-like CANTAB tasks on an iPad, and the parent/carer completed the questionnaires. The second session was typically conducted at the child's school in a quiet room. During the second session children completed assessments of maths, IQ, and the Letters Numbers Sequencing task.

4.2.4 Data preparation

Due to wide age-range of participants in the sample it was important to account any age differences within the analyses. Any assessments that were not previously standardised according to normative data within administration manuals were standardised prior to analyses. The maths component tasks contained different age-appropriate task content for children in Primary 2 to Primary 4, and those in Primary 5 to Primary 7 to avoid floor or ceiling effects. Children's raw scores were transformed into *z*-scores based on scores from others in their year group. Raw scores on the CANTAB assessments were transformed into *z*-scores for further analyses based on age as paediatric normative data for the CANTAB version used in this study was not available at the time of data analysis. The following variables comprising measures of impairment were reverse scored so that higher score indicated better performance: Stop Signal Task Median RT All Go Trials, Intra-Extra Dimensional Errors, Spatial WM Errors, Spatial WM Strategy.

4.2.5 Analyses

Analyses were conducted using IBM SPSS Statistics 24. Distribution of each variable was checked using skewness and kurtosis *z*-scores which is deemed as an appropriate method for small sample sizes ($n< 50$; Field, 2018; Kim, 2013; Tabachnik & Fidell, 2013). As some of the variables were not normally distributed, correlational analyses were implemented using the more conservative nonparametric statistical test of Spearman's rho correlation coefficient, which reduces inflation under non-normal distributions (Bishara & Hittner, 2015; Field, 2018; Kim, 2013). All statistical tests were two tailed, with an alpha significance level of $p < .05$. To decrease false-positives due to multiple correlations on all maths outcome variables, the Benjamini-Hochberg correction[11] was applied using a false discovery rate of 0.05 to determine significance (Benjamini & Hochberg, 1995). Each outcome measure was ranked by ascending order of original *p* value (from most significant to least significant). A rank value was then assigned to each outcome measure and the Benjamini-Hochberg critical *p* value

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[11] Thank you to Sarah McGeown for suggesting taking this approach.

was calculated ((I/M) *Q; where I = rank, M = total number of tests, and Q =discovery rate). Original *p* values were compared with the Benjamini-Hochberg critical *p* value. The largest *p* value that was smaller than the Benjamini-Hochberg critical *p* value was identified and all values above it was considered as statistically significant.

4.2.6 Power analysis

A medium-large effect size was expected based on previous association between ADHD and maths (e.g., Alloway, 2011; Friedman et al., 2018) and ADHD and cognition (e.g., Fried et al., 2105; Gau & Shang, 2010). A priori power analysis using G*Power was conducted to test two-tailed correlations between variables using a medium (*d* = .30), and large (*d* = .50) effect size (Faul et al.,2007). Results showed that to achieve power of 0.8, a total sample of 29 participants would be necessary to detect a large effect size, and 84 participants would be necessary to detect a medium effect size.

4.3 Results

4.3.1 Non-completers

Thirteen children failed to complete at least one of the maths tasks. Non completers differed in age (*t* (42) = -4.56, *p* = .000), such that younger children were less likely to complete maths observations. Completers and non-completers did not differ on any of the cognitive scores, IQ, nor on any of the parent questionnaires (all *p*'s > .05).

Fourteen children had missing data on at least one of the cognitive assessments. Non-completes were younger (*t* (39.37) = -3.61, *p* = .001) and had lower parent reported birthweight (*t* (26.59) = -3.20, *p* = .003) than those with complete cognitive data. Non-completers on cognitive assessments also had lower (i.e., less difficulties) SDQ scores (*t* (37.33) = -2.39, *p* = .022) and ODD scores (*t* (18.40) = -2.38, *p* = .028]. Lastly, children with incomplete cognitive data had lower scores on the procedural skill accuracy (*t* (29) = -2.17, *p* = .039) and efficiency (*t* (29) = -3.37, *p* = .002) than completers. Completers and non-completers did not differ on the remaining measures (all *p*'s > .05).

4.3.2 Descriptive statistics and correlations

Principal descriptive statistics are reported in Tables 4.1 and 4.2. Spearman's rho zero order correlations between variables assessing maths, parent reported symptoms of ADHD-Inattention and ADHD-Hyperactivity/Impulsivity, and key outcome measures of cognition are presented in Table 4.3 (see Appendix D and Appendix E for all other inter-correlations). Due to the small number of participants, effect sizes are also reported (medium $r \geq .30$; large $r \geq .50$) of correlations relating to the hypotheses, rather than only focusing on statistical significance levels (Field, 2018). To date, maths components have not been investigated in the context of ADHD. As such, associations between the components and broader maths achievement are briefly reported. Based on previous arguments against using IQ as a covariate in assessments of neurocognitive function, IQ was not included as a covariate in the analysis (Antonini et al., 2016; Dennis et al., 2009). Additionally, differences in age were already accounted for in the standardisation of scores and, thus, age was not included as a covariate (McDougal et al., 2020)[12].

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[12] The correlations between age and FSIQ with all cognitive and maths variables can be found in Appendix D and Appendix E.

Table 4.3 Descriptive statistics for parent questionnaires, IQ, and maths tasks

	N	Min-Max	Mean	SD
Parent questionnaires of ADHD and co-occurring symptoms				
Conners ADHD-Inattentive T-score[1]	44	51-90	81.41[a]	10.43
Conners ADHD-Hyperactive/Impulsive T-score[1]	44	46-90	84.66[a, c]	9.01
Conners Conduct Disorder T-Score[1]	44	43-90	71.36	15.00
Conners Opposition Defiant Disorder T-Score[1]	44	44-90	77.41[a]	16.33
Autism Quotient-10 Total	44	0-10	4.43	2.77
Movement-ABC Checklist Total	43	0-60	19.21	15.65
Strengths and Difficulties Questionnaire Total	44	12-36	22.32	6.12
IQ[1]				
WASI Full Scale IQ	42	75-125	97.64	12.89
BPVS IQ	43	72-120	95.60	11.97
Maths achievement[1]				
WIAT Mathematics Problem Solving	44	66-121	92.32	12.24
WIAT Numeracy	44	67-120	92.30	11.52
WIAT Fluency Composite	43	67-124	90.98[b]	13.01
Maths components[2]				
Factual Knowledge Total Correct	39	2-12	7.62	3.07
Conceptual Understanding Total Correct	38	0-12	6.79	4.01
Procedural Skill Accuracy Total Correct	31	1-10	5.74	2.90
Procedural Skill Efficiency (RT)	31	3.61- 27.55	11.78[b]	6.30

a. Negative skew ($Z_{skewness}$ > -1.96); [b]. Positive skew ($Z_{skewness}$ > + 1.96); [c]. High kurtosis ($Z_{skurtosis}$ > 1.96). *WASI* Wechsler Abbreviated Scale of Intelligence; BPVS British Picture Vocabulary Scale; WIAT Wechsler Individual Achievement Test

[1] Scores standardised based on age

[2] Raw scores presented in this table for ease of interpretation/descriptive purposes.

Table 4.4 Descriptive statistics for cognitive tasks (raw) [1]

	N	Min-Max	Mean	SD
Stop Signal Task Stop Signal RT (ms)	43	227.25-486.95	366.58	76.37
Intra-Extra Dimensional Errors	43	12- 217	55.12[b, c]	33.67
Spatial WM Between Search Errors	40	0- 35	20.60[a, c]	7.54
Spatial WM Strategy	40	5-14	9.25	1.72
Letters Numbers Sequencing Scaled Score	36	3-14	7.33	3.24
Stockings of Cambridge Problems Solved	41	2-9	5.37	1.80
Spatial Span Reverse	41	2-7	3.90	1.45
Spatial Span Forwards	43	2-8	4.23	1.59
Delayed Matching to Sample % Correct (12s delays)	40	0-100	51.50	26.37
Immediate Verbal Recognition Memory	23	13-36	28.43	5.97
Delayed Verbal Recognition Memory	22	22-36	29.91	4.12
Stop Signal Task Median RT	43	422-721	575.31	71.38

[a]. Negative skew ($Z_{skewness} > -1.96$); [b]. Positive skew ($Z_{skewness} > 1.96$); [c]. High kurtosis ($Z_{skurtosis} > 1.96$)

[1] Raw scores presented in this table for ease of interpretation/descriptive purposes.

Table 4.5 Correlations between maths, cognition and parent reported ADHD symptoms[1]

	Maths Problem Solving	Numeracy	Maths Fluency	Factual Knowledge Accuracy	Conceptual Understanding Accuracy	Procedural Skill Accuracy	Procedural Skill Efficiency
ADHD-Inattentive	.117	-.124	.093	-.055	.171	.268	.127
ADHD-Hyperactive/Impulsive	-.113	-.174	-.159	-.317*	-.028	-.239	-.222
Stop Signal Task Stop Signal RT (ms)	.172	.013	-.121	.004	.227	-.004	-.336
Intra-Extra Dimensional Errors	.179	.288	.174	.295	.027	.263	.357*
Spatial WM Between Search Errors	.382*◊	.441**◊	.341*	.271	.031	.304	.407*
Spatial WM Strategy	-.153	-.090	.103	.369*	-.041	.295	.361
Letters Numbers Sequencing Scaled Score	.696**◊	.459**◊	.441**	.336	.633**◊	.371*	-.004
Stockings of Cambridge Problems Solved	-.172	-.069	-.164	-.107	-.164	-.019	.345
Spatial Span Reverse	.520**◊	.417**◊	.340*	.392*	.289	.405*	.373*
Spatial Span Forwards	.215	.203	.162	.291	.084	.365*	.162
Delayed Matching to Sample % Correct (12s)	.398*◊	.282	.173	.364*	.283	.187	-.146
Immediate Verbal Recognition Memory	.653**◊	.594**◊	.494*	.719**◊	.681**◊	.565**	.607**◊
Delayed Verbal Recognition Memory	.554**◊	.513*◊	.586**	.488*	.670**◊	.487*	.505*
Stop Signal Task Median RT (all trials)	.298	.211	.359*	.205	.054	.148	.292

* *p* < .05, ** *p* < .01, ◊ significant effect after Benjamini-Hochberg correction.

Stop Signal Task Stop Signal RT = inhibitory control; *Intra-Extra Dimensional* = set shifting; *Spatial WM* = WM updating; *Letters Numbers Sequencing* =verbal WM; *Stockings of Cambridge* = planning; *Spatial Span Reverse* =visuospatial WM; *Spatial Span Forwards* =visuospatial STM; *Delayed Matching to Sample* =visuospatial short term recognition memory; *Stop Signal Task Median RT* =processing speed.

[1] Correlations are based on z-scores .

4.3.2.1 Maths achievement and components

Achievement scores on the WIAT Mathematics Problem Solving subtest showed positive correlations with factual knowledge (r = .565, p < .001), conceptual understanding (r = .625, p < .001), and procedural accuracy (r =.733, p < .001) and efficiency (r = .373, p = .039). Similarly, achievement scores on the WIAT Numeracy subtest showed a positive correlation with factual knowledge (r = .636, p < .001), conceptual understanding (r = .459, p = .004), and procedural accuracy (r =.605, p < .001) and efficiency (r = .491, p = .005). Maths Fluency achievement scores were positively correlated with factual knowledge (r = .501, p = .001), conceptual understanding (r = .343, p = .035), and procedural accuracy (r =.555, p = .001) and efficiency (r = .511, p = .003).

4.3.2.2 ADHD symptoms and maths

Maths Achievement. Children's scores on the WIAT Mathematics Problem Solving, WIAT Numeracy, and WIAT Maths Fluency achievement tests did not strongly correlate with parent-rated symptoms of hyperactivity/impulsivity nor inattention (r's < .30).

Maths Components. There was a negative correlation between accuracy on the factual knowledge task and parent-rated symptoms of hyperactivity impulsivity (r = -.317, p = .049). This association was no longer statistically significant following Benjamini-Hochberg correction. All other associations between ADHD symptoms and maths components were non-significant (p's> .05, r's< .3).

4.3.2.3 Cognition and maths

Maths Achievement. Achievement scores on the WIAT Mathematics Problem Solving subtest significantly correlated with Spatial WM Between Search Errors (*r* = .382, *p* = .015) and Letter Number Sequencing (*r* = .696, *p* < .001). WIAT Mathematics Problem Solving also showed significant associations with scores on Spatial Span Reverse (*r* = .520, *p* = .001), Delayed Matching to Sample (*r* = .398, *p* = .011), Immediate (*r* = .653, *p* =.001) and Delayed Verbal Recognition Memory (*r* = .554, *p* =.007).

Children's WIAT Numeracy scores were positively related to Spatial WM Between Search Errors (*r* = .441, *p* = .004) and Letter Number Sequencing (*r* =.459, *p* = .005). Numeracy attainment scores were also significant correlated with Spatial Span Reverse (*r* = .417, *p* = .007), and Immediate (*r* = .594, *p* =.003) and Delayed Verbal Recognition Memory (*r* =.513, *p* =.015).

Achievement scores on Maths Fluency did not show significant associations with any of the cognitive outcome measures following Benjamini-Hochberg corrections. Moderate effect size associations were found for Spatial WM Between Search Errors (*r* = .341), Letter Number Sequencing (*r* = .441), Spatial Span-Reverse (*r* =.340), Immediate (*r* =.494) and Delayed Verbal Recognition Memory (*r* = .586) as well as Stop Signal Task Median RT (*r* =.359).

Maths Components. Accuracy on the factual knowledge task was significantly associated with Immediate Verbal Recognition Memory (*r* = .719, *p* < .001). All other associations were not significant following Benjamini-Hochberg corrections. Moderate effect size associations were found between factual knowledge accuracy and Spatial

WM Strategy (*r* = .369), Spatial Span Reverse (*r* = .392), Letter Number Sequencing (*r* =.336) and Delayed Verbal Recognition Memory (*r* =.488, *p* =.025).

Scores on the conceptual understanding task significantly correlated with Letter Number Sequencing (*r* = .633, *p* < .001), as well as Immediate (*r* = .681, *p* = .001) and Delayed Verbal Recognition Memory (*r* = .670, *p* =.001). All other associations between cognition and conceptual understanding were non-significant (*p*'s > .05, *r*'s < .3).

Accuracy scores on the procedural skill task did not show significant associations with any of the cognitive outcome measures following Benjamini-Hochberg corrections. Moderate effect size associations were found for Spatial WM Between Search Errors (*r* = .304), Letter Number Sequencing (*r* = .371), Spatial Span Forwards (*r* =.365) and Reverse (*r* = .405), as well as with Immediate (*r* =.565, *p* =.008) and Delayed Verbal Recognition Memory (*r* =.487).

Efficiency RT scores on the procedural skill task generated a significant association with Immediate Verbal Recognition Memory (*r* = .607). All other correlations were not statistically significant following Benjamini-Hochberg correction. Moderate effect size associations were found with Stop Signal Task RT (*r* = -.336), Intra-Extra Dimensional Errors (*r* = .357), Spatial WM errors (*r* =.407) and strategy use (*r* = .361), Stockings of Cambridge Problems Solved (*r* =.345), Spatial Span-Reverse (*r* =.373, *p* = .043), as well as Immediate (*r* = .505, *p* = .019) and Delayed Verbal Recognition Memory (*r* = .505).

4.4 Discussion

The present study provided a comprehensive investigation of the relationship between cognitive constructs and ADHD symptoms with maths performance in a well characterised, drug naïve, sample of children with high ADHD symptoms. Contrary to the hypothesis, symptoms of inattention did not yield meaningful associations with children's maths performance. Findings generally showed that cognitive functioning positively correlated with both standardised maths attainment scores and more specific maths skills. The present findings suggest that cognition, rather than behavioural ADHD symptoms, are more informative for characterising maths performance. In particular, verbal and visuospatial aspects of memory functioning showed the strongest associations with maths across the board. Although inferences are correlational, these imply that verbal and visuospatial memory domains could be particularly important for supporting maths performance in children with high ADHD symptoms and represent viable targets for future research on maths in ADHD.

4.4.1 Maths and ADHD symptoms

The current findings failed to show meaningful associations between parent-rated ADHD symptoms with any of the maths outcome measures. This contrasts with previous studies identifying symptoms of inattention as closely affiliated with maths performance in ADHD (Tosto et al., 2015). Previous studies demonstrating a negative association between inattention symptoms and maths rely on teacher ratings of behaviour (e.g., Rogers et al., 2011; Thorell, 2007). ADHD symptom manifestations and ratings will vary across the home and school settings in line with environmental demands (Narad et al., 2015). Thus, it is possible that teacher ratings of inattention symptoms are more closely aligned to the contextual demands of the academic performance assessments used here than that of parent-based ratings, which are more closely affiliated with behavioural inattention in the home environment. Further, although other studies report significant associations of maths performance with both parent and teacher ratings of inattention, cognitive factors tend to mediate this relationship (e.g., Antonini et al., 2016; Gremillion & Martel, 2012). As such, the present findings add to the growing notion that common cognitive pathways, rather than clinical diagnosis, could be more informative for maths difficulties in ADHD (Astle et al., 2019; Gathercole et al., 2018).

4.4.2 Maths and cognition

Maths achievement. In line with previous findings standardised attainment scores on the WIAT showed positive associations with tasks tapping into visuospatial WM and verbal WM processes (Alloway, 2010; Antonini et al., 2016; Gathercole et al., 2018; Gremillion & Martel, 2012; Sturm et al., 2018). This implies that storage, manipulation, and active updating of phonological and visuospatial information is linked to performance on attainment tests. To illustrate, the Mathematics Problem Solving subtest required children to listen to orally presented problems, identify, and hold the most relevant phonological information ‘online’, whilst concurrently trying to solve the problem, and updating previously held information with the newly identified solution (Bull & Lee, 2014; Cragg et al., 2014). As well as mobilising these critical verbal WM processes, children relied on visuospatial stimuli, such as coloured pictures, shapes, and graphs to accommodate problem solving. Plausibly, visuospatial WM processes were engaged to retain, update, and manipulate relevant visuospatial information in a similar manner (Fung & Swanson, 2017). Furthermore, all three of the WIAT subtest will have capitalised on children’s ability to solve simple arithmetic sums (e.g., Numeracy: 5 + 1 + 5 + 2 =? Fluency 1 + 2 =?). Successful navigation of such sums relies on children's memory for well-established phonological codes for relevant arithmetic facts (Dehaene, 1992; Holmes & Adams, 2006). Children with limited WM storage capacity likely experience interference and consequently forget accurate answers (Cragg et al., 2017). Some items required children to hold an interim solution online (i.e., 5 + 1 = 6) whilst computing another part of the sum (e.g., 5 + 2 = 7) and updating any old computations with the most appropriate answer (e.g., 6 + 7 = 13). Additionally, visuospatial WM processes were likely engaged for more complex aspects of numerical computations requiring identification of inverse relationships between addition and subtraction operations, borrowing and carrying procedures, as well as spatial organisation and alignment of digits on columnar problems (Bull, 2008).

It is possible that the association between verbal and visuospatial WM tasks with attainment scores were driven by the inherent involvement of the central executive (Friedman et al., 2018). However, scores on the Spatial Span Reverse task which assessed visuospatial WM without updating requirements showed even stronger correlations with standardised attainment scores than the Spatial WM task which taxed visuospatial WM updating. These findings are consistent with previous research implicating objective measures of both storage, manipulation, and updating and of verbal and spatial information as important to maths achievement tests (Alloway 2011; Gremillion & Martel, 2012; Holmes et al., 2014).

The present findings also implicate other modality-specific storage processes in children's maths attainment. For example, delayed recognition memory for visuospatial information, as indexed by the Delayed Matching to Sample task, substantially correlated with the Mathematics Problem Solving subset, but not with

Numeracy or Fluency subtests. This suggests that retaining relevant visuospatial information in memory over a delay plays a particularly important role in children's problem-solving where pictorial stimuli are used. Contrary to this, immediate and delayed verbal aspects of memory were related to all aspects of children's attainment scores to which basic arithmetic was fundamental. This implies that children rely more heavily on the phonological loop to retrieve verbal codes for numerical information. Indeed, previous research shows that during Mathematics Problem Solving children employ the phonological loop to convert visually presented quantitative information into verbal codes (Rasmussen & Bisanz, 2005). Additionally, many of these tasks likely relied on children's basic knowledge of arithmetic facts necessitating successful retrieval of phonological codes for well-established arithmetic fact solutions from long term memory (Geary, 2004).

Processing speed, indexed by the Stop Signal Task Median RTs, showed a moderate association with the Maths Fluency assessment, requiring children to solve simple arithmetic sums under timed conditions. Processing speed promotes faster counting skill thereby reducing decay of information in online WM during calculations and facilitates development of arithmetic problem associations in memory (Cirino et al., 2015; Fuchs et al., 2006; 2008; 2010; Geary, 2011). The association between processing and Numeracy failed to reach a notable effect size. Studies with neurotypical children indicate that processing speed is more closely associated with basic arithmetic fact retrieval than more complex procedural computations such as those found in the Numeracy subtest (Andersson 2010; Cowan & Powell, 2014; Cragg et al., 2017). The association between Mathematics Problem Solving and processing speed approached a moderate effect size (= .298). Clark and colleagues (2014) suggested that processing speed is especially critical for facilitating fast retrieval or activation of math-related information (e.g., shapes, words, or digits) but as children develop, higher order executive processes are employed for more complex problem solving. This parallels studies showing that processing speed directly relates to children's basic arithmetic fluency, and indirectly to more advanced problem solving (Fuchs et al., 2006; 2008; 2010; Rose et al., 2011). Although some studies show that children's processing speed is a viable predictor of maths achievement independent of WM, these associations may have been exaggerated due to numerically oriented measures of processing speed (e.g., Bull & Johnston, 1997; Geary, 2011; Sturm et al., 2018). The current findings extend support for the role of processing speed even in the absence of numerical stimuli. Where a larger sample size allows, it would be interesting to assess its direct/indirect contributions in the context of more complex maths skills.

*Maths components***.** Echoing previous findings in a neurotypical population, factual knowledge was moderately associated with visuospatial WM and verbal WM processes (Cragg et al., 2017). This finding is in line with theories suggesting that WM supports activation and retrieval of arithmetic facts in the long-term memory store, via repeated practice solving basic arithmetic sums (Cragg et al., 2017; Gremillion & Martel, 2012). The strongest association was found between immediate recognition memory and factual knowledge performance, which suggests the ability to retrieve phonological codes is especially important for fact fluency. This pattern of results is consistent with that of Holmes and Adams (2006) who demonstrated substantial associations between children's mental arithmetic and the central executive, as well as verbal and visuospatial STM processes. Factual knowledge also showed moderate effect size correlations with children's performance delayed memory tasks including delayed short-term visual recognition memory, and delayed verbal recognition memory. During maths acquisition STM helps cultivate networks for learned facts in long term memory using linguistic and visuospatial codes (Dehaene & Cohen, 1995; Geary, 2004). The findings here support the idea that children's fluid retrieval of number facts from memory (e.g., 2 + 3 = 5) is supported by activation and retrieval of spatially stored symbol representations (e.g., activation of symbol 5 when presented with digits 2 and 3), as well as phonological codes (e.g., "two plus three is five") from long term memory.

Conceptual understanding of maths principles and rules was significantly related to verbal WM, supporting previous findings by Cragg and colleagues (2017) that only verbal WM predicted conceptual understanding in a neurotypical sample. Other aspects of verbal memory, namely, immediate and delayed verbal recognition memory also showed significant associations with children's conceptual understanding. This suggest that the ability to reason and identify conceptually based numerical relationships is propagated by retrieval of phonological information from long term memory and its' active processing during computations. For example, when asked to reason on a double plus one problem such as "if 42 + 42 = 84, then 42 + 43 =?", children with high conceptual understanding likely realised that the second addend has increased by 1 (i.e., from 42 to 43) and, as such, all they have to do is to add 1 to the original answer. Identifying this conceptually based shortcut will require retrieval of phonological codes from long term memory (i.e., "four plus one is five") whilst simultaneously updating the answer in the context of the presented problem (i.e., "eighty-five"). Children with limited access to delayed memory for numerical facts may instead opt to solve the sum manually, which is more time consuming and prone to errors. Additionally, overloaded verbal WM capacity can result in overlooking or losing track of the pertinent information necessary for identifying and using these conceptually based rules successfully (Lucangeli & Carbele, 2006; Zentall et al., 1994).

Consistent with previous findings in neurotypical children, procedural skill (i.e., children's ability to execute addition and subtraction operations accurately and efficiently) showed meaningful associations with both visuospatial and verbal aspects of memory (Andersson, 2008; Cragg et al., 2017; Cowan & Powell, 2014). This suggests that more complex computations mobilise verbal and visuospatial manipulation of numerical information, as well as activation and retrieval of visuospatial and phonological codes in STM. For example, in being asked to solve 6 + 7 =? children with higher visuospatial WM capacity may opt for the decomposition strategy in which a sum is broken down into two parts: (1) 6 + 6 = 12, and (2) 12 + 1 = 13. The solution of these constituent segments will be facilitated by accurate activation and retrieval of relevant phonological and/or visuospatial codes from long term memory (i.e., 6 + 6 = 12). The maintenance of this interim solution 'online' will be supported by active rehearsal whilst the child is concurrently engaged in solving the second part of the problem (i.e., 12 + 1 = 13), and the updating of the old solution with the new ones (i.e., updating 12 with 13; Andersson, 2008; Robinson and Dube, 2013). Children with low WM capacity on the other hand will be more likely to engage in less efficient strategies such as counting on or using their fingers, which are more prone to errors. Arguably, children's factual fluency supports procedural efficiency by promoting engagement of retrieval-based strategies to minimize cognitive load imposed by finger counting or counting on (Geary, 2004; Geary et al., 1991; Lemaire & Siegler, 1995; Siegler & Shrager, 1984). Indeed, the similar pattern of findings in relation the significance of visuospatial aspects of memory performance for both factual knowledge and procedural skill supports this notion. The findings here suggest that both the retention of visuospatial information in memory as well as its executive updating could be important for supporting children’s procedural skills. The finding that delayed short-term visual recognition memory was related to factual knowledge, but not procedural skills could imply that decay of visuospatial information is particularly critical for retrieve numerical facts. Indeed, there is some evidence to suggest that although domain general updating is important for more advanced maths computations, its’ influence is exerted via domain-specific maths competencies such as retrieving relevant maths codes and operations from memory (Friedman et al., 2018).

Procedural strategy efficiency (i.e., RTs on correctly answered trials) showed a modest association with children’s inhibitory control performance. However, this was in the opposite direction – better inhibitory control performance was associated with poorer procedural task efficiency. This finding is difficult to explain, but one possibility could be that children who were less impulsive in their responses on the Stop Signal Task, took longer to solve procedural computations to ensure that the answer was correct, resulting in slower RTs for correctly answered procedures. Another explanation could be that this reflects a methodological issue in relation to the Stop Signal Task. Not only did this task take the longest to complete, but observation notes showed that many children did not like the auditory feedback that it produced. For example, if the child took too long to respond the iPad would say “Too slow” repeatedly. This, on top of the “beeps” may have frustrated many of the children and led them to provide invalid responses (e.g., tapping quickly on a specific arrow to avoid a beep/negative feedback).

Procedural efficiency showed meaningful associations with children's set shifting performance. This is consistent with previous findings showing that cognitive flexibility promotes effortless shifting between different operations (e.g., addition and subtraction), solution strategies (e.g., counting all and decomposition), notations (e.g., verbally presented digits and Arabic numerals) and different steps during more complex multistep problems (Andersson, 2010; Clark et al., 2010; Robinson & Dube, 2013; Siegeler and Araya, 2005). Cragg and colleagues (2017) found that shifting performance on a card sorting task did not show significant associations with children's procedural efficiency. Fried and colleagues (2015) proposed that traditional card sorting tests of cognitive flexibility fail to segregate shifting competence due to their dependence on WM processes and fine motor skills. Indeed, their use of the Intra-Extra Dimensional digital touch screen assessment produced more robust evidence for shifting weaknesses in children with ADHD than that of card sorting traditional tests. Nonetheless, it is possible that the relationship between set shifting, and procedural efficiency was affected by the Intra-Extra Dimensional stimuli which included visuospatial lines and shapes (Bull & Lee, 2014; Friso-van den Bos et al., 2013)

Planning also showed a notable association with procedural skill efficiency. Planning helps organise knowledge and correctly execute a sequence of steps during complex computations (Davidson et al., 1994). Plausibly, planning skills may be employed during procedural computations necessitating the organisation and execution of several steps (Rourke, 1993). Impaired planning skills are likely to impede upon children's ability to plan and keep track of a correct sequence of steps necessary more difficult computations (Dowker, 2005). A previous study showed that planning skill accounted for a unique variance in maths achievement scores of 7-year-olds neurotypical children (Cai et al., 2016). However, all three assessments used to index planning used numerical stimuli. The current findings suggest that non-numerical planning processes in children with high ADHD difficulties are related to children's ability to plan and carry out procedural computations efficiently.

The hypothesised relationship between inhibitory control, cognitive flexibility, and planning with other aspects of maths was not found. This echoes previous suggestions that inhibition and set shifting are not as important for maths performance as WM processes (Bull & Lee, 2014; Cragg et al., 2017; Friso-van den Bos et al., 2013). Additionally, although inhibition has been traditionally cited as a core feature of ADHD, more recent evidence suggests that group differences between children with ADHD and neurotypical peers yield larger effect sizes for measures of memory than inhibition (Barkley, 1997; Coghill et al., 2014). The present findings extend evidence on the less prominent role of inhibitory control difficulties in ADHD within the context of maths. Another possibility is that the involvement of inhibitory control and cognitive flexibility is domain specific. Indeed, inhibitory control tasks comprising numerical stimuli are more likely to yield significant associations with maths performance than those comprising non-numerical items (Andersson & Lyxell, 2007; Bull & Scerif, 2001; Cragg & Gilmore, 2014). Similarly, although another study found that attentional switching in children aged 7-15 years with ADHD uniquely predicted numerical operation competencies, this was indexed by switching between counting upwards and downwards (Preston, Heaton, Watson & Selke, 2009). Plausibly, navigating numbers during this task could have been confounded by children's counting abilities and thereby exaggerated associations with maths.

4.4.3 Potential role of co-occurrences

This study sought to encompass the real-life complexities of children referred to CAMHS clinics for ADHD evaluation, where high rates of co-occurrences with other neurodevelopmental conditions is the rule rather than the exception. As such, the preliminary implications of visuospatial and verbal aspects of memory could reflect the profile of co-occurring symptom constellations in the present sample. Parent ratings on the Conners indicated that 80% children met criteria for ODD and ratings on the Movement-ABC Checklist showed that over half of the children also had motor difficulties akin to DCD. Rhodes and colleagues (2012) found that although boys with ADHD were impaired on visuospatial aspects of memory, those with ADHD + ODD and ODD alone performed substantially worse on verbal, as well as visuospatial memory assessments. It may be plausible to suggest that ODD confers added risk to difficulties in verbal memory and the high rates of ODD symptoms here were driving the large association between verbal memory and maths. Future research may benefit from comparing cognitive and maths performance in children with ADHD with and without co-occurring ODD symptomatology to identify appropriate targets for intervention suitable for each of these presentation profiles. Furthermore, although children with DCD and ADHD have been found to be comparable on maths achievement scores, their cognitive profiles differ. Children with ADHD mainly show difficulties with verbal and visuospatial WM tasks, whilst in DCD these difficulties also extend to verbal and visuospatial storage aspects of memory (Alloway, 2011; Loh et al., 2011). Plausibly, high rates of movement difficulties in this sample contributed to the stronger associations between memory storage and maths found here. It would be interesting for future studies to compare specific memory processes associated with group differences on mathematic performance profiles of children with ADHD with and without co-occurring DCD. Together, this illustrates the effects of co-occurring conditions on memory performance and demonstrates the importance of characterising samples when addressing cognitive signatures of academic functioning.

4.4.4 Limitations

The findings of this study should be interpreted in light of several caveats. First, due to the small sample size and large number of outcome measures, the reported associations are correlational and thus no causal inferences can be made between the cognitive and maths variables. Future research would benefit from replicating these findings using a larger sample of children and extending the analysis within a predictive model. Specifically, it would be interesting to explore the extent to which cognitive factors mediate the relationship between ADHD diagnosis and children's maths outcomes.

Second, although participants were recruited via a clinic referral route, ratings of ADHD were based exclusively on parent reports. Although parent ratings yield high diagnostic accuracy, multi-setting corroboration of difficulties by teacher reports is a fundamental criterion to obtaining an accurate ADHD diagnosis (Alder et al., 2015; APA, 2013; Bied et al., 2017). Thus, the implications of the present finding should be considered within the context of children with high ADHD symptoms who, even at the subclinical level, show persisting academic disadvantages (Loe & Feldman, 2007). Such dimensional approaches are becoming increasingly recognised as more favourable than using diagnostic categories (Astle et al., 2019; Gathercole et al., 2018; Holmes et al., 2014). It is also important to note that recruitment of children at point of referral to the ADHD clinic allowed for assessment of a drug-naïve sample in the absence of confounding effects of medication treatment that would typically characterise samples with an existing diagnosis.

Third, children were tested in two very different environments. Specifically, cognitive assessments were conducted at home and after school hours, whilst the educational and IQ assessments were predominantly administered at school. As the cognitive tasks on the iPad were game-like, these were deemed as more appropriate for administration at home (where parental consent was sought) than school-based educational tasks. However, it cannot be ruled out that being asked to do 1.5 hours of cognitive testing after being cognitively engaged all day at school likely impacted children's performance. Lastly, the verbal WM measure required children to manipulate numbers and letters, potentially confounding the observed relationships with maths (Cowan & Powell, 2014).

4.4.5 Conclusions

Maths difficulties are well documented in children with ADHD, although the precise mechanisms behind these remain vague. The present study supports previous research which suggests cognitive factors could be more informative than clinical ADHD symptoms for maths attainment and, additionally, extends this notion to more intricate domains of factual knowledge, conceptual understanding, and procedural skill. To the best of the author's knowledge this represents the first comprehensive exploration of the association between cognition and more specific components of maths in the context of ADHD. The current finding demonstrate that visuospatial and verbal aspects of memory are closely affiliated with maths performance in a well characterised and diverse sample of children with high ADHD symptoms. Critically, the present finding point to the potential role of visuospatial and verbal memory processes as an important factor requiring further exploration. Additionally, it demonstrates both the overlap and divergence of the mobilised cognitive mechanisms as a function of specific maths components. Previous efforts to improve academic performance by means of psychological and pharmacological interventions result in marginal and short-lived improvements (Molina et al., 2009; Rapport et al., 2013). It may be plausible to suggest that this could be due to the incompatibility between the targeted processes and children’s underlying maths vulnerabilities (Kadosh et al., 2013). Based on the current findings, future interventions would benefit from decomposing maths performance further beyond that of generic achievement scores as any one or all three components could lead to lower attainment scores. Consequently, this can help facilitate the development of tailored remediation strategies according to children’s needs. Further, future research and intervention efforts should be carefully tuned to the clinical diversity of the underlying population This will be imperative for embracing real-life complexities of neurodevelopmental conditions.

5 Chapter 5: Cognition and maths in children with ADHD with and without co-occurring movement difficulties

Chapter 4 revealed that cognitive processes, and in particular memory processes, correlate with maths performance in children referred for ADHD evaluation. ADHD symptoms did not show meaningful associations with maths, suggesting that cognition, rather than symptoms, could be key. The chapter also revealed a high degree of co-occurrences with other developmental disorder symptoms. Of specific interest was the finding that half of the children showed high movement difficulties akin to DCD. Given the almost non-existent literature on the co-occurrences between ADHD and DCD, the focus for this chapter was to explore whether or not children with high ADHD symptoms with and without co- occurring motor difficulties vary in their cognitive and maths profiles. The chapter includes a publication under review:

Kanevski, M., Booth, J.N., Stewart, T.M., Rhodes, S.M. (2021). Cognition and maths in children with Attention-Deficit/Hyperactivity Disorder with and without co-occurring movement difficulties. *Research in Developmental Disabilities* (under review).

5.1 Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is characterised by high and persistent levels of inattention, hyperactivity, and impulsivity (APA, 2013). ADHD is diagnosed in 1-2% of children in the UK and even more children experiencing difficulties below diagnostic thresholds (Alloway et al., 2010; Russell et al., 2014; Sayal et al., 2018). Around 50% of children with ADHD meet criteria for Developmental Coordination Disorder (DCD), also known as *dyspraxia* (Brossard-Racine et al., 2012; Watemberg et al., 2007). DCD is estimated to affect between 2-6% of children in the UK (Cleaton et al., 2020; Lingam et al., 2009). DCD hinders children's development of motor coordination skills with negative consequences on daily functioning (APA, 2013). Even in the absence of clinical DCD, many children with ADHD show motor difficulties (Schoemaker et al., 2005). Both ADHD and DCD are associated with lower performance in cognitive and academic domains including maths (Daley & Birchwood, 2010; Pieters et al., 2012; Tosto et al., 2015; Wilson et al., 2020) and a co-occurring diagnosis of both during childhood significantly increases risk for poor academic outcomes in adulthood (Rasmussen & Gillberg, 2000). However, little is known about the effects of co-existence between these disorders in the context of cognitive and maths performance.

5.1.1 ADHD

Research supports a negative association between ADHD symptoms and maths performance, even after controlling for confounding factors such as IQ and medication (Tosto et al., 2015). Children with ADHD score lower on standardised achievement tests and are more likely to have a learning difficulty in maths than their neurotypical peers (Friedman et al., 2018; Gremillion & Martel, 2012; Holmes et al., 2014; Mayes et al., 2000). Children falling just below a clinical ADHD diagnosis also struggle with maths, suggesting that even subthreshold symptoms increase risk for maths difficulties (Loe & Feldman, 2007; Czamara et al., 2013).

Maths underachievement in ADHD has been linked to lower cognitive functioning (Gathercole et al., 2018; Friedman et al., 2018). Specifically, diminished performance on neuropsychological tasks assessing Executive Functions (EFs), memory, and processing speed are documented in ADHD (Coghill et al., 2014; Mayes & Calhoun, 2007; Rhodes et al., 2012; Sonuga-Barke et al., 2010; Willcutt et al., 2005) and are important for maths performance (Biederman et al., 2004; Bull et al., 2008;

Cragg et al., 2017; Dehaene & Cohen, 1995; Geary 2004; 2011; Holmes and Adams, 2006). Neurocognitive vulnerability profiles in ADHD are highly heterogenous, with marked within-group variability (Coghill et al., 2005). For example, one study found that although as a group, drug naïve boys with ADHD showed poorer performance on cognitive tasks, including inhibition and visuospatial memory, 25% of the sample did not show difficulties on any assessments when compared to controls (Coghill et al., 2014). Evidence for neuropsychological heterogeneity also exists for other EF domains including working memory (WM) and cognitive flexibility, as well as tasks with low executive demands assessing memory storage and processing speed (Kofler et al., 2019; Rhodes et al., 2012; Roberts et al., 2017; Willcutt et al., 2005). Educational profiles in ADHD are equally subject to within-group variability – not all children with ADHD struggle with maths (Czamara et al., 2013; Capano et al., 2008; Mayes et al., 2019; Shalev et al., 1995). Differential patterns of performance in cognitive processes which underpin maths learning are proposed to be at the core of this heterogeneity (de Souza et al., 2019).

5.1.2 DCD

DCD is characterised by atypical development of motor function, including significant and persistent difficulties in acquisition and execution of fine (e.g., holding a pencil) and gross (e.g., hopping) movements to age-expected milestones (APA, 2013; Jane et al.,2018). Even children with high DCD symptoms who do not meet clinical cut-offs show motor difficulties (Sartori et al., 2020; Valentini et al., 2015). Children with DCD struggle with their visuomotor integration – the harmonious coordination of visual perception and fine motor coordination (Coetzee et al., 2020; Gómez-Moya et al., 2020; Nobusako et al., 2018). Visuomotor integration is thought to be critical for early maths learning via things like mapping visual representations of numbers when learning to count, writing numbers, and sorting objects such as numbers and shapes based on mathematical concepts (Pitchford et al., 2016). Visuomotor integration has been shown to predict maths performance in children (Kim et al., 2018; Pitchford et al., 2016). Arguably, difficulties with visuomotor integration may put children with DCD at greater risk for maths underattainment.

Like those with ADHD, children with DCD show lower neurocognitive functioning (Alloway, 2011; Asonitou et al., 2012; Bernardi et al., 2018; Rigoli et al. 2013; Sartori et al., 2020) even when ADHD symptoms are accounted for (Piek et al., 2007; Leonard et al., 2015). Additionally, children with DCD also show heterogeneous neurocognitive profiles (Sumnet et al., 2016; Vaivre-Douret et al., 2011). A differentiating characteristic of DCD is weaker visuospatial processing, including tasks with low motor demands (Sartorti et al., 2020; Tsai et al., 2008; Wilson et al., 2013). Previous research demonstrates lower visuospatial task performance in children with DCD when compared to those with ADHD (Alloway, 2011; Loh et al., 2011). Given strong associations between visuospatial processes and children's maths performance (e.g., Allen et al., 2019), diminished visuospatial cognition in DCD could increase these children's risk for maths difficulties.

Indeed, children with DCD struggle academically and, on average, achieve two GCSEs at secondary school compared to their peers who achieve seven (Harrowell et al., 2018). A previous study showed that 88% of children with DCD struggle with maths (Vaivre-Dourete et al., 2011). Although research in this area is scarce, lower maths scores are documented in broad achievement tests (Alloway, 2007), as well as more specific maths skills such as fact retrieval and calculation procedures (Gomez et al., 2015; Pieters et al., 2012). Addressing DCD and ADHD, Alloway (2011) found that children in both clinical groups scored lower on a maths attainment assessment than their neurotypical peers. Notably, children with ADHD mainly showed difficulties on measures of verbal and visuospatial WM, with intact short-term memory performance. Difficulties in the DCD group manifested more broadly across all aspects of memory, marked by particularly low scores on visuospatial memory tasks. Thus, although children with ADHD and DCD were indistinguishable in their maths achievement scores, different cognitive processes may have contributed to broad educational difficulties in each of the groups.

5.1.3 Co-occurrence between ADHD and DCD

The source of co-occurrence between ADHD and DCD remains contested. Some suggest a commonly shared genetic aetiology (Fliers et al., 2009; Martin et al., 2006). A more accepted model views ADHD and DCD as two separate disorders characterised by distinct risk factors, which under co-existence add up to increased difficulty than observed in either of the disorders alone (Goulardins et al., 2017). Loh and colleagues (2011) found evidence for substantially lower perceptual reasoning IQ scores in DCD and ADHD + DCD groups, but not in children with ADHD alone suggesting that weaker visuospatial processing is a distinct manifestation of DCD. However, another study using a larger sample found that children with concurrent ADHD + DCD did not differ from the ADHD-only group on perceptual reasoning and WM IQ indices (Parke et al., 2020). Both studies relied on composite IQ scores limiting findings to the domain of intellectual functioning, thereby masking other memory subdomains (e.g., visuospatial storage vs visuospatial updating).

The notion of additivity between ADHD and DCD is also found for maths performance. Visser and colleagues (2020) found that children with DCD were more likely to show poorer numeracy skills than their neurotypical peers, as well as difficulties in basic and complex number processing. The DCD group was nonetheless less impaired in maths than the ADHD and combined ADHD + DCD groups. Notably, the ADHD + DCD group had the lowest maths scores. The difference between the ADHD and ADHD + DCD groups in maths did not reach statistical significance, suggesting that maths difficulties could be predominantly attributed to ADHD. The authors note that further research focusing on more specific aspects of maths and contribution of cognitive processes is necessary. Indeed, their study used a total maths score which can mask problems in more specific numerical skills (Dowker, 2005; Furlong et al., 2015). This includes (1) *factual knowledge* – the ability to retrieve learned arithmetic facts from memory, (2) *conceptual understanding* – the ability to identify and understand conceptually based relationships among numbers and operations, and (3) *procedural skill* – the ability to apply computational procedures accurately and efficiently (Dowker, 2005; Geary, 2004; Hiebert & Lefevre, 1987). Research in neurotypical children shows that these distinct, yet highly correlated, skills collectively contribute to broad maths attainment (Cragg et al., 2017). A handful of studies suggests that these skills could be impaired in children with ADHD and DCD (Benedetto-Nasho & Tannock, 1999; Friedman et al., 2018; Gomez et al., 2017; Pieters et al., 2012; Zentall et al., 1994). These components have yet to be addressed in the context of co-occurring ADHD and DCD. Exploring these separate skills will be better for informing formulation of interventions tailored to children's needs than broad achievement scores (Kadosh et al., 2013).

Notably, research shows that between 16-50% of children with ADHD also have a co-occurring Autism Spectrum Disorder (ASD; Leitner, 2014; Pehlivanidis et al., 2020). Similarly, motor difficulties represent a fundamental feature in ASD, with around 60-80% of children with ASD showing poor motor functioning (Dewey et al., 2001; Green et al., 2009). Very little research exists on the prevalence of ASD in children with DCD, but one study found that 17% of children with DCD score above threshold for ASD symptoms (Sumner et al., 2016). Despite this, much of the previous research excludes children with pervasive developmental disorders from participating. Given the high overlap between DCD and ASD in motor functioning, the co-occurrence between these must be considered (Caçola et al., 2017). Furthermore, children with ADHD seldom meet criteria for just a single ‘pure’ ADHD diagnosis, and rather evidence suggest that two and even three co-occurring disorders is generally the norm (Jensen & Steinhausen, 2015). To maximise generalisability, co-occurring disorders such as ASD should be screened for, rather than act as a reason for exclusion from participation.

Another methodological issue in some studies is inclusion of children that have a history of pharmacological ADHD treatment (Alloway, 2011; Friedman et al., 2018; Gathercole et al., 2018; Holmes et al., 2014; Loh et al., 2011). Medication improves behavioural symptoms, cognitive task performance, and academic functioning in ADHD (Posey et al., 2007; Powers et al., 2008; Rhodes et al., 2006; Vaidya et al., 1998). Even under 24-hour wash out requirements, children with a history of stimulant treatment score better in these domains than their non-medicated ADHD peers (Semrud-Clikeman et al., 2008). Thus, children with previous history of medication treatment likely preserve related advantages even when off medication. Assessment of a drug naïve sample is necessary to help identify targets for psychological/educational interventions.

Up until 2013, the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV) did not allow for concurrent diagnoses (Harris et al., 2015). However, ADHD seldom occurs in isolation and co-occurrences with other disorders is the rule rather than the exception (Larson et al., 2011). This means that our understanding of educational difficulties in ADHD is limited to research that either excluded children with co-occurring DCD or failed to screen for DCD symptoms, making it difficult to characterise educational difficulties in a way that reflects real-life diagnostic complexities (Goulardins et al., 2015). Appropriate characterisations of ADHD samples, which inherently co-exist with other disorders, is crucial for guiding choices around appropriate intervention strategies tailored to children's needs.

5.1.4 Aims

Despite high rates of co-occurrence, little research exists on the co-existence between ADHD and DCD. The aim of the current study was to compare children with clinically high ADHD symptoms with and without co-occurring movement difficulties on a comprehensive set of cognitive and maths assessments. Based on previous findings of diminished visuospatial processing in DCD, it was expected that the children with co-occurring movement difficulties would show poorer scores on visuospatial aspects of memory than those without motor difficulties. Furthermore, given the importance of visuospatial memory and visuomotor integration to maths, it was likely that children with co-occurring motor difficulties would perform more poorly on maths assessments,. Another aim was to statistically explore whether there are differences in the associations between maths and cognition in the two groups. Identifying whether children with ADHD with and without motor difficulties differ in terms of their cognitive and maths profiles will be imperative for informing optimal intervention methods. The current study builds on previous methodological and interpretational constrains. Maths performance was indexed by both composite achievement scores as well as more specific maths skills, namely, the factual, conceptual, and procedural domains. To the authors knowledge, this is the first study to provide such a comprehensive characterisation of cognition and maths performance in an ADHD sample with and without co-occurring motor difficulties. Furthermore, to maximise generalisability to clinical populations, this study included an extensive characterisation of frequently co-occurring developmental disorders. All children were drug naïve at time of testing which reduces the confounding effects posed by medication treatment.

5.2 Method

5.2.1 Participants

Forty-three drug naïve children aged 6-12 years participated (*M* = 101.53 months *SD* = 19.58). Children were recruited from the ADHD assessment waiting list at the Child and Adolescent Mental Health Services (CAMHS) in NHS Lothian. The following exclusion criteria were applied: (1) primary language other than English, (2) current/previous stimulant treatment, (3) known chromosomal condition, (4) IQ score ≤ 70, or (5) scores within the typical range (< 60) on the Conners 3-Parent (Conners, 2008) DSM-5 Inattention and/or Hyperactivity-Impulsivity subscales. Children with other co-occurring neurodevelopmental disorders were included. One child was excluded as their parent failed to complete the movement difficulties questionnaire. All parents and children provided consent/assent prior to participation.

Favourable ethical opinion was granted by the NHS North West Haydock Research Ethics Committee.

ADHD + co-occurring motor difficulties group . The ADHD + co-occurring motor difficulties group included 25 children with elevated scores on the Conners 3-Parent (T-scores ≥60; Conners, 2008) DSM-5 Inattention and/or Hyperactivity-Impulsivity subscales, and concurrently had an elevated score on the Movement ABC-2 Checklist indicating serious movement difficulty (score ≤ 5th percentile; Schulz et al., 2011). Of these, 13 children received a clinical diagnosis of ADHD as confirmed by the clinical psychology team at CAMHS, nine did not meet criteria for clinical diagnosis, and an additional five were still awaiting evaluation. Two of the children in this group also had an ASD diagnosis, confirmed by the clinical CAMHS team and a further three were referred for further ASD evaluation.

ADHD group. The ADHD-only[13] group included 18 children without significant movement difficulties. Children in this group had a typical movement score (≥5th percentile) on the Movement ABC-2 Checklist and an elevated score on the Conners 3-Parent DSM-5 ADHD-Combined symptom presentation (one child in this group met criteria for predominantly hyperactive-impulsive presentation). In terms of clinical diagnoses, 11 children had a clinically confirmed ADHD diagnosis, five children did not meet criteria for a clinical ADHD diagnosis, and two were still awaiting evaluation for ADHD. Furthermore, two children in this group had a clinical ASD diagnosis, and an additional four were referred to another clinical team for suspected ASD.

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[13] This group is referred to as ADHD-only for ease of interpretation when comparing to ADHD + DCD group, but please note that neither refer to ‘pure’ ADHD as demonstrated by high rates of co-occurrences in the results section.

5.2.2 Materials

5.2.2.1 Parent questionnaires

ADHD symptoms. The 110 item Conners 3-Parent assessed DSM-5 symptom criteria for ADHD-Inattention, ADHD- Hyperactivity-Impulsivity, Conduct Disorder (CD) and Oppositional Defiant Disorder (ODD). A T-score ≥60 indicated clinically atypical symptoms levels.

DCD symptoms. The Movement ABC-2 Checklist obtained parents' views about children's motor difficulties in day-to-day settings. The Movement ABC-2 is appropriate for children aged 5-12 years, with high classification agreement (80%-90%) to the Movement-ABC Test (Schoemaker et al., 2012). Children were scored as having a serious movement difficulty if they scored ≤ 5th percentile.

Autism. The AQ-10 was used to index autistic traits in the sample (Allison et al., 2012). Parents/carers indicated the extent to which they agreed or disagreed with ten statements in relation to their child's behaviour. A score > 6 was used as a cut off for considering referral for a specialist diagnostic assessment for autism.

Behavioural and emotional difficulties. The Strengths and Difficulties Questionnaire (SDQ; Goodman, 2001) was used to screen for behavioural and emotional difficulties. A total score of ≥17 reflected high levels of difficulties.

5.2.2.2 IQ

The Wechsler Abbreviated Scale of Intelligence (WASI-II; Wechsler, 2011) assessed children's intellectual functioning. Together, the Vocabulary and Similarities subtest T-Scores provided the Verbal Comprehension Index while the Block Design and Matrix Reasoning T-Scores together provided the Perceptual Reasoning Index. Furthermore, a Full- Scale IQ score was generated from all four subtests. The British Picture Vocabulary Scale (BPVS-III; Dunn & Dunn, 2009) provided an index of receptive vocabulary IQ. Children with a BPVS and WASI-II FSIQ score ≤ 70 were deemed as potentially having an intellectual disability and were excluded from the study. Cognitive functioning

5.2.2.3 Cognitive tasks

Children completed eight tasks from the Cambridge Neuropsychological Test Automated Battery (CANTAB®, 2018) on an iPad and one assessment from the Wechsler Intelligence Scale for Children (WISC-V; Wechsler, 2016). Paediatric normative data for the CANTAB version used here was not available at the time of analysis, and so all raw scores were transformed into *z*-scores using participants' age. The following variables were reverse scored so that higher scores indicated better performance: Stop Signal RT, Stop Signal Median RT All Go Trials, Intra-Extra Dimensional Errors, and Spatial WM Errors. The cognitive tasks, as well as their respective outcome measures and domains, are summarised in Table 5.1

Table 5.1 Cognitive tasks and domains

Task	Outcome measure	Domain
Stop Signal Task	Stop signal RT	Inhibitory control
	Stop signal median RT	Processing speed
Intra-Extra Dimensional Set Shift	Intra-Extra dimensional errors	Cognitive flexibility/set shifting
Stockings of Cambridge	Problems solved in minimum moves	Planning
Spatial WM	Between Search Errors	Visuospatial WM updating
	Strategy (6-8 boxes)	Visuospatial WM strategy
Delayed Matching to Sample	% Correct responses on 12s delay trials	Delayed short term recognition memory
Spatial Span	Spatial span forwards length	Visuospatial STM
	Spatial span reverse length	Visuospatial WM
Verbal Recognition Memory*	Immediate recognition accuracy	Immediate verbal recognition memory
	Delayed recognition accuracy	Delayed verbal recognition memory
Letters Numbers Sequencing	Maximum letter number sequence accurately recalled	Verbal WM updating

*This task was administered only to those aged 8 years and over

Inhibitory control. The Stop Signal Task assessed children's inhibitory control. Participants responded to arrows pointing in either left or right direction by pressing corresponding buttons. Responses had to be withheld when an auditory signal was heard. The key outcome measure was the stop signal reaction time (Stop Signal RT) in milliseconds (ms).

Cognitive flexibility. The Intra-Extra Dimensional Set Shift measured attentional set-shifting. Participants selected abstract shapes and were prompted to learn rules regarding their choices via feedback. Once a rule was learned, the stimuli and/or rules changed, and participants shifted attention to previously trivial stimulus attributes. The key outcome was the total number of times that an incorrect stimulus was selected, adjusted for every stage that was not reached (Intra-Extra Dimensional Errors).

Visuospatial WM updating and strategy. The Spatial Working Memory (Spatial WM) task visuospatial WM updating. Participants were shown square 'boxes' and were asked to find a concealed token by looking in each box, with the caveat that once found, a token would not be hidden in the same box twice. The number of boxes increased from four, six, and eight items. The key outcome measure was the number of times participants incorrectly revisited a box in which a token was previously found (Spatial WM Between Search Errors).

Planning. The Stockings of Cambridge task assessed planning. Participants copied a model pattern of three stacked coloured balls using a pre-specified minimum number of moves ranging from two, three, four, and five. The key outcome measure was the total number of problems solved in the minimum number of moves (Stockings of Cambridge Problems Solved).

Verbal WM updating. The Letters Numbers Sequencing task (WISC-V) measured verbal WM updating. Participants listened to letters and numbers and recited the numbers in ascending numerical order and the letters in alphabetical order. The total number of items increased from two to eight. The outcome measure was children’s scaled score for the total number of trials (max = 30) for which the letters numbers sequence was correctly recited.

Visuospatial STM and WM. The Spatial Span task indexed visuospatial STM storage and visuospatial WM. Participants reproduced the order in which boxes change colour in a forward sequence (Spatial Span Forwards; STM storage) and in reverse sequence (Spatial Span Reverse; visuospatial WM). The number of boxes increased from two to nine items, depending on the child's progress. The outcome measure was the maximum correct span length.

Delayed short term recognition memory. The Delayed Matching to Sample assessed delayed short-term visual recognition memory. Participants selected a previously presented pattern from a choice of four patterns shown either simultaneously or at zero, four, and twelve second (s) delays. The outcome measure was percentage of trials on which participants correctly responded upon first attempt on 12s delays (Delayed Matching to Sample % Correct 12s delay).

Verbal recognition memory. The Verbal Recognition Memory (VRM) task assessed immediate and delayed memory for verbal information. Children were presented with a list of 18 words and were asked to identify previously presented words from a larger list of words. Outcome measures were the total number of distinct words participants correctly recalled (1) immediately after presentation (VRM Immediate Recognition), and (2) following a 20-minute delay (VRM Delayed). This task required children to be able to read words and was only administered to children aged over eight years.

Processing speed. The median RT (ms) on all Go trials in the Stop Signal Task was used to assess children's processing speed (Stop Signal Task Median RT All Go Trials).

5.2.2.4 Maths tasks

5.2.2.4.1 Maths achievement.

Maths attainment was assessed using standardised scores on the Wechsler Individual Achievement Test (WIAT®-III; Wechsler, 2017) subtests: Mathematics Problem Solving, Numeracy, and Maths Fluency. On the Mathematics Problem Solving, children solved word problems relating to time, money, measurement, geometry, probability or reading graphs. The Numeracy subtest measured written calculation skills. The Maths Fluency subtests measured written maths calculation fluency under timed conditions on addition, subtraction, and multiplication sums.

5.2.2.4.2 Maths components.

Children completed three tasks assessing specific maths skills. To eliminate floor or ceiling effects, items of varying difficulty were presented depending on the child's year at school. Raw scores were transformed into *z*-scores based on children's year group. All tasks relating to the assessment of children's maths competencies are summarised in Table 5.2

Table 5.2 Maths tasks and domains

Task	Outcome measure	Domain
Wechsler Individual Attainment Test (WIAT)		
Mathematics Problem Solving	Total accuracy	Maths problem solving
Numeracy	Total accuracy	Numerical operations
Maths Fluency (addition, subtraction, and multiplication*)	Total accuracy	Arithmetic fluency
Maths component skills		
Factual knowledge	Total accuracy	Knowledge of addition and subtraction facts
Conceptual understanding	Total accuracy	Understanding and applying conceptual principles
Procedural skill task	Total accuracy	Procedural computations accuracy
	Mean RT for accurate trials	Procedural computations efficiency

*This task was administered only to those aged 8 years and over

Factual knowledge. The factual knowledge task (Cowan et al., 2011; Simms et al., 2015) assessed knowledge of arithmetic facts. Children were asked to quickly solve single digit addition sums, each presented on the screen for four seconds. The outcome measure was the total number of correct responses provided within the four seconds limit (max = 12).

Conceptual understanding. The conceptual understanding task (Cowan et al., 2011; Simms et al., 2015) assessed children's understanding and application of maths concepts. Participants were presented with double-digit addition and subtraction sums on the screen with its corresponding answer (e.g., 31 + 45 = 76). After six seconds, another related sum appeared below it but this time without an answer (e.g., 76-45

=?). Children were asked to use the first sum to help solve the second sum. There were 12 experimental trials, three for each conceptual principle: double plus one (e.g., 42 + 42 = 84, 42 + 43 =?), related by commutativity (e.g., 48 + 21 = 69, 21 + 48 =?), related by inversion (e.g., 79-17 = 62, 62 + 17 =?) and identical (e.g., 56-27 =29, 56-27 =?). Children had six seconds to provide an answer for the second sum. The problems were designed so that children were unlikely to solve the sum within this time limit unless they relied on conceptual insight. The outcome measure was the total number of correct responses provided within the time limit (max = 12).

Procedural Skill. The procedural skills task (Cragg et al., 2017) assessed children's ability to execute maths procedures accurately and efficiently. Children received 10 experimental trials comprising addition and subtraction operations using single and double-digit numbers and were instructed to give an answer as quickly as possible. The outcome measures were the total correct responses (i.e., accuracy max = 10) and the mean RT in seconds for correctly answered trials (i.e., efficiency). The mean RT scores were reverse scored so that higher scores indicated better performance.

5.2.3 Procedure

Testing was conducted across two to three sessions and typically took place either at home (first session) or at school in a quiet room (second and third sessions). The total assessment time was around three hours per child. At the first session children completed the CANTAB tasks on an iPad, while the parent/carer completed the questionnaires. During the other sessions children completed assessments of maths, IQ, and the verbal WM task.

5.2.4 Statistical analysis

5.2.4.1 Statistical approach

Analyses were conducted using IBM SPSS Statistics 24. Independent sample *t*-tests and chi squared (x^2) tests were used to compare groups on sociodemographic, clinical, and IQ characteristics. Additionally, independent sample *t*-tests were run to compare groups on all cognitive and maths outcome measures. Correlational analyses between maths and cognition scores were implemented using Spearman's rho correlation coefficient, with the Benjamini-Hochberg correction applied using a false discovery rate of 0.05 (Benjamini and Hochberg, 1995). The Fisher's *r*-to-*z* test was used to compare the correlation values between the groups (Raghunathan and Rosenthal, 1996; Field, 2018 pp.362).

Dependent variables were checked for outliers using conventional criteria of *z*-score > 3.29 (Field, 2018; Tabachnik & Fidell, 2013). No univariate outliers were identified. Multivariate outliers were also screened for the maths and cognition variables using Mahalanobis distance scores. Chi-square distributions of the Mahalanobis distance scores for the maths (df = 7) and cognitive (df = 11) variables were all non-significant (p > .001) and so no multivariate outliers were identified.

Normality within each group was checked using skewness and kurtosis *z*-scores using a cut-off of 1.96 (alpha level of p < .05) deemed appropriate for detecting non-normality in smaller samples (Kim, 2013; Tabachnik & Fidell, 2013). Three of the outcome measures violated the assumption of normality: Intra-Extra Dimensional Errors (both groups), Spatial WM Between Search Errors (ADHD + co-occurring motor difficulties group) and WIAT Maths Fluency Composite (ADHD + co-occurring motor difficulties group). Non-parametric variant Mann-Whitney U test for paired comparisons were used as an alternative to compare groups on these variables. (Field, 2018; pp.286)

5.2.4.2 Power considerations

A power analysis using G*Power was conducted to test two-tailed *t*-test using a medium (*d* = .50), and large (*d* = .80) effect size (Faul et al.,2007). To achieve power of 0.8, a total sample of 54 participants would be necessary to detect a large effect size and 132 participants would be necessary to detect a medium effect size. Due to the small sample size, it was possible that the analysis would not be able to detect significant effects. However, small sample sizes are common in this research area (e.g., Bikic et a., 2018; Downs et al.,2016). Previous researchers challenge reliance on *p*-values and instead suggest using effect size estimates to explore important differences that could otherwise be missed by *p*-values (Field & Wright, 2006). As such, effect size magnitudes using Hedges *g* (0.2 = small effect, 0.5 = medium effect, 0.8=large effect) which is less biased than Cohen's *d* in smaller samples (Borenstein et al., 2021; Lakens, 2013). For the non-parametric Mann Whitney U tests effect sizes were calculated using *r* where 0.1 = small effect, 0.3 = moderate effect and 0.5 = large effect (Field, 2018 pp.295).

5.3 Results

5.3.1 Non-completers

Overall, 9.98% of values were missing on the cognitive and maths assessments. Thirteen children did not complete at least one of the mathematics outcomes measures. Participants with missing observations the mathematics assessments were younger [*t* (41) = -4.63, *p* < .001] and had higher motor difficulty scores [*t* (41) = 2.03, *p* = .048] than those with complete maths data. Completers and non-completers did not differ on IQ, cognitive scores, nor did they differ on parent rated clinical characteristics of ADHD-Inattention, ADHD-Hyperactivity/Impulsivity, ODD, CD, or ASD (all *p*'s > .05). Thirteen children had missing data on at least one of the cognitive assessments. Non-completes were younger [*t* (41) = -3.55, *p* = .001] and had lower parent reported birthweight [*t* (26.22) = -2.97, *p* = .006] than those with complete cognitive data. Non-completers on cognitive assessments also had lower (i.e., less difficulties) SDQ scores [*t* (35.29) = -2.64, *p* = .012] and ODD scores [*t* (16.79) = -2.62, *p* = .018]. Lastly, children with incomplete cognitive data had lower procedural efficiency RT scores [*t* (28) = -3.20, *p* = .003] than completers. Completers and non-completers did not differ on the remaining measures (all *p*'s > .05).

5.3.2 Group differences

Group characteristics are presented in Table 5.1. Groups did not differ from each other in age, sex, nor on the Scottish Index of Multiple Deprivation (SIMD). Similar proportions of children in each group scored high on symptoms of ODD and CD, as well as high emotional and behavioural difficulties indexed by the SDQ. Two children in the ADHD + co-occurring motor difficulties group were of low birthweight (< 2500g) and four children were born preterm (< 37 weeks; Anderson et al., 2011; Franz et al., 2018). The groups had comparable verbal and perceptual IQ scores.

As indicated by the chi-square test, children in the ADHD + co-occurring motor difficulties group were more likely to score above the threshold required for further referral of diagnostic assessment of ASD, than children in the ADHD-only group, x^2 (1) = 6.52, p = .014. Although the AQ-10 is not a diagnostic tool, a total score of 6 or higher flags consideration of further referral for specialist assessment for ASD. The option of including AQ-10 scores as a covariate was explored. A further *t*-test revealed that children in the ADHD + co-occurring motor difficulties group scored significantly higher on the AQ-10 questionnaires (M = 5.36, SD = 2.9) than the ADHD-only group (M = 3.00, SD = 1.9), *t* (41) = 3.01 *p* = .003, 95% CI [0.88, 3.84]. Thus, the assumption of independence of the covariate (AQ-10 scores) and the treatment effect (group) was violated. This suggest that the AQ-10 scores and Movement-ABC scores shared some of the variance, and so it would not be statistically sound to correct for differences in AQ-10 scores (Dennis, et al., 2009; Field, 2018; Miller & Chapman, 2001). Furthermore, this was unlikely to occur by chance (circumstances under which an ANCOVA could be regarded as legitimate) as previous research shows that children with ASD, and ADHD with co-occurring ASD, are at higher risk for motor difficulties (Ament et al., 2015; MacNeil & Mostofsky, 2012; Schurink et al.,2012). As such, it was decided not to include AQ-10 scores as a covariate[14] (e.g., see Bauermeister et al., 2005 for similar approach with ODD scores). Descriptive statistics for each group are presented in Table 5.3.

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[14] For readers interested in the group differences generated when groups were divided into children scoring high and low on the AQ-10 please refer to Supplementary File 1.

Table 5.3 Sociodemographic, clinical, and IQ characteristics of groups

	ADHD + co-occurring motor difficulties (n = 25)	ADHD-only(n = 18)	$\chi2$ (or *t*)	*p*
Sociodemographic characteristics				
Age in months, Mean (SD)	100.4 (19.54)	103.11 (20.09)	-0.44	.660
Boys n (%)	15 (60%)	15 (83%)	1.94	.163
Lowest SIMD-Quintile n (%)	12 (44%)	8 (44.4%)	.001	.977
ADHD Symptoms				
Conners Inattention T-Score, Mean (SD)	82.80 (9.44)	79.39 (11.92)	1.05	.301
Conners Hyperactive Impulsive T-Score, Mean (SD)	83.44 (10.35)	86.06 (6.94)	-0.93	.358
Clinically high symptoms of other co-occurring disorders				
Conners ODD n (%)	19 (76%)	15 (83%)	0.35	.712
Conners CD n (%)	19 (76%)	13 (72%)	0.78	1.00
AQ-10 n (%)	10 (40%)	1 (6%)	7.53	.014
SDQ n (%)	20 (80%)	15 (83%)	0.08	1.00
Perinatal complications				
Low Birthweight	2 (8%)	0	2.24	.502
Preterm Birth	4 (16%)	0	4.63	.127
IQ				
WASI Verbal Comprehension, Mean (SD)	101.04(10.99)	94.33 (12.65)	1.82	.077
WASI Perceptual Reasoning, Mean (SD)	97.32 (14.55)	97.44 (16.77)	-0.03	.979

SD standard deviation; *SIMD-Q* Scottish Index of Multiple Deprivation Quintile; *ODD* Oppositional Defiant Disorder; *CD* Conduct Disorder; *AQ-10* Autism Quotient; *SDQ* Strengths and Difficulties Questionnaire; *WASI* Wechsler Abbreviated Scaled of Intelligence

Table 5.4 Descriptive statistics and group differences in cognitive and mathematics scores

	ADHD + co-occurring motor difficulties		ADHD-only				
	N	Mean (SD)	N	Mean (SD)	*g/r*	*t/U*	*p*
Cognition							
Stop Signal Task RT (ms)	24	-0.08 (0.96)	18	0.06 (0.95)	-0.14	-0.45	.653
Intra-Extra Dimensional Set Shift Errors	24	-0.10 (0.88)	18	0.12 (1.04)	0.10	245.50	.453
Spatial WM Between Search Errors	24	-0.09 (0.89)	16	0.14 (1.00)	0.12	214.50	.539
Letters Numbers Sequencing Scaled Score	20	7.60(2.91)	16	7.00 (3.69)	0.18	0.55	.589
Stockings of Cambridge Problems Solved	24	-0.02 (0.85)	17	0.03 (1.07)	-0.05	-0.18	.860
Spatial Span Forwards	24	-0.17 (0.87)	16	0.16 (1.00)	-0.35	-1.15	.256
Spatial Span Reverse	**24**	**-0.30 (0.84)**	**16**	**0.41 (0.95)**	**-0.77**	**-2.48**	**.018**
Delayed Matching to Sample % Correct (12s delay)	24	-0.01 (0.93)	18	0.02 (0.96)	-0.03	-0.11	.911
Stop Signal Task Median RT Go Trials (processing speed; ms)	24	-0.15 (0.94)	18	0.17 (0.95)	-0.39	-1.10	.280
VRM Immediate	12	-0.19 (0.92)	11	0.19 (0.93)	-0.31	-0.77	.450
VRM Delayed	11	-0.14 (0.98)	11	0.16 (0.89)	-0.33	-0.96	.349
Maths							
WIAT Mathematics Problem Solving	25	92.12(12.03)	18	93.11(13.00)	-0.08	-0.26	.798
WIAT Numeracy	25	92.56(12.25)	18	92.50(10.84)	0.00	0.02	.987
WIAT Maths Fluency	24	88.67(10.16)	18	94.50(15.95)	0.19	265	.212
Factual Knowledge Accuracy	21	-0.02 (0.97)	17	-0.01 (0.96)	-0.01	-0.05	.964
Conceptual Understanding Accuracy	21	0.02 (1.03)	16	-0.07 (0.86)	0.10	0.30	.763
Procedural Skill Accuracy	17	0.16 (0.95)	13	-0.12 (0.88)	0.31	0.84	.409
Procedural Skill Efficiency (RT)	17	-0.04 (1.03)	13	0.11 (0.83)	-0.15	-0.42	.675

RT reaction time; *VRM* Verbal Recognition Memory; *WIAT* Wechsler Individual Achievement Test

5.3.2.1 Cognition

Children in the ADHD + co-occurring motor difficulties group had lower Spatial Span Reverse scores, indexing visuospatial WM (*M* = -0.30, *SD* =0.84) than the ADHD-only group (*M*=0.41, *SD* =0.95, *t* (38) =-2.48, *p* =.018, 95% CI [-1.29, -0.13], *g*=-0.77). No other statistically significant differences were found between these groups (all *p* values> 0.05, Hedge's *g* from -0.03 to 0.39).

5.3.2.2 Maths

Group differences on the standardised achievement scores (*g*'s between 0.00 to 0.19) and maths component assessments (*g*'s between -0.01 to 0.31) were all not statistically significant (*p's*> 0.05).

5.3.3 Correlations

The correlations between maths and cognition scores in the two groups are presented in Tables 5.3 and 5.4.

5.3.3.1 IQ

Perceptual IQ scores on the WASI significantly correlated with Mathematics Problem Solving Scores (*r* = .638, *p* = .001) only in the ADHD + co-occurring motor difficulties group, showing greater perceptual IQ was associated with greater maths problem solving skills. In the ADHD-only group higher comprehension IQ scores were significantly associated with higher conceptual understanding accuracy rates (*r* = .618, *p* = .011). All other associations were non-significant.

5.3.3.2 Cognition

Letters Numbers Sequencing scores, indexing verbal WM, significantly correlated with the WIAT Mathematics Problem Solving scores in both the ADHD + co-occurring motor difficulties group (*r* = .671, *p* = .001) and ADHD-only group (*r* = .738, *p* = .001), such that greater verbal WM was associated with higher problem-solving. Spatial WM Between Search Errors, assessing visuospatial WM updating, showed significant associations with procedural skill efficiency RTs only in the ADHD-only group (*r* = .786, *p* = .001), such that greater visuospatial WM updating was associated with higher procedural efficiency. All other associations between EF tasks and maths measures were not statistically significant.

In the ADHD + co-occurring motor difficulties group, higher Spatial Span Revere scores (visuospatial WM) were associated with greater achievement scores on the WIAT Mathematics Problem Solving achievement subtest (*r* = .753, *p* < .001), as well as higher scores on more specific maths knowledge skills including factual knowledge accuracy (*r* = .620, *p* = .004), and procedural skill accuracy (*r* = .669, *p* = .003). Additionally, higher immediate verbal recognition memory scores were associated with greater factual knowledge accuracy (*r* = .894, *p* < .001) and Mathematics Problem Solving scores on the WIAT (*r* = .691, *p* = .013) only in the ADHD + co-occurring motor difficulties group.

In the ADHD-only group, only the delayed verbal recognition memory scores significantly correlated to accuracy on the conceptual understanding task (*r* = .742, *p* = .009). All other associations failed to reach statistical significance.

5.3.4 Comparing correlations between groups

Fisher’s *r*-to-*Z* transformation revealed that correlations between visuospatial WM updating scores and procedural skill efficiency were significantly different for the two groups (*Z* = -2.05, *p* = .040), with stronger associations in the ADHD-only group. Notably, group differences in the correlations between visuospatial WM and WIAT Mathematics Problem Solving scores were on the threshold for statistical significance (*Z* = 1.95, *p* = .050), with more substantial associations for the ADHD + co-occurring motor difficulties group. All other contrasts of correlation coefficients between the groups were non-significant

Table 5.5 Correlation matrix for ADHD + co-occurring motor difficulties group

	Maths Problem Solving	Numeracy	Maths Fluency	Factual Knowledge Accuracy	Conceptual Understanding Accuracy	Procedural Accuracy	Procedural RT
WASI Perceptual Reasoning	.638**◊	.451*	.460*	.175	.179	.517*	.066
WASI Verbal Comprehension	.373	.042	.066	.204	.485*	.196	-.189
Stop Signal Task RT (ms)	.068	-.034	-.193	.038	-.114	-.038	-.268
Intra-Extra Dimensional Set Shift Errors	.276	.353	.070	.298	.152	.200	.228
Spatial WM Between Search Errors	.257	.367	.243	.153	-.096	.048	.208
Letters Numbers Sequencing Scaled Score	.671**◊	.409	.441	.168	.508*	.400	-.134
Stockings of Cambridge Problems Solved	-.252	-.182	-.166	-.088	-.128	-.111	.325
Spatial Span Forwards	.437*	.331	.085	.275	.100	.274	-.123
Spatial Span Reverse	.753**◊	.535**	.356	.620** ◊	.493*	.669**◊	.475
Delayed Matching to Sample % Correct (12s delay)	.383	.428*	.217	.455*	.116	.348	.115
VRM Immediate	.691*◊	.605*	.387	.894** ◊	.793**	.576	.491
VRM Delayed	.530	.598	.492	.579	.642*	.486	.492
Stop Signal Task Median RT Go Trials (ms)	.177	.151	.282	.200	-.060	.010	.318

* p < .05, ** p < .01, ◊ significant effect after Benjamini-Hochberg correction for multiple testing

WASI Wechsler Abbreviated Scale of Intelligence; *VRM* Verbal Recognition Memory

Table 5.6 Correlation matrix for ADHD-only group

	Maths Problem Solving	Numeracy	Maths Fluency	Factual Knowledge Accuracy	Conceptual Understanding Accuracy	Procedural Skill Accuracy	Procedural Skill RT
WASI Perceptual Reasoning	$.567^{*}$	$.494^{*}$	.456	$.519^{*}$	$.533^{*}$	.538	.265
WASI Verbal Comprehension	$.521^{*}$	$.497^{*}$	.461	.379	$.618^{*}$◊	.390	.036
Stop Signal Task RT (ms)	.277	.155	-.050	-.079	$.594^{*}$	.209	-.291
Intra-Extra Dimensional Set Shift Errors	.100	.262	.294	.279	-.041	.540	$.582^{*}$
Spatial WM Between Search Errors	$.500^{*}$	$.539^{*}$	.433	.459	.262	$.639^{*}$	$.786^{**}$◊
Letters Numbers Sequencing Scaled Score	$.738^{**}$◊	$.564^{*}$	$.546^{*}$	$.548^{*}$	$.761^{**}$◊	.320	.272
Stockings of Cambridge Problems Solved	-.127	.087	-.128	-.090	-.146	.256	.364
Spatial Span Forwards	.447	.251	.386	.418	.495	.068	-.036
Spatial Span Reverse	.283	.301	.280	.269	.254	.538	.152
Delayed Matching to Sample % Correct (12s delay)	.025	-.011	.188	.072	.010	$.564^{*}$	.388
VRM Immediate	.564	$.629^{*}$	.582	.571	.593	.516	$.709^{*}$
VRM Delayed	$.638^{*}$	.409	$.756^{**}$	.449	$.742^{**}$◊	.593	.369
Stop Signal Task Median RT Go Trials (ms)	.263	.263	.328	.226	.075	.424	.324

* p < .05, ** p < .01, ◊ significant effect after Benjamini-Hochberg correction for multiple testing

WASI Wechsler Abbreviated Scale of Intelligence; *VRM* Verbal Recognition Memory

5.4 Discussion

This study assessed children with high ADHD symptoms with and without co-occurring motor difficulties on a comprehensive set of cognitive and maths assessments. Although the two ADHD groups could not be differentiated based on maths performance, the ADHD + co-occurring motor difficulties group showed substantially lower visuospatial WM performance. Comparison of the correlation coefficients between the groups revealed differences in associations between some maths domains and visuospatial memory domains. Specifically, visuospatial WM updating and procedural skill efficiency scores were more strongly correlated in ADHD-only group, while visuospatial WM scores showed stronger associations with maths problem solving attainment scores in the ADHD + co-occurring motor difficulties group. Collectively, findings suggest that although children with ADHD with and without movement difficulties are comparable in maths performance, lower visuospatial WM is a distinct characteristic of children with concurrently high DCD symptoms. Furthermore, the results point to differential contribution of visuospatial memory performance with and without updating demands to more complex maths problem solving and procedural calculations in these groups.

5.4.1 Group differences

The hypothesis relating to more diminished visuospatial memory in the ADHD + co-occurring motor difficulties group was only partially supported. Children in the ADHD + co-occurring motor difficulties group performed lower on the visuospatial WM task, consistent with previous research pointing to weaker visuospatial memory processing as a hallmark of DCD (Alloway, 2011). However, children in the ADHD + co-occurring motor difficulties group were comparable to their ADHD-only counterparts on visuospatial WM updating which also taxed visuospatial memory processes. On the Spatial WM task, children use a self-directed elimination strategy to remember and update which boxes they already opened to check for tokens and must avoid going back to for duration of the trial, and concurrently remember and update which boxes are still left to check. This emphasises updating requirements of the task as, although participants recall previous token locations, the main focus is on being able to continuously update visuospatial content in WM (Smith et al., 2013). However, on the Spatial Span Reverse task sequences are explicitly displayed, memorised, and reverse ordered, primarily taxing WM manipulation capacity (Jaeggi et al., 2010; Wells et al., 2018). Such sequence reversal is insufficient for tapping into the updating domain of WM (Conway et al., 2005; Engle et al., 1999; Wells et al., 2018). The present findings therefore imply that children with ADHD + co-occurring motor difficulties are comparable to their ADHD-only peers on visuospatial WM updating but show marked difficulties on visuospatial WM manipulation.

The lack of statistically significant findings in relation to visuospatial STM storage (Spatial Span Forwards) implies that children with concurrent DCD struggle more with the manipulation subdomain of visuospatial WM, than retention of visuospatial information. To illustrate how this translates in the context of maths, we can take a sum such as *15 + 7 =?* . One way to solve this would be to decompose the problem into subproblems: (1) *5 + 7 = 12*, and (2) *10 + 12 = 22*. Visuospatial storage would be involved in storing the interim solution *12* in memory, while manipulation would help visualise and restructure the problem into the easier format. Carrying and borrowing procedures in more complex calculations (e.g., *70-19 =?)* are also heavily reliant on the child's ability to re-organise and manipulate content, for example in *70-19 =?* the *70* is manipulated to first become a *10* where *10-9 = 1*, thereafter the *70* transforms into a *60* where *60-10 = 50*. While the child may have no difficulty in storing a particular solution (i.e., *10-9 = 1*), it is the transformation into variable formats that could be problematic. Thus, intervention strategies for children with ADHD + DCD may benefit by specifically supporting children’s skill in manipulating digits in visuospatial formats.

The finding that groups did not differ on any EF assessments suggests that children with ADHD and co-occurring motor difficulties are generally indistinguishable from their ADHD-only peers when higher order executive processes are involved. This is in line with previous arguments that EF difficulties are a feature of ADHD (Piek et al., 2004). Nonetheless, research by Leonard and colleagues (2015) found that children with DCD also struggle with EF performance, even where ADHD symptoms are accounted for. Based on the current study, it cannot be ruled out that both groups struggle with EF when compared to neurotypical children. Future research would benefit from incorporating normative data and including a DCD-only group to establish whether EF difficulties are a specific manifestation of DCD.

Unlike Loh and colleagues (2011), this study did not find evidence for better perceptual IQ in the ADHD-only group. This could be the product of their recruitment of children from schools, as opposed to the clinically referred sample used here. Another study, which also recruited a clinical group of children, found that perceptual reasoning IQ scores in the ADHD and ADHD + DCD groups were comparable (Parke et al., 2020). This highlights the effects that different recruitment contexts can have on emerging results and the generalisability of their implications. Similar to the current findings, Parke and colleagues (2020) also found that children in the ADHD and ADHD + DCD groups did not differ in their verbal IQ scores. However, they also identified a group of children with ADHD + co-occurring reading/written expression disorder – this group scored substantially lower on verbal IQ than the ADHD-only and ADHD + DCD groups. Literacy difficulties are common in ADHD (Mayes & Calhoun, 2006). In the present study, children in the ADHD + co-occurring motor difficulties group had higher verbal IQ scores, although this failed to reach statistical significance when they were compared to the ADHD-only group. Given that children's literacy abilities were not included here, it is possible that children in the ADHD-only group had varying reading/writing abilities, which could explain the lack of significant findings in verbal IQ scores.

The finding that children in the ADHD and ADHD + co-occurring motor difficulties groups did not differ from one another on any of the broader maths scores is consistent with previous research (Alloway, 2011; Visser et al., 2020). Importantly, the current study extends this to more specific maths components of the factual, conceptual, and procedural subdomains. Visser and colleagues (2020) found that their DCD group scored higher on maths than the ADHD and combined ADHD + co-occurring motor difficulties groups, suggesting that maths difficulties are mainly due to ADHD difficulties. However, other research shows that maths achievement profiles of children with ADHD are indistinguishable from those with DCD (Alloway, 2011), autism (Bullen et al., 2020), low WM (Holmes et al., 2014), and learning difficulties (Gathercole et al., 2018) implying that lower maths attainment is not exclusive to ADHD. More recent research shows that children's cognitive profiles are more informative for identifying struggling learners than traditional diagnostic groupings (Astle et al., 2019). It would be interesting for future research to further explore whether data-driven cognitive subgroups that cut across diagnoses are more informative for domain-specific maths skills than the categorical approach used here.

5.4.2 Comparing correlations between groups

Statistical comparison of the correlations revealed that associations between maths and cognition in both groups were generally similar, however, some notable exceptions were evident. Specifically, visuospatial WM updating showed stronger associations with procedural skill efficiency in the ADHD-only group. It could be that children in the ADHD-only group relied more heavily on procedural strategies that tax WM updating, such as decomposition strategies (e.g., in *15 + 7 =?* (1) *15 + 7 = 12*, and (2) *10 + 12 = 22,* then updating old solution *12* with new answer *22*). By contrast, it is possible that children in the ADHD + co-occurring motor difficulties did not capitalise on updating-based strategies as much and instead relied on less mature and more time-consuming manual counting strategies (e.g., finger counting and counting on). It is also possible that due to impairment to fine motor skills children in the ADHD+ co-occurring motor difficulties are still in the process of finger counting skill mastery (Barrocas et al., 2020; Gomez et al., 2015)

In theory these latter strategies are more prone to errors but, despite taking longer to compute, the ADHD + co-occurring motor difficulties group were more accurate in their calculations than their ADHD-only counterparts (moderate effect size differences). Similarly, it is unlikely that children in the ADHD + co-occurring motor difficulties opted for faster visuospatial retrieval-based strategies as this should have resulted in higher efficiency rates. Notably, WM updating is shown to be important to virtually all arithmetic strategies including decomposition, retrieval, and counting on (Cragg et al., 2017). Thus, whichever strategy children opted for should have resulted in some level of WM mobilisation. These findings also can’t be explained by greater updating difficulties in the ADHD-only group, as the groups showed similar performance on this domain. Further research is therefore necessary to explore this further.

Visuospatial WM (i.e., w/o updating requirements) performance was more strongly associated with WIAT Mathematics Problem Solving attainment scores in the ADHD + co-occurring motor difficulties group than the ADHD-only group. This implies that for the ADHD + co-occurring motor difficulties group visuospatial WM was particularly important for successful navigation of math problem solving. This subtest required children to encode, store and manipulate visuospatial stimuli such as coloured pictures, shapes, and graphs to accommodate problem solving (Fung & Swanson, 2017). Plausibly, more pronounced difficulties with visuospatial WM in the ADHD + co-occurring motor difficulties group resulted in greater difficulties with maths problem solving. However, this difference in the correlations fell on the threshold of significance (p = .050) and so further research is necessary before conclusive remarks can be made.

Verbal WM performance significantly related to Mathematics Problem Solving attainment scores in both groups. This subtest required children to listen to orally presented problems, identify, and hold the most relevant phonological information ‘online’, whilst concurrently trying to solve the problem – updating previously held information with newly identified solutions (Bull & Lee, 2014; Cragg et al., 2017). This suggest that children’s ability to solve word problems is closely linked to retrieval and storage of relevant phonological information in memory and its’ active processing during problem solving. Children with low verbal WM capacity may therefore benefit from intervention strategies that support cyclic rehearsal and reduce demands on active updating of phonological information.

Previous evidence interprets comparable cognitive correlates of maths performance in diagnostic subgroups (e.g., Alloway, 2011; Mayes et al., 2020). However, these correlations were not statistically compared, and research mainly focused on standardised attainment scores. The statistical comparison of the correlation coefficients in the current study showed that the majority of the correlations between a wide range of cognitive domains (i.e., EFs, memory and processing speed) were statistically comparable across the two groups and extends this finding to domain-specific maths skills. It is therefore possible that diagnostic subgroups are simply not informative to children's maths difficulties from a practical perspective.

5.4.3 Limitations

There was no clinical confirmation of DCD diagnosis in the present study. The current study uses a more stringent (≤ 5th percentile) cut-off for identifying children with DCD. Some studies use a score of ≤ 15th percentile to identify children with DCD (e.g., Gomez et al., 2015; Pieters et al., 2012). However, these studies rely on the Movement ABC-2 Performance Test, typically administered by a trained professional to objectively assess children's ability to complete motor tasks. The current study utilised the parent-completed Movement ABC-Checklist, which is more open to parents' subjective interpretation of their child's abilities. Furthermore, whilst scores ≤ 5th percentile (red zone) indicate 'significant' motor impairment, scores between 6th and 15th percentile are interpreted as 'at risk' of developing a movement difficulty requiring continued monitoring[15]. To minimise ambiguity the more definitive cut-off of the 5th percentile was selected. This more conservative cut-off was also selected in line with other studies and suggestions that definite motor impairment is implicated when standard scores are below 2 SDs, which is more diagnostically accurate for differentiating between children with typical motor functioning (Barnett & Wiggs, 2012; Griffiths et al., 2017; Staples et al., 2012; Toussaint-Duyster et al., 2020; Zoia et al., 2002).

To receive a DCD diagnosis, motor difficulties cannot be attributed to underlying ADHD difficulties of distractibility, impulsivity, or hyperactivity (Goulardins et a., 2015). Children in the ADHD-only and ADHD + co-occurring motor difficulties groups did not differ in their parent rated ADHD symptoms of inattention and hyperactivity-impulsivity. This suggests that lower motor abilities in the ADHD + co-occurring motor difficulties sample were unlikely due to ADHD symptoms and is consistent with previous findings showing that motor difficulties are not part of an ADHD phenotype (Farran et al., 2020).

Another limitation relates to the finding that the ADHD + co-occurring motor difficulties group were significantly more likely to score above the AQ-10 threshold required for further referral for ASD evaluation, which could lead to the possibility that high autism traits were driving group differences. Previous research shows that children with ASD, and ADHD with co-occurring ASD, are at higher risk for motor difficulties (Ament et al., 2015; MacNeil & Mostofsky, 2012; Schurink et al., 2012). Papadopoulos and colleagues (2013) showed that children with ADHD without a co-occurring ASD diagnosis had typical movement scores, suggesting that movement

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[15] Only three children scored between the 6th and 15th percentile: running the *t*-test analysis with these three participants in the ADHD + DCD group did not change the pattern of results in the group comparisons of cognitive and maths performance profiles.

difficulties are predominantly due to ASD. Although their results are based on a small sample (N = 14), motor difficulties are increasingly becoming recognised as an important characteristic of ASD (Fournier et al., 2010; Langmaid et al., 2016). Excluding children who flagged as having high autism traits would be counterintuitive to the complexities of children's clinical reality. Equally, correcting for AQ-10 scores as a covariate when these scores share variance with movement difficulties would not be statistically appropriate (Dennis, et al., 2009; Field, 2018; Miller & Chapman, 2001). It is also important to note that unlike the Movement ABC-Checklist and the Conners ADHD questionnaires (used to classify children into their respective groups), the AQ-10 is not used for diagnostic purposes and is much less comprehensive. Rather, it screens children for further referral for ASD evaluation, and a failure to score high on this questionnaire does not rule out autism (Weir et al., 2020). Indeed, information gathered from the CAMHS clinical team revealed that both groups very similar proportions of children with a confirmed clinical ASD diagnosis and referrals for further ASD evaluation. This renders it unlikely that differences between the two groups could have been driven by autism. The current findings do, however, highlight the importance for screening for co-occurring ASD symptoms when exploring ADHD and DCD samples. Rather than excluding children with ASD from participation future work would benefit from including children with ASD in their samples, to improve our understanding of the effects of concurrent diagnoses on cognitive and academic functioning.

5.4.4 Conclusions

This is the first study to comprehensively investigate cognitive and maths profiles in a well characterised and drug naïve sample of children with high ADHD symptoms with and without co-occurring motor difficulties. Findings showed that whilst children with ADHD and ADHD + co-occurring motor difficulties show similar maths performance, those with ADHD + co-occurring motor difficulties can be distinguished by weaker visuospatial WM performance. This can be particularly informative for clinical distinctions between different types of diagnoses, as well as for informing interventions tailored to children’s needs. Few notable differences were identified between the two groups in terms of the pattern of associations between cognition and maths. Most of the statistical comparisons of the correlations revealed comparable associations. Although further research is necessary before conclusions can be made, the current findings point to the notion that similar cognitive processes contribute to maths performance in both groups. Therefore, future research would benefit from using cognitive dimensions, rather than diagnosis or symptoms, for exploring pathways of maths difficulties.

6 Chapter 6: Data-driven profiles of cognitive performance in ADHD: implications for maths

The preceding study chapters demonstrated that cognitive dimensions are more informative mechanisms in relation to maths, than ADHD symptoms (Chapter 4) and diagnostic categories based on co-occurring movement difficulties (Chapter 5). The present chapter explores the utility of a traditional categorical grouping approach (i.e., clinical ADHD vs no clinical ADHD diagnosis) to that of a data-driven grouping approach using children's cognitive performance. The chapter includes a publication under review:

Kanevski, M., Booth, J.N., Stewart, T.M., Rhodes, S.M. (2021). Cognitive Heterogeneity in ADHD Implications for Maths *Developmental Psychology* (under review).

6.1 Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is characterised by persistent and impairing levels of inattention, hyperactivity, and/or impulsivity (APA, 2013). It is estimated to affect 1-2% of children, with an additional 5% who fall below the threshold required for a clinical diagnosis but are nonetheless negatively impacted by their symptoms (Czamara et al., 2013; Hong et al., 2014; Karalunas & Nigg, 2020; Marcus & Barry, 2012; Russell et al., 2014; Sayal et al., 2018; Thapar & Langley, 2006). Previous research indicates that children with ADHD struggle with maths (Capano et al., 2008; Du Paul et al., 2013; Tosto et al., 2015). This is evidenced by lower maths grades at school, poorer standardised achievement scores, and lower arithmetic performance when compared to neurotypical peers (Antonini et al., 2016; Friedman et al., 2018; Holmes et al., 2014; Kim et al., 2020). However, other studies have not found evidence for differences between ADHD and neurotypical peers in maths performance (e.g., Capano et al., 2008; Capodieci & Martinussen, 2017; DuPaul et al., 2013). One plausible explanation for within group heterogeneity in maths is differences in underlying cognitive abilities (Kofler et al., 2017; Geary et al., 2007). Neurocognitive performance is also subject to marked within-group variability in ADHD (Coghill et al., 2014; Kofler et al., 2019) although the implications of neurocognitive heterogeneity in ADHD for maths skills remain unclear.

The Diagnostic and Statistical Manual (DSM-5) classifies children with ADHD into one of three categories based on symptom presentations: (1) *ADHD-Inattentive* subtype, (2) *ADHD-Hyperactive/Impulsive* subtype, and (3) *ADHD-Combined* subtype (APA, 2013). Although categorical classification systems offer clear criteria for diagnosis, these subtypes are not always supported. For example, presentation profiles can shift over time such that hyperactivity symptoms decline with age and children may grow up to meet criteria for a different ADHD subtype (Lahey et al.,1994; Todd et al., 2008; Willcutt et al., 2012). Furthermore, these diagnostic subtypes are not always informative for identifying children at risk for maths difficulties. Although lower maths performance has been linked to inattention, notable associations with hyperactive-impulsive symptoms are also found (see Tosto et al., 2015). Research shows that higher order cognitive processes mediate associations between behavioural ADHD symptoms and maths attainment (Antonini et al., 2016; Calub et al., 2019; Friedman et al., 2018; Gremillion & Martell, 2012). This renders cognitive functioning as an alternative and potentially more informative contender for ADHD classification.

Diminished cognitive performance is a core feature of ADHD (Castellanos & Tannock, 2002; Kofler et al., 2019; Nigg et al., 2005; Willcutt et al., 2005). Prominent ADHD theories propose that difficulties with Executive Functions (EF) underpin behavioural manifestations (Barkley, 1997; Lyon & Krasnegor, 1996; Johnson et al. 2009; Pennington & Ozonoff, 1996). EF refer to distinct but highly interrelated higher order cognitive skills responsible for maintaining goal-oriented behaviour: inhibitory control, working memory (WM) updating, set shifting, and planning (Miyake et al., 2000; Diamond, 2013). These processes have previously been implicated in maths abilities in children with ADHD (Biederman et al., 2004; Nuñez et al., 2020; Roberts et al., 2017) and learning difficulties (Astle et al., 2018; Gathercole et al., 2018; Sikora et al., 2002), as well as in neurotypical populations (Best et al., 2011; Bull et al., 2008; Cai et al, 2016; Cragg et al., 2017; Geary, 2011; Holmes & Adams, 2006). Thus, EF profiles offer a compelling strategy for identifying children at risk for maths difficulties.

Some models view WM as the core difficulty in ADHD (Rapport et al., 2001). WM includes the ability to work (i.e., store, update, and manipulate) with information in memory which is no longer perceptually available (Diamond, 2013). According to the predominant model by Baddeley and Hitch (1974) the WM system features three specialised components: (1) *phonological loop,* responsible for short term storage of verbal information, (2) *visuospatial sketchpad,* which oversees short term retention of visuospatial information, and (3) *central executive* which manages simultaneous storage and manipulation of information in the modality-specific storage systems. Notably, the central executive, also referred to as the attentional control system, employs other key EF processes including inhibitory control, shifting, and updating (Baddeley, 1996; Miyake et al., 2000; Friso-Van Den Bos et al., 2013). Children with ADHD struggle with all three subcomponents of the WM system, and these difficulties are marked by substantially higher effect sizes when compared with other EF constructs (Rapport et al., 2008; Kofler et al., 2019). *V*erbal WM is sometimes found to be less affected in ADHD than visuospatial WM, (Rhodes et al., 2012; Willcutt et al., 2005). However, a recent meta-analysis found evidence for substantial verbal WM difficulties in children and adolescents with ADHD (Ramos et al., 2020); effect size magnitudes were within the medium range, pointing to within-group heterogeneity in WM capacity.

Others regard WM as one of a variety of EF deficits stemming from inadequately regulated or underdeveloped inhibitory control (Barkley, 1997; Sonuga-Barke, 2002). Nonetheless, within-group heterogeneity in both inhibitory control and WM task performance suggests that these are likely to be part of an EF difficulty assortment that may or may not comprise a cognitive ADHD profile (Coghill et al., 2014; Kofler et al., 2019). Indeed, although children with ADHD are frequently outperformed by their neurotypical peers on EF tasks (Gau & Shang, 2010; Kempton et al., 1999; Pennington & Oznoff, 1996; Rhodes et al., 2004; 2005 Toplak et al., 2008*),* others argue that these group-level differences are driven by a small subsample of children (Sonuga-Barke et al., 2008). Furthermore, estimates suggest that around 30-50% of children with ADHD show intact performance on EF tasks (Boyer et al., 2018; Coghill et al., 2014; Kofler et al., 2019; Nigg et al., 2005; Rhodes et al., 2005; Roberts et al., 2017; Trinczer & Shalev, 2018; Wåhlstedt et al., 2009 Willcutt et al., 2005). Notably, Kofler and colleagues (2019) found that 35% of children were classed as “impaired” when EF was considered as a unitary construct, but when inhibitory control, WM, and set shifting were considered separately 89% showed a difficulty on at least one of these domains. Interestingly, 10% of children with ADHD had intact EF performance on all EF tasks, although planning was not assessed (Kofler et al., 2019).

Based on this variability at the cognitive level, grouping children using ADHD diagnoses/symptoms risks exaggerating within-group homogeneity (Coghill & Sonuga-Barke, 2012). A more favourable approach would be to explore data-driven patterns in EF performance and to determine whether this variability can help identify subgroups of struggling learners in a meaningful way.

WM consistently emerges as a strong predictor of maths in ADHD and neurotypical populations (Allen et al., 2019; Calub et al., 2019; Friedman et al., 2018; Cragg et al., 2017; Friso-Van Den Bos et al., 2013). While inhibitory control and set shifting show strong associations with maths attainment, their role generally becomes negligible once WM is considered (Cragg et al., 2017; Bull & Lee, 2014; Lee & Bull, 2016; Friso-Van Den Bos et al., 2013). Thus, it is possible that maths difficulties are primarily navigated by children’s WM profiles. Variability is also evident within the different WM subcomponents assessing storage with and without concurrent processing (Gomez et al., 2014; Martinussen et al.,2005; Rhodes et al., 2004; 2012). Generally, greater difficulties are found on tasks tapping into the central executive, *followed by the visuospatial sketchpad, and the phonological loop (Kofler et al., 2020; Martinussen et al., 2006; Rapport et al., 2008; Willcutt et al., 2005).* Memory storage without updating demands has also been implicated in neurotypical children’s maths performance (Andersson, 2008; Bull et al., 2008; Cragg et al., 2017; Holmes and Adams, 2007; Passolunghi et al., 2008), although is relatively understudied in ADHD. Thus, it is possible that children found to have ‘intact’ EF in previous work have difficulties in other memory domains not assessed (Roberts et al, 2017). In a previous analysis (Chapter 4) both working and storage aspects of memory, but not other EF processes, showed moderate-large associations with maths outcomes. Thus, any examination pertaining to cognitive difficulties and maths in ADHD would also benefit from a more comprehensive consideration of memory profiles and their implications for maths.

Some researchers have turned to data-driven analytical strategies to group children according to cognitive dimensions (e.g., Astle et al., 2019; Kofler et al., 2017; Nunez et al., 2020; Roberts et al., 2017). These studies identify distinct groups depending on children's cognitive performance and demonstrate that these cognitive groups show differential patterns of academic attainment. However, these studies generally focus on a select few cognitive processes which makes it difficult to rule out whether or not children struggle with some other aspect of cognition that was not tested. Further, much of the previous literature focuses on wider academic difficulties indexed by subtest/composite maths attainment scores. Although these can be useful for identifying struggling learners, they confound more specific numerical skills (Cragg & Gilmore, 2014; Dowker, 2005). Plausibly, interventions may be ineffective in targeting relevant difficulties if homogenous maths underachievement profiles are assumed (Furlong et al., 2015). Three key maths component skills are proposed to contribute to children's attainment (Baroody, 2003; Cowan et al., 2011; Cragg et al., 2017; Cragg & Gilmore, 2014; Dowker, 2005; Geary, 2004). *Factual knowledge* – the ability to retrieve arithmetic facts from memory (e.g., knowing from memory that 2+3 = 5, rather than using less sophisticated finger counting strategies). *Conceptual understanding* – the ability to understand maths rules and procedures (e.g., addition is inversely related to subtraction). Lastly, *procedural skill* comprises the ability to select and execute appropriate numerical strategies accurately and efficiently (e.g., 'carrying' when adding above 10). Despite inter-correlations, difficulties across the components can occur independently (Dowker, 2005; Gilmore & Papadatou-Pastou, 2009). A total composite score provided by achievement tests makes it difficult to ascertain which maths skill is causing children to make mistakes. Exploring these components in more detail will be important for identifying pathways of underachievement and in formulating optimal interventions tailored to children's difficulties (Cragg et al., 2017; Kadosh et al., 2013).

In sum, despite recent advances, there exists no comprehensive examination of ADHD subtypes which encompasses all theoretically relevant cognitive constructs. Furthermore, the implications of cognitive subtypes to specific maths skills in children with ADHD remains unknown. Exploring cognitive classification systems offers a promising approach to enhance clinical prediction and define etiological pathways of difficulties which can help identify children who are in the most, and least, need for academic intervention (Karalunas & Nigg, 2020). The purpose of this study was therefore to explore subgrouping approaches that would be most informative to children's maths component outcomes. The first approach used diagnostic category-based subgroups depending on whether or not children received a clinical ADHD diagnosis (i.e., clinical ADHD vs subclinical ADHD). The second data-driven, bottom-up, approach grouped children using (1) key theoretical EF domains that are implicated in ADHD, and (2) key WM processes which were previously implicated in maths performance. In each approach, groups were compared on their performance on a comprehensive battery of tests assessing cognition, intelligence, and maths, as well as on parent-rated symptoms of ADHD and other co-occurring disorders. Data-driven clusters were also compared on rates of clinical ADHD diagnosis. The current study was exploratory in nature, however, based on emerging research (e.g., Astle et al., 2019; Roberts et al., 2017) it was expected that cognitive profiles would be more informative in differentiating between children's maths performance when compared to diagnostically driven subgroups.

6.2 Method

6.2.1 Participants

Participants were 44 drug naïve children recruited from the ADHD assessment waiting list at the Child and Adolescent Mental Health Services (CAMHS) in NHS Lothian. Children were aged 6 to 12 years (*M* = 101.34 months, *SD* = 19.39). All children scored high (≥60) on the Conners 3-Parent DSM-5 ADHD symptom scales (Conners, 2008). Forty-one children scored high on both ADHD-Inattentive and Hyperactivity-Impulsivity scales, one child scored high on the ADHD-Inattentive scale only, and two children scored high on the ADHD-Hyperactivity-Impulsivity scale only. Diagnostic outcomes were confirmed by CAMHS following clinical evaluation. In total 24 children received a clinical ADHD diagnosis – of these, three had a co-occurring ASD diagnosis, and an additional four were referred for further ASD assessment. A further 15 children did not receive a clinical ADHD diagnosis following clinical evaluation – two of these had an ASD diagnosis and a further two children were referred for ASD assessment. Lastly, five children were still awaiting diagnostic confirmation – of these, one child was also undergoing ASD assessment. The following exclusion criteria were applied to all participants: (1) primary language other than English, (2) current/previous stimulant medication treatment, (3) a known chromosomal condition, (4) an IQ score ≤ 70, or (5) a score within the typical range (< 60) on the Conners 3-Parent DSM-5 Inattention and Hyperactivity-Impulsivity subscales. Children with other co-occurrences were included. Sociodemographic and clinical characteristics of the sample can be found in Table 6.1. All parents and children provided consent/assent before participating.

Table 6.1 Descriptive and clinical information for the full sample

	ADHD (N = 44)
Sociodemographic characteristics	
Age in months, Mean (SD)	101.34 (19.39)
Boys *n* (%)	31 (70%)
SIMD Quintiles *n* (%)	
1 (most deprived)	10 (23%)
2	10 (23%)
3	4 (9%)
4	5 (11%)
5 (least deprived)	15 (34%)
ADHD symptoms	
Conners ADHD Inattention T-Score, Mean (SD)	81.41 (10.43)
Conners ADHD Hyp/Imp T-Score, Mean (SD)	84.66 (9.01)
CAMHS diagnosis	
ADHD *n* (%)	24(55%)
ASD *n* (%)	5 (11%)
No ADHD diagnosis *n* (%)	15 (34%)
Awaiting evaluation *n* (%)	5 (11%)
Co-occurring symptoms n (%)	
Conners Oppositional Defiant Disorder	35 (80%)
Conners Conduct Disorder	33 (75%)
Strengths and Difficulties Questionnaire	36 (82%)
Movement ABC Checklist	25 (57%)
Autism Quotient-10	12 (27%)
Perinatal complications n (%)	
Low Birthweight < 2500g	3 (7%)
Preterm Birth < 37 weeks	4 (9%)

SIMD Scottish Index of Multiple Deprivation; *CAMHS* Child and Adolescent Mental Health Service

6.2.2 Measures

6.2.2.1 Parent questionnaires

ADHD, ODD, and CD symptoms. The 110 item Conners 3-Parent assessed DSM-5 symptom criteria for the ADHD symptoms (Inattentive and Hyperactive/Impulsive), ODD, and CD. A T-score ≥60 indicated clinically atypical symptom levels. The Conners DSM-5 Symptom Scales provide good internal consistency (Chronbach's alpha = .90), test-retest reliability (*r* = 0.89) and interrater reliability (*r* = .84) (Kao & Thomas, 2010).

Movement difficulties. The Movement ABC Checklist-2 (Movement ABC-2 Schulz et al., 2011) obtained parents' views about children's movement difficulties in day-to-day settings. The Movement ABC-2 is appropriate for children aged 5-12 years, with high classification agreement (80%-90%) to the Movement ABC Test (Schoemaker et al., 2012). The Movement ABC-2 Checklist can be completed by parents as they observe the child in a wide variety of contexts. Higher scores indicated higher movement difficulties. The Movement ABC-2 Checklist has been reported to have good internal consistency (α = 0.94; Schoemaker et al., 2012).

ASD traits. Parents completed the Autism Spectrum Quotient-10 (AQ-10) to assess autism traits (Allison, Auyeung, & Baron-Cohen, 2012). A score of > 6 was used as a cut off point for high scores, requiring consideration of further assessment of ASD (sensitivity 0.95, specificity 0.97; Allison et al., 2012).

Behavioural and emotional difficulties. The Strengths and Difficulties Questionnaire (SDQ; Goodman, 2001) assessed behavioural and emotional difficulties. A total score ≥17 reflecting high levels of difficulties (Goodman, 2001). The

SDQ has good test-retest reliability (*r* = 0.70) and internal consistency (α = 0.73; Algorta et al., 2016; Goodman & Goodman, 2009; Stone et al., 2010).

6.2.2.2 IQ

The Wechsler Abbreviated Scale of Intelligence (WASI-II; Wechsler, 2011) assessed children's intellectual functioning. A Full-Scale IQ (*r* = .96) score was also calculated using all four subtests: Vocabulary, Similarities Block Design, and Matrix Reasoning. The British Picture Vocabulary Scale (BPVS-III; Dunn & Dunn, 2009) was used to provide an index of receptive vocabulary IQ. Children with a BPVS and WASI-II Full-Scale IQ score ≤ 70 were deemed as potentially having an intellectual disability and were excluded from the study.

6.2.2.3 Cognitive tasks

The selection of cognitive tasks was largely informed by the comprehensive literature reviews (Chapters 1 and 2). Specifically, this was achieved by identifying domains that are frequently implicated in ADHD (Coghill et al., 2014; Kofler et al., 2019; Nigg et al., 2005; Rhodes et al., 2012; Rhodes et al., 2005; Rhodes et al., 2006; Willcutt et al., 2005) and, concurrently, those which have been shown to be important to children maths performance (Anonini et al., 2016; Andersson, 2010; Clark et al., 2010; Cowan et al., 2011; Cragg et al., 2017; Gilmore et al., 2015; Gremillion and Martel, 2012).

6.2.2.3.1 EF tasks

Participants completed four tasks from the Cambridge Neuropsychological Test Automated Battery (CANTAB®, 2018) on a touch screen iPad and one assessment from the Wechsler Intelligence Scale for Children (WISC-V; Wechsler, 2016).

Paediatric normative data for the CANTAB version used here was not available at the time of analysis, and so all raw scores were transformed into *z*-scores using participants' age. Measures of impairment were reverse scored so that higher scores indicated better performance: Stop Signal RT, Stop Signal Median RT All Go Trials, Intra-Extra Dimensional Errors, and Spatial WM Errors.

The Stop Signal Task examined children's response inhibitory control. Participants responded to an arrow pointing in either left or right direction by pressing corresponding buttons. Responses had to be withheld if an auditory signal is heard. The key outcome measure was the stop signal reaction time (Stop Signal RT) in milliseconds (ms) – the length of time between go stimulus and stop stimulus at which the children successfully withheld their response on 50% of trials.

The Intra-Extra Dimensional task measured attentional set-shifting – the ability to flexibly switch attention between different stimuli characteristics. Participants selected abstract shapes and were prompted to learn rules regarding their choices via audio feedback. Once a rule was learned, the stimuli and/or rules are changed, and participants had to shift attention to previously trivial stimulus attributes. The key outcome measure was the total number of times an incorrect stimulus was selected, adjusted for every stage (9 experimental stages in total) that was not reached (Intra-Extra Dimensional Errors).

The Spatial WM task examined visuospatial WM with updating. Participants were shown square 'boxes' and were asked to find a concealed token by looking in each box, with the caveat that once found, a token will not be hidden in the same box twice. The number of boxes increased from four, six, and eight items. The key outcome measure was the number of times participants incorrectly revisited a box in which a token was previously found (Spatial WM Between Search Errors).

The Letters Numbers Sequencing task (WISC-V) assessed verbal WM with updating. Participants listened to randomly presented letters and numbers and had to recite the numbers in ascending numerical order and the letters in alphabetical order. The total number of items increased from two to eight. The key outcome variable was children's scaled score for the total number of trials (max = 30) for which the letters numbers sequence was correctly recited.

The Stockings of Cambridge task assessed children's ability to monitor, evaluate, and update a sequence of planned moves. Participants copied a model pattern of three stacked coloured balls using a pre-specified minimum number of moves ranging from 2, 3, 4 and 5. The key outcome measure was the total number of problems solved in the minimum possible number of moves (Stockings of Cambridge Problems Solved).

6.2.2.3.2 Memory storage tasks.

The Delayed Matching to Sample assessed delayed short-term visual recognition memory. Participants selected a previously presented pattern from a choice of four patterns shown either simultaneously or at zero, four, and twelve second (s) delays. The outcome measure was percentage of trials on which participants correctly responded upon first attempt on 12s delays (Delayed Matching to Sample % Correct 12s).

The Spatial Span task indexed visuospatial STM storage and visuospatial WM. Participants reproduced the order in which boxes change colour in a forward sequence

(Spatial Span Forwards; visuospatial STM) and in reverse sequence (Spatial Span Reverse; visuospatial WM). The number of boxes increased from two to nine items, depending on the child's progress. The outcome measure was the maximum correct span length.

Processing speed. The median RT (ms) on all Go trials in the Stop Signal Task was used to assess children's processing speed (Stop Signal Task Median RT All Go Trials).

6.2.2.4 Maths tasks

Maths achievement. Maths attainment was assessed using standardised scores on the Wechsler Individual Achievement Test (WIAT®-III; Wechsler, 2017) subtests: Mathematics Problem Solving (r = .91), Numerical Operations (r = .93), and Maths Fluency (r = .94; Wechsler, 2018). On the Mathematics Problem Solving, children solved word problems relating to time, money, measurement, geometry, probability or reading graphs. The Numeracy subtest measured written calculation skills. The Maths Fluency subtests measured written mathematics calculation fluency under timed conditions on addition, subtraction, and multiplication sums.

Maths components. Participants completed three tasks assessing specific maths skills. The maths component tasks contained content of varying difficulty depending on the child's year at school. As such, children's raw scores were transformed into z-scores based on their age.

The factual knowledge task (Cowan et al., 2011; Simms et al., 2015) assessed knowledge of arithmetic facts. Children were asked to quickly solve single digit addition sums, each presented on the screen for four seconds. The outcome measure was the total number of correct responses provided within the four seconds limit (max = 12).

The conceptual understanding task (Cowan et al., 2011; Simms et al., 2015) assessed children's understanding and application of maths concepts. Participants were presented with double-digit addition and subtraction sums on the screen with its corresponding answer (e.g., 31+45 = 76). After six seconds, another related sum appeared below it but this time without an answer (e.g., 76-45 =?). Children were asked to use the first sum to help solve the second sum. There were 12 experimental trials, three for each conceptual principle: double plus one (e.g., 42+42 = 84, 42+43 =?), related by commutativity (e.g., 48+21 = 69, 21+48 =?), related by inversion (e.g., 79-17 = 62, 62+17 =?) and identical (e.g., 56-27 = 29, 56-27 =?). Children had six seconds to provide an answer for the second sum. The problems were designed so that children were unlikely to solve the sum within this time limit unless they relied on conceptual insight. The outcome measure was the total number of correct responses provided within the time limit (max = 12).

The procedural skills task (Cragg et al., 2017) assessed children's ability to execute maths procedures accurately and efficiently. Children received 10 experimental trials comprising addition and subtraction operations using single and double-digit numbers and were instructed to give an answer as quickly as possible. The outcome measures were the total correct responses (i.e., accuracy max = 10) and the mean RT in seconds for correctly answered trials (i.e., efficiency). The mean RT scores were reverse scored so that higher scores indicated better performance.

6.2.3 Procedure

Testing was conducted across two to three sessions and typically took place either at home (first session) or at school (second and third sessions). At the first session children completed the game-like CANTAB tasks on an iPad, while the parent/carer completed the behaviour questionnaires. The second session was typically conducted at the child's school in a quiet room. During the other sessions children completed assessments of maths, IQ, and the verbal WM task.

6.2.4 Data analysis

All analyses were conducted using IBM SPSS Statistics 24. The first analysis compared children with a clinical ADHD diagnosis to those without a clinical diagnosis who had high parent ADHD symptoms (i.e., subclinical ADHD) on cognition, maths, and parent-rated symptoms of ADHD and co-occurring disorders. In the second analysis a hierarchical clustering method was applied to children's EF *z*-scores to explore data-driven subgroups. The third analysis involved a hierarchical cluster analysis using children's *z*-scores on WM and storage memory tasks. Cluster groups were compared on cognition, and maths, as well as symptoms of ADHD and co-occurring disorders. Furthermore, rates of clinical ADHD diagnosis in each cluster were examined.

Before analysis, data were checked for univariate outliers using criteria of a *z*-score > 3.29 (Field, 2018; Tabachnik & Fidell, 2013). No outliers were identified for any of the cognitive or maths variables. One extreme univariate outlier was identified for the Conners 3-P ADHD Hyperactivity-Impulsivity scale. Because extreme values reflect the clinical reality of this sample, this outlier was retained. Multivariate outliers were also screened for using Mahalanobis distance scores for each respective analysis. Chi-square distributions of the Mahalanobis distance scores for the cognitive (*df* = 5), maths (*df* = 7) and parent questionnaire (*df* = 7) variables were all non-significant ($p > .001$).

6.2.4.1 Diagnostic subgroup profiles

Independent sample *t*-tests were used to compare children with ADHD (N = 24) and subclinical ADHD (N = 15) on the cognitive, maths, and parent questionnaire data. Normality within each group was checked using skewness and kurtosis *z*-scores using a cut-off of 1.96 (alpha level of $p < .05$) suitable for detecting non-normality in smaller samples (Kim, 2013; Tabachnik & Fidell, 2013). Non-parametric variant Mann-Whitney U test was used as an alternative to compare groups on variables that did not meet normality assumptions (Field, 2018). Effect size magnitudes for this analysis were calculated using Hedges *g* (0.2 = small effect, 0.5 = medium effect, 0.8 = large effect). For the non-parametric Mann Whitney U tests effect sizes were calculated using *r* (0.1 = small effect, 0.3 = moderate effect, and 0.5 = large effect; Field, 2018).

6.2.4.2 Cluster analysis

Two separate cluster analyses were conducted: (1) EF criterion variables, and (2) memory criterion variables. Cluster analysis is a multivariate statistical method used to identify homogenous groups of data objects based on similarities in characteristics within the group and dissimilarities between other groups (Tan et al., 2005). Hierarchical cluster analysis was selected as it is deemed more appropriate for dealing with smaller data sets and facilitates more objective solutions than the alternative K-means clustering (Embrechts et al., 2013; Roberts et al., 2017).

In agglomerative clustering each observation begins as its own cluster (Köhn & Hubert, 2014). The similarity distance between each cluster is then calculated and similar observations are sequentially combined with each other until all observations are merged to produce a single large cluster. The measure of similarity used to merge children into the clusters was defined using Ward's method with Squared Euclidean distance (Ward, 1963). Ward's method identifies pairs of clusters that need to be merged based on the criteria that the merger leads to a minimal possible increase in within-cluster variation (Dwyer et al., 2020). Ward's method defines the distances between any two clusters as the magnitude of increase in the error sums of squares upon merging. Thus, Ward's method merges clusters that minimise error sum of squares in each iteration (i.e., reducing the merging cost). Ward's method consistently demonstrates good recovery of cluster structures and is less susceptible to noise than other methods (Everitt et al., 2011; Mojena, 1977).

6.2.4.2.1 Selection of criterion cluster variables

In cases where the number of participants is small relative to the number of variables, the cluster classification may be weakened, so the number of variables was considered (Basagaña et al., 2013). Whilst Dolnicar (2002) suggests that there is no rule of thumb for sample size in cluster analysis, others recommend that the sample size should be $N = 2^m$ (i.e., 2 to the power of *m*) where *m* is the number of variables (Formann, 1984). Thus, based on the current sample size, five variables were deemed as appropriate to be used in each cluster analysis. To avoid issues around multicollinearity, a collinearity diagnostic of absolute correlation values was used – all intercorrelations were below the required threshold ($r < 0.8$) and so were retained as individual cluster variables (Dormann et al. 2012; Tabachnik & Fidell, 2001). In line with previous studies, only children with complete data on cognitive criterion variables were included in the cluster analysis[16] (Astle et al., 2019; Chen et al., 2018; McDougal et al., 2020; Vanbinst et al., 2015).

Cluster Analysis 1 (EF; N = 34). EF criterion cluster variables included (1) Stop Signal RT (response inhibitory control), (2) Intra-Extra Dimensional Errors (set shifting), (3) Spatial WM Between Search Errors (visuospatial WM), (4) Letters Numbers Sequencing (verbal WM), and (5) Stockings of Cambridge Problems Solved (planning).

Cluster Analysis 2 (Memory; N = 31). An alternative memory-based cluster solution was also explored using criterion memory variables which showed significant correlations with maths in Study Chapter 2: (1) Spatial WM Between Search Errors (visuospatial WM with updating), (2) Spatial Span Reverse (visuospatial WM w/o updating), (3) spatial span forward (visuospatial memory storage), (4) Letters Numbers Sequencing (verbal WM with updating), and (5) Delayed Matching to Sample percent correct at 12s delays (delayed short term recognition memory for visuospatial information).

6.2.4.2.2 Cluster identification

In line with previous suggestions, the optimal cluster solution was informed using a visual inspection of the dendrogram figures and the more objective agglomeration coefficients (de Souza Salvador et al., 2019; Yim & Ramdeen, 2015). A sudden jump to a large coefficient between two consecutive stages indicated combination of potentially heterogeneous clusters and acted as a stopping point for the cluster

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[16] For comparisons of completers and non-completers for each cluster analysis please refer to Appendix K.

process (Yim & Ramdeen, 2015). Another important consideration was that the emerging clusters are clinically relevant and include an adequate number of participants to allow for validation analysis (Bonafina et al., 2000). Once the clusters were identified, groups were characterised on their performance across each of the cognitive criterion variables.

Cluster Analysis 1 (EF; N = 34). The first clustering technique used Multivariate Analysis of Variance (MANOVA)17 with follow-up univariate ANOVAs to compare groups. Post hoc Gabriel tests were used to contrast the three groups in their performance (Field, 2018). In cases where homogeneity of variance assumption was violated, the Games-Howell posthoc test was used (Field, 2018). MANOVAs were interpreted using partial omega squared (ω p 2) which produces less bias in smaller samples than partial eta squared (Lakens, 2013; Okada, 2013). Partial omega squared effect size magnitudes were: .01 = small effect; .06 = medium effect; and large effect = .14 (Cohen, 1988).

Cluster Analysis 2 (Memory; N = 31). For the second clustering strategy groups were compared using *t*-tests. Effect size magnitudes for the *t*-tests and univariate group comparisons were calculated using Hedges *g* (0.2 = small effect, 0.5 = medium effect, 0.8 = large effect) which is less biased than Cohen's *d* in smaller samples (Borenstein et al., 2021; Lakens, 2013).

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[17] A MANOVA was selected as it reduces Type 1 error rates and accounts for the relationship among the dependent variables (Field, 2018)

6.2.4.2.3 Cluster validity

To explore cluster validity, the identified cluster groups were compared on their age, IQ, and maths performance. The clusters were also compared on performance on other cognitive tasks, as well as ADHD and co-occurring disorder symptoms of ODD, CD, ASD, and movement difficulties. Lastly, the rates of ADHD diagnosis in each cluster were compared using Fisher's exact test (Field, 2018).

6.3 Results

6.3.1 Diagnostic subgroup profiles

The results of the diagnostic group comparisons are presented in Tables 6.2 and 6.3.

Age & IQ. There were no statistically significant differences (all *p*'s> .05) between children with and without a clinical ADHD diagnosis on age and IQ (*g*'s ranging from -0.09 and 0.26).

Cognition. There were no statistically significant differences (all *p*'s> .05) between children with and without a clinical ADHD diagnosis any of the cognitive outcome variables (*g*'s ranging from -0.12 and 0.56).

Maths. Children with a clinical ADHD diagnosis were more accurate on their factual retrieval than children with subclinical ADHD: *t* (32) = 2.28 *p* = .029, *g* = 0.67, 95% CI [0.07, 1.32]. Children in the clinical ADHD group also had higher accuracy rates on the conceptual understanding task than children without a clinical ADHD diagnosis: *t* (31) = 2.05 *p* = .049, *g* = 0.61, 95% CI [0.00, 1.23]. The difference between groups on the WIAT Maths Problem Solving achievement scores was on the threshold of significance, such that children with clinical ADHD diagnosis attained higher scores on this subtest than children with subclinical ADHD *t* (37) = 2.02 *p* = .052, *g* = 0.56, 95% CI [-3.49, 12.25]. All other group differences in maths outcomes were non-significant (*g*'s ranging from -0.11 to 0.31).

ADHD and co-occurring symptoms. Children with a clinical ADHD diagnosis had significantly lower ODD scores on the Conners 3-P than those with subclinical ADHD (36.11) = -2.64 *p* = .012, *g* = 0.37, 95% CI -21.85, -2.88]. All other group differences in the parent questionnaire outcomes were non-significant (*g*'s ranging from -0.05 to -0.41).

Table 6.2 Performance of diagnostic groups (excluding N = 5 awaiting evaluation) on cognition, age, IQ and parent questionnaires

	ADHD			Subclinical ADHD			Group contrasts		
	N	Mean	SD	N	Mean	SD	*t/U*	*p*	*g/r*
EF tasks									
Stop Signal Reaction Time (inhibitory control)	23	0.19	0.97	15	-0.20	0.85	1.28	.210	0.36
Intra-Extra Dimensional Errors (shifting)	23	-0.10	1.14	15	0.09	0.64	-0.60	.550	-0.17
Spatial WM Between Search Errors	21	-0.03	1.08	14	0.16	0.76	-0.55	.585	-0.16
Letters Numbers Sequencing	19	7.63	3.08	12	7.08	3.60	0.45	.654	0.14
Stockings of Cambridge Problems Solved (planning)	22	-0.06	0.86	14	0.26	1.01	-1.02	.316	-0.29
Other cognitive tasks									
Spatial Span Reverse	22	0.03	1.08	14	-0.12	0.81	0.44	.660	0.13
Spatial Span Forwards	23	-0.06	0.95	15	0.08	1.03	-0.44	.664	-0.12
Delayed Matching to Sample	21	0.26	0.83	14	-0.31	0.90	1.94	.061	0.56
Processing Speed (SST Median Reaction Time)	23	0.16	1.01	15	0.02	0.72	0.44	0.66	0.13
Age & IQ									
Age (months)	24	99.21	16.28	15	101.20	23.36	-0.31	.755	-0.09
WASI FSIQ	22	100.18	13.90	15	96.13	11.48	0.93	.358	0.26
BPVS	24	96.58	12.16	14	94.43	13.14	0.51	.612	0.14
Parent questionnaires									
Conners ADHD Inattentive	24	82.42	9.40	15	80.47	12.17	169.50	.743[a]	-0.05
Conners ADHD Hyperactive-Impulsive	24	84.96	7.17	15	86.67	5.68	207.50	.432[a]	0.14
Conners Conduct Disorder	24	69.29	15.80	15	76.13	10.74	-1.47	.149	-0.41
Conners Oppositional Defiant Disorder	24	72.83	16.93	15	85.20	12.21	253.50	**.033**[a]	0.37
Autism Quotient Total	24	4.46	2.93	15	4.73	2.52	-0.30	.766	-0.08
Movement ABC Checklist Total	24	19.00	15.72	14	21.00	16.48	-0.37	.712	-0.11
Strengths and Difficulties Questionnaire Total	24	21.71	5.57	15	23.40	6.12	-0.89	.380	-0.25

[a] *U* Mann Whitney U test

Table 6.3 Performance of diagnostic groups (excluding N = 5 awaiting evaluation) on maths attainment and component skills

	ADHD			Subclinical ADHD			Group contrasts		
	N	Mean	SD	N	Mean	SD	*t/U*	*p*	*g/r*
Maths attainment									
WIAT MPS	24	95.75	12.42	15	87.73	11.56	2.01	**.052**	0.56
WIAT Numeracy	24	94.25	10.96	15	89.87	13.07	1.13	.266	0.31
WIAT Maths Fluency	23	93.65	13.25	15	87.27	12.62	114.5	.083^{a}	-0.28
Maths components									
Maths Factual Component Accuracy	20	0.33	0.79	14	-0.37	1	2.28	**.029**	0.67
Maths Conceptual Accuracy	19	0.31	0.9	14	-0.3	0.79	2.05	**.049**	0.61
Maths Procedural Accuracy	16	0.14	0.95	10	-0.05	1.05	0.48	.637	0.16
Maths Procedural Efficiency RT (s)	16	0.05	1.00	10	0.17	0.71	-0.32	.751	-0.11

WIAT Wechsler Individual Achievement Test*; MPS* Mathematics Problem Solving

6.3.2 Cluster Analysis 1 – EF clusters

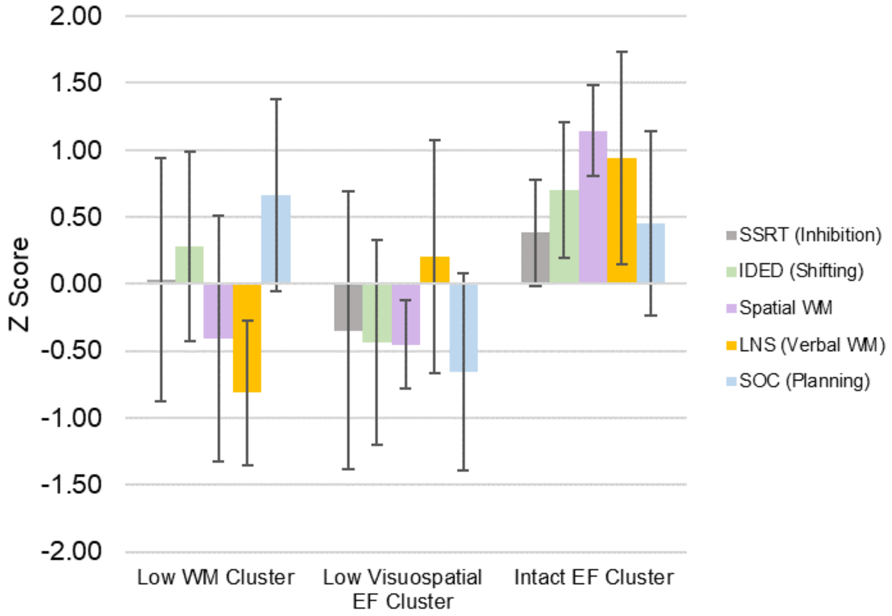
6.3.2.1 Cluster identification

Initial inspection of the dendrogram indicated a three or potentially five cluster solutions (Appendix F). The agglomeration coefficient schedule also indicated a sudden jump at the 4-5 cluster combination and then again at 2-3 cluster combination (Appendix G). As such, 2, 3, 4, and 5 cluster solutions were considered, with the 3-cluster solution generating the most homogenous and interpretable subgroupings.

6.3.2.2 EF characteristics of subgroups

Performance of each cluster on the EF criterion variables is illustrated in Figure 6.1. The descriptive statistics for each cluster and analysis results are provided in Table 6.3. The MANOVA revealed that the groups significantly differed in performance on the EF criterion variables $V = 1.45$, F (10,56) = 14.88, $p < .001$, $\omega_p^2 = 0.68$. Separate univariate ANOVAs revealed significant differences between the group clusters on shifting ($p = .002$, $\omega^2_p = 0.27$), spatial WM ($p < .001$, $\omega^2_p = 0.52$), verbal WM ($p < .001$, $\omega^2_p = 0.45$), and planning ($p < .001$ $\omega^2_p = 0.40$). The difference in inhibitory control scores was not statistically significant ($p = .187$) although were of a moderate effect size ($\omega^2_p = 0.04$). Significance values and effect sizes of the univariate group comparisons can be found in Appendix H.

Figure 6.1 Performance of clusters on criterion EF variables



* Error bars are based on the standard deviations.

SSRT Stop Signal Reaction Time; *IDED* Intra-Extra Dimensional; *LNS* Letters Numbers Sequencing; *SOC* Stockings of Cambridge.

Low WM cluster

The Low WM cluster was characterised by low verbal WM and visuospatial WM performance. Children in this cluster had significantly lower verbal WM scores on the Letter Number Sequencing task than children in the Low Visuospatial EF(p = .004, g = -1.18) and children in the Intact EF cluster (p< .001, g = -2.29). Furthermore, children in the Intact EF cluster made significantly more search errors on the Spatial WM task than the Intact EF cluster (p< .001, g = -1.73).

Low Visuospatial EF cluster

Children in the Low Visuospatial EF cluster scored lower on EF tasks containing visuospatial stimuli. They made greater shifting errors on the Intra-Extra Dimensional task than the Low WM cluster (p = .036, g = 0.82) and the Intact EF cluster (p = .002, *g* = -1.41). Children in the Low Visuospatial EF cluster also solved fewer planning problems on the Stockings of Cambridge task than Cluster 1 (*p*< .001, *g* = 1.52) and Cluster 3 (*p* = .005, *g* = -1.30). Moreover, children in the Low Visuospatial EF cluster made more search errors on the Spatial WM task than the Intact EF cluster (*p* = < .001, *g* = -4.04) but were comparable to the Low WM cluster (*p* = .987, *g* = 0.05). Children in this cluster also had the lowest inhibitory control scores on the Stop Signal Task, although this did not reach statistical significance (*p* = .086, *g* = -0.71)

Cluster 3 ***Intact EF***

Children in the Intact EF cluster were distinguished by generally higher EF performance than the other groups. Children in this cluster made fewer errors on the Spatial WM task than the Low WM cluster (*p*< .001, *g* = -1.73) and Low Visuospatial EF cluster (*p*< .001, *g* = -4.04). Furthermore, the Intact EF cluster had higher verbal WM scores than Low WM cluster *(p*< .001, *g* = -2.29). Children in the Intact EF cluster made fewer shifting errors on the Intra-Extra Dimensional task than children in the Low Visuospatial EF cluster (*p* = .002, *g* = -1.41). Other meaningful effect size differences were also found on other EF tasks despite not reaching statistical significance. Specifically, the Intact EF cluster scored higher on the verbal WM (*p* = .097, *g* = -0.73) and inhibitory control tasks (*p* = .197. *g* = -0.71) than the Low Visuospatial EF cluster, as well as scoring higher on the set shifting task than the Low WM cluster (*p* = .444, *g* = -0.55)

6.3.2.3 Cluster validity

The validity of the EF clusters was examined by comparing groups on age, IQ, and maths scores. To explore whether clusters differed in ADHD diagnosis and co-occurring symptoms, groups were also compared on the parent completed questionnaires relating to co-occurring symptoms. The descriptive statistics for each cluster and results of the univariate ANOVAs are provided in Tables 6.4 and 6.5.

Table 6.4 Descriptive data and ANOVA comparisons between EF clusters (age, IQ, cognition, and symptoms)

	Low WM cluster N = 13		Low Visuospatial EF cluster N = 13		Intact EF cluster N = 8		*ANOVA*			Group Contrasts
	Mean	SD	Mean	SD	Mean	SD	*F* (2, 31)	*p*	ω^2_p	
Criterion EF variables										
Stop Signal RT (inhibitory control)	0.04	0.91	-0.35	1.04	0.38	0.39	1.77	.187	0.04	NS
Intra-Extra Dimensional Errors (shifting)	0.28	0.71	-0.44	0.76	0.70	0.51	7.43	**.002**	0.27	2<1, 1=3, 2<3
Spatial WM Between Search Errors	-0.41	0.92	-0.45	0.33	1.14	0.34	19.29	**.000**	0.52	1 = 2, 1<3, 2<3
Verbal WM Scaled Score	4.69	1.75	8.00	2.83	10.38	2.56	14.79	**.000**	0.45	1< 2, 1<3, 2=3
SOC Problems Solved (planning)	0.66	0.72	-0.66	0.74	0.45	0.68	12.18	**.000**	0.40	2<1, 1=3, 2<3
Age & IQ										
Age (months)	108.88	18.51	114.18	18.30	109.00	17.55	1.00	.378	0.00	NS
WASI FSIQ	84.75	8.48	99.64	13.90	107.29	9.27	7.84	**.002**	0.29	1=2, 1<3, 2=3
BPVS	91.38	11.88	95.27	13.92	104.00	11.69	2.87	.072	0.10	NS
Other cognitive processes [a]										
Spatial Span Forwards	0.04	1.15	-0.16	0.74	0.59	1.01	1.42	.260	0.03	NS
Spatial Span Reverse	0.05	0.83	0.07	0.97	0.57	0.98	0.93	.408	0.00	NS
Delayed Matching to Sample	-0.50	1.13	0.03	0.93	0.37	0.30	2.24	.126	0.08	NS
Processing Speed (SST Median RT)	-0.09	0.91	-0.11	0.97	0.13	0.94	.185	.832	-0.06	NS
ADHD symptoms and co-occurrences										
Conners ADHD Inattention	78.46	13.97	81.46	9.96	84.50	9.12	0.70	.507	-0.02	NS
Conners ADHD Hyperactivity-Impulsivity	83.38	9.01	82.54	12.89	86.25	5.97	0.34	.714	-0.04	NS
Conners Oppositional Defiant Disorder	79.62	14.50	74.38	19.38	80.75	13.59	0.49	.616	-0.03	NS
Conners Conduct Disorder	75.46	14.79	67.15	15.64	70.75	17.74	0.90	.417	-0.01	NS
Autism Quotient	4.38	2.06	4.00	2.97	3.38	2.00	0.42	.659	-0.04	NS
Movement ABC	15.69	14.73	23.31	15.83	12.63	14.58	1.45	.249	0.03	NS
Strengths and Difficulties Questionnaire	24.46	6.46	23.08	7.37	19.38	4.87	1.54	.231	0.03	NS

[a] *F* (2,27); *SOC* Stockings of Cambridge.

Table 6.5 Descriptive data and ANOVA comparisons between EF clusters (maths)

	Low WM cluster N = 13		Low Visuospatial EF cluster N = 13		Intact EF cluster N = 8		*ANOVA*			Group Contrasts
	Mean	SD	Mean	SD	Mean	SD	*F* (2,25)	*p*	ω^2_p	
WIAT MPS	84.25	9.72	95.55	12.38	104.71	9.96	7.25	**.003**	0.31	1 = 2, 1< 3, 2 = 3
WIAT Numeracy	86.25	12.34	90.36	13.06	105.29	9.12	6.18	**.007**	0.27	1 = 2, 1< 3, 2< 3
WIAT Maths Fluency	84.50	12.68	91.64	11.84	105.71	16.55	5.70	**.009**	0.25	1 = 2, 1< 3, 2 = 3
Factual Knowledge accuracy	-0.50	0.96	0.03	0.92	0.73	0.79	3.66	**.040**	0.16	1 = 2, 1< 3, 2 = 3
Conceptual Understanding accuracy	-0.57	0.67	0.29	1.13	0.73	0.81	4.23	**.026**	0.19	1 = 2, 1< 3, 2 = 3
Procedural accuracy	-0.46	0.67	-0.08	1.04	0.87	0.54	5.24	**.013**	0.23	1 = 2, 1< 3, 2 = 3
Procedural efficiency RT (s)	0.15	0.78	-0.38	1.00	0.74	0.69	3.74	**.038**	0.16	1 = 2, 1 = 3, 2< 3

WIAT Wechsler Individual Achievement Test*; MPS* Mathematics Problem Solving

Age & IQ. A univariate ANOVA revealed no significant difference between the groups in age p = .378, ω^2_{p} = 0.00. The MANOVA revealed that the groups significantly differed in their intelligence scores V = .370*,* F (4,62) = 3.52, p = .012, ω_{p}^2 = 0.13. Separate univariate ANOVAs on the IQ scores showed significant differences between the groups on the WASI FSIQ (p = .002, ω^2_{p} = 0.29), but not on the BPVS (p = .072, ω^2_{p} = 0.10). Children in the Low WM cluster had significantly lower FSIQ scores on the WASI than children in the Intact EF cluster (p< .001, g = -2.16) and the Low Visuospatial EF cluster (p = .066, g = -1.09). Meanwhile children in the Intact EF cluster had higher FSIQ scores than the Low Visuospatial EF cluster (p = .218, g = -0.52). Notably, children in the Low WM cluster also had lower verbal IQ scores on the BPVS then Cluster 3 although this failed to reach statistical significance (p = .069, g = -0.90)

ADHD and co-occurring symptoms. Rates of clinical ADHD diagnosis in the Low WM cluster (N = 6), Low Visuospatial EF cluster , (N = 6) and the the Intact EF cluster (N = 5) were similar. Fisher's exact test showed that here was no significant association between cluster membership and whether or not children received a clinical ADHD diagnosis (p = .171).

The MANOVA revealed that the groups did not significantly differ on any of the parent-rated questionnaires V = .618*,* F (14,52) = 1.66, p = .093, ω_{p}^2 = 0.12. Univariate group comparisons were all non-significant (p's > .05) in relation to ADHD symptoms (g's ranging between 0.06 and -0.41), ODD (g's ranging between -0.07 and -0.31), CD (g's ranging between-0.18 and 0.46), ASD (g's ranging between 0.13 and 0.42), movement difficulties (*g*'s ranging between 0.18 and 0.58) and emotional and behavioural difficulties (*g*'s ranging between 0.17 and 0.72[18]).

Other cognitive processes. The MANOVA revealed that the groups did not significantly differ on their performance on the other cognitive tasks $V = .257, F\ (4,24) = .920$, $p = .508$, $\omega_p^2 = -0.01$. Univariate group comparisons between the groups were all non-significant (*p*'s > .05) on the delayed matching to sample task (*g*'s ranging between -0.37 and -0.78), spatial span forwards (*g*'s ranging between 0.17 and -0.69), spatial span reverse (*g*'s ranging between -0.02 and -0.46) and processing speed (*g*'s ranging between 0.02 and -0.20).

Maths. A MANOVA revealed significant differences between the clusters in maths scores $V = .812, F\ (14,40) = 1.95$, $p = .049$ $\omega_p^2 = 0.12$. There were significant differences between the groups on all WIAT achievement subtests (Figure 6.2) including Mathematics Problem Solving ($p = .003$, $\omega^2_{p} = 0.31$), Numeracy ($p = .007$, $\omega^2_{p} = 0.27$), and Maths Fluency ($p = .009$, $\omega^2_{p} = 0.25$). There were significant differences between the groups on the maths component tasks (Figure 6.3) including factual knowledge ($p = .040$, $\omega^2_{p} = 0.16$), conceptual understanding ($p = .026$, $\omega^2_{p} = 0.19$), and procedural skill accuracy ($p = .013$, $\omega^2_{p} = 0.23$) and efficiency ($p = .038$, $\omega^2_{p} = 0.16$). The profile of maths performance in each cluster is described below.

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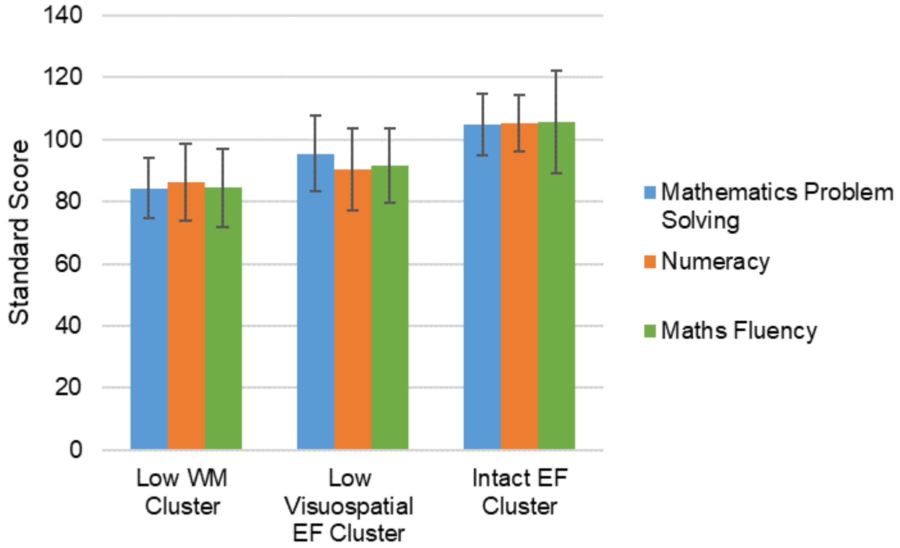
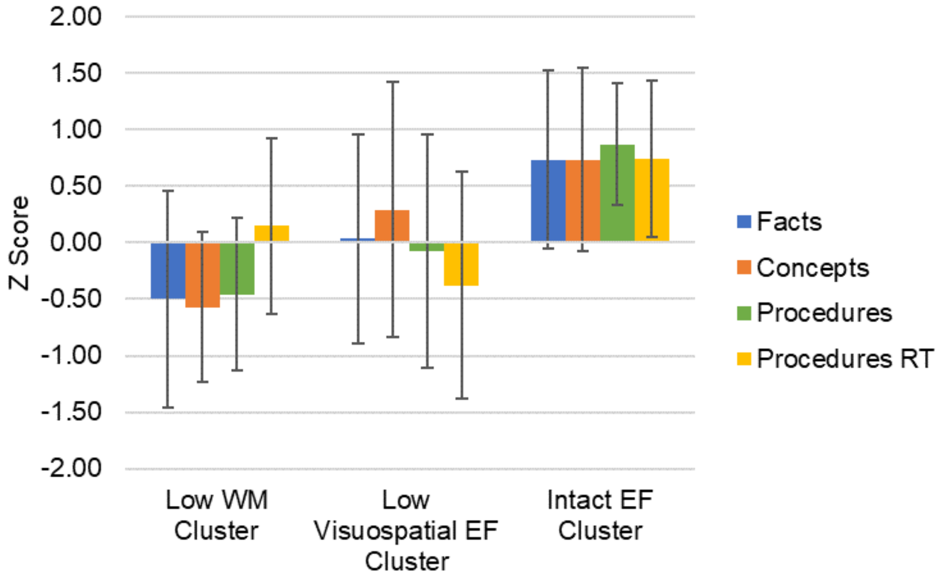
[18] This effect size was generated for differences between Cluster 1 and Cluster 3 on the SDQ, where Cluster 1 had higher emotional and behavioural difficulty scores.

Figure 6.2 Performance of EF clusters on standardised maths attainment



*Error bars are based on the standard deviations.

Figure 6.3 Performance of EF clusters on maths component tasks



*Error bars are based on the standard deviations.

Low WM cluster

Children in the Low WM cluster had the lowest maths achievement scores. Their attainment scores (i.e., < 90) classified them as 'Low Average Achievers' when compared to WIAT population norms. Children in the Low WM cluster had significantly lower attainment scores than the Intact EF cluster on Mathematics Problem Solving (*p* = .003, *g* = -1.75), Numeracy (*p* = .007, *g* = -1.42), and Maths Fluency (*p* = .008, *g* = -1.25) subtests. Children in this cluster also had the lowest scores on more specific maths tasks. They were significantly less accurate than children in the Intact EF cluster on factual retrieval (*p* = .035, *g* = -1.16), conceptual understanding (*p* = .029, *g* = -1.51), and procedural computations (*p* = .012, *g* = -1.80)

Low visuospatial EF cluster

Children in the Low Visuospatial EF cluster generally acted as the intermediate group scoring higher than the Low WM cluster but lower than children in the Intact EF cluster. Children in the Low Visuospatial EF cluster had WIAT scores (i.e., 90-95) on the lower threshold of ‘Average Achievers’ compared to population norms. The Low Visuospatial EF cluster did not differ significantly from the Low WM cluster on Mathematics Problem Solving (*p* = .083, *g* = -0.85), Numeracy (*p* = .766, *g* = -0.27) nor Maths Fluency (*p* = .531, *g* = -0.49) subtests. This cluster also had significantly lower scores than the Intact EF cluster on the Numeracy subtest (*p* = .028, *g* = -1.07), but did not significantly differ from the Intact EF cluster on Mathematics Problem Solving (*p* = .196, *g* = -0.67) nor in Maths Fluency (*p* = .067, *g* = -0.86). In relation to more specific maths components, children in the Low Visuospatial EF cluster did not significantly differ from the Low WM cluster on factual knowledge (*p* = .463, *g* = -0.48), conceptual understanding, (*p* = .126, *g* = -0.77), procedural skill accuracy (*p* = .657, *g* = -0.36), nor procedural skill efficiency RTs (*p* = .437, *g* = 0.48). Moreover, this cluster did not differ significantly from the Intact EF cluster on factual knowledge (*p* = .295, *g* = -0.67), conceptual understanding *(p* = .676, *g* = -0.36), nor procedural skill accuracy (*p* = .067, *g* = -0.89). Children in the Low WM cluster had significantly slower procedural efficiency RTs than Cluster 3 (*p* = .033, *g* = -1.04)

Cluster 3 ***Intact EF***

Children in the Intact EF cluster had the highest maths attainment scores. Their WIAT scores (i.e., > 100) categorised them on the upper threshold of 'Average Achievers' when compared to population norms. Children in the Intact EF cluster scored significantly higher than the Low WM cluster on Mathematics Problem Solving (*p* = .003, *g* = -1.75), Numeracy (*p* = .007, *g* = -1.42), and Maths Fluency (*p* = .008, *g* = -1.25) subtests. Children in this cluster also had significantly higher Numeracy achievement than the Low Visuospatial EF cluster (*p* = .028, *g* = -1.07), but did not differ significantly from them on Mathematics Problem Solving (*p* = .196, *g* = -0.67) nor Maths Fluency (*p* = .067, *g* = -0.86). The Intact EF cluster generally performed better on the maths component tasks. This cluster also had the highest scores on most maths skill tasks. They were significantly more accurate than the Low WM cluster on fact retrieval (*p* = .035, *g* = -1.16), conceptual understanding (*p* = .029, *g* = -1.51), and procedural computations (*p* = .012, *g* = -1.80). The Intact EF cluster did not differ significantly from the Low WM cluster in procedural computation efficiency RTs (*p* = .453, *g* = -0.67). There were no significant differences between the Intact EF and Low Visuospatial EF clusters on factual knowledge (*p* = .295, *g* = -0.67), conceptual understanding (*p* = .676, *g* = -0.36), and procedural skill accuracy (*p* = .067, *g* = -0.89).

Lastly, children in the Intact EF cluster had significantly faster procedural efficiency RTs than the Low Visuospatial EF cluster(p = .033, g = -1.04).

6.3.3 Cluster Analysis 2 – Memory clusters

6.3.3.1 Cluster identification

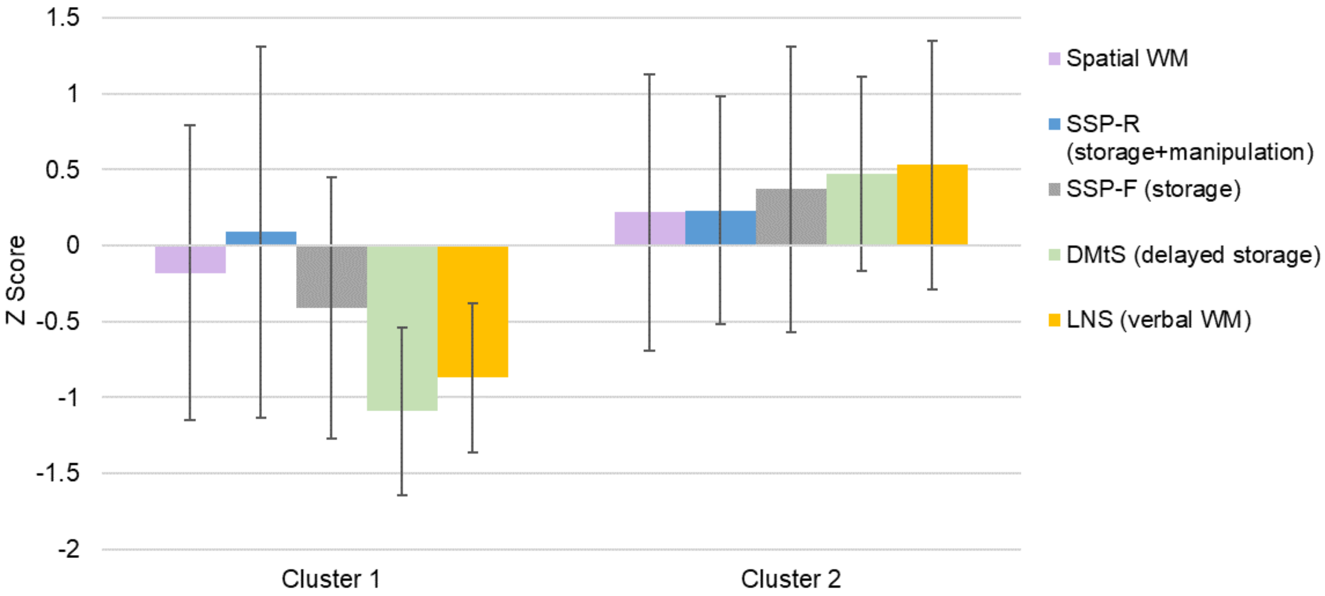
Initial inspection of the dendrogram revealed that a two-cluster solution would be most appropriate (Appendix I). The agglomeration coefficient schedule indicated a sudden jump at the 2-3 cluster combination (Appendix J). A 2 and 3-cluster solution was explored, with the 2-cluster solution generating the most homogenous and informative subgroupings.

6.3.3.2 Memory characteristics of subgroups

The performance of each cluster on the EF criterion variables is illustrated in Figure 6.4 and the results of the group comparisons are presented in Table 6.6.

Children in Cluster 1 had significantly lower scores than Cluster 2 on Spatial Span Forwards t (29) = -2.21, p = .035, 95% CI [-1.5, -.06], g = 0.72, Delayed Matching to Sample t (29) = -6.61, p< .001, 95% CI [-2.04, -1.08], g = 2.14, and Letters Numbers Sequencing t (29) = -1.16, p< .001, 95% CI [-6.41, -2.68], g = -1.60. The two groups did not significantly differ on Spatial WM Between Search Errors nor Spatial Span Reverse scores (p's > .05; g = -0.36 and g = -0.13, respectively).

Figure 6.4 Performance of clusters on criterion memory variables



*Error bars are based on standard deviation

SSP-R Spatial Span Reverse; *SSP-F* Spatial Span Forwards; *DMtS* Delayed Matching to Sample; *LNS* Letters Numbers Sequencing

6.3.3.3 Cluster validity

Age & IQ. Children in Cluster 1 had significantly lower IQ scores on WASI FSIQ *t* (29) = -4.00, *p* = .001, *g* = -1.29, 95%, CI [-26.90, -8.70] and BPVS *t* (29) = -2.14, *p* = .041, *g* = 0.69, 95% CI [-19.11, -0.44]. There were no significant differences between the cluster groups in age (*p*> .05, *g* = 0.34).

ADHD and co-occurring symptoms. Four children in Cluster 1 had a clinical ADHD diagnosis and 12 children in Cluster 2 received a clinical diagnosis. Fisher's exact test showed that here was no significant association between cluster membership and whether or not children received a clinical ADHD diagnosis (*p* = .407). Furthermore, the two cluster groups did not significantly differ on any of the parent rated questionnaires on ADHD symptoms and co-occurring symptoms (*p*'s> .05, effect size *g*'s ranging from 0.07 and 0.64).

Other cognitive processes. There were no statistically significant differences between the two memory clusters on inhibitory control, set shifting, planning, nor processing speed (*p*'s> .05, effect size *g*'s ranging from -0.02 and -0.14).

Maths. Children in Cluster 1 had lower achievement scores than Cluster 2 (Figure 6.5). The attainment scores of Clusters 1 (i.e., < 90) classified them as 'Low Average Achievers' when compared to WIAT population norms. Meanwhile Cluster 2's scores WIAT scores (i.e., 90-95) classifies them as 'Average Achievers' compared to population norms. Cluster 1 scored significantly lower than Cluster 2 on the Mathematics Problem solving *t* (29) = -4.26, *p*< .001, 95% CI [-25.46, -8.95], *g* = -1.38, and Numeracy subtests *t* (29) = -2.62, *p* = .010, 95% CI [-21.25, -2.63], *g* = -0.85. The cluster groups did not significantly differ on WIAT Maths Fluency attainment scores (*p*> .05; *g* = -0.56). Children in Cluster 1 scored significantly lower than Cluster 2 on tasks assessing more specific maths skills (Figure 6.6) including factual knowledge *t* (28) = -2.33, *p* = .027, 95% CI [-1.63, -0.11], *g* = -0.78, conceptual understanding *t* (28) = -2.95, *p* = .006, 95% CI [-1.79, -0.32], *g* = -0.99, and procedural skill accuracy *t* (25) = -4.16, *p*< .001, 95% CI [-1.78, -0.60], *g* = -1.48. The groups did not differ on their procedural skill RT efficiency scores (*p*> .05, *g* = -0.14).

Figure 6.5 Performance of memory clusters on standardised maths attainment

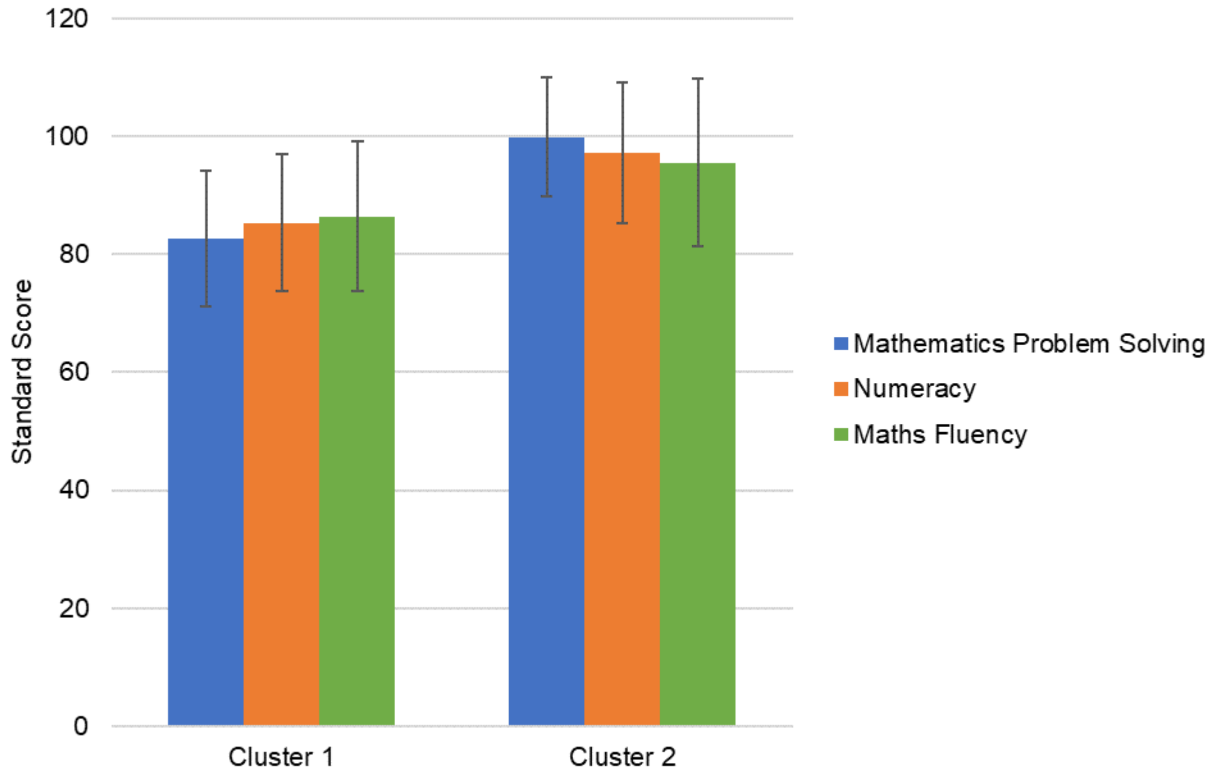
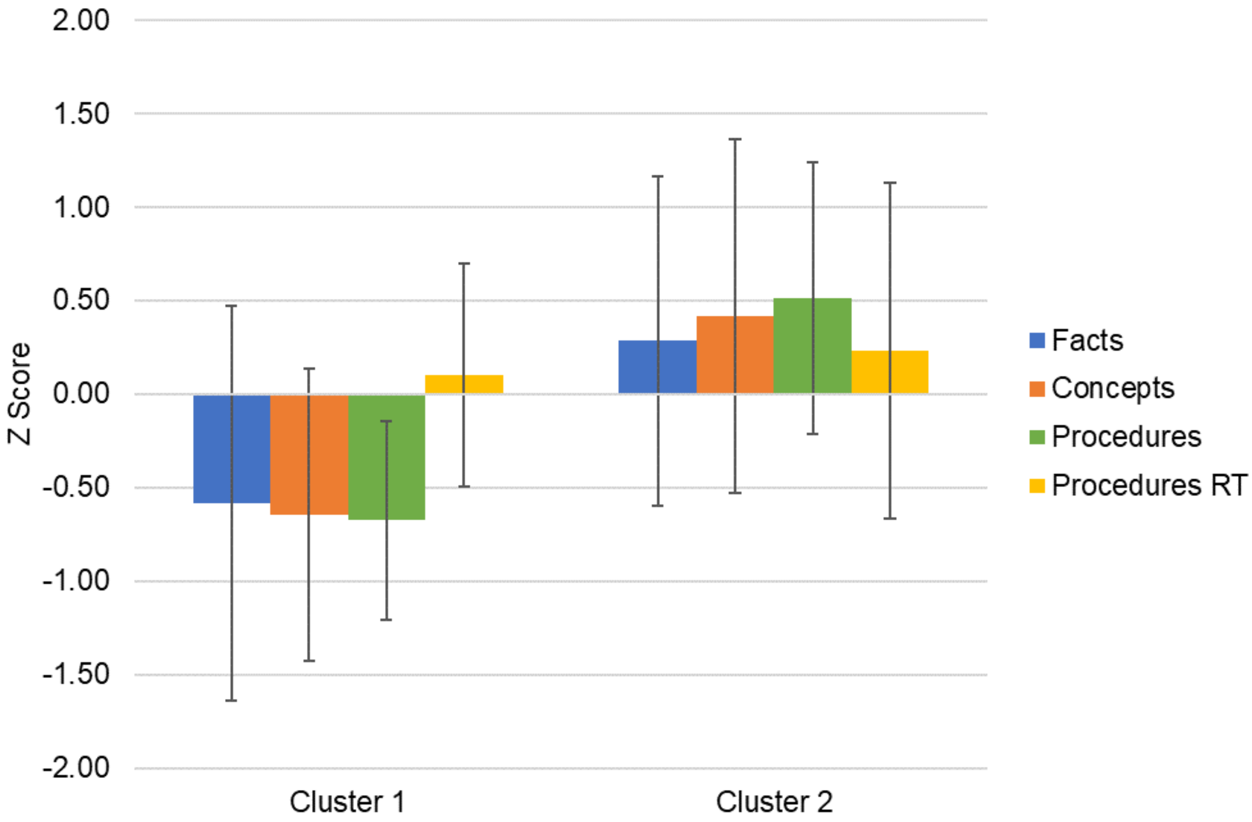


Figure 6.6 Performance of EF clusters on maths component tasks



*Error bars are based on standard deviation

Table 6.6 Results of comparisons between memory cluster groups

	Cluster 1 N = 10		Cluster 2 N = 21		Group contrasts		
	Mean	SD	Mean	SD	*t/U*	*p*	*g/r*
Criterion Memory Variables							
Spatial WM Between Search Errors	-0.18	0.97	0.22	0.91	-1.16	.258	-0.36
Spatial Span Reverse	0.09	1.22	0.23	0.75	-0.32	.752	-0.13
Spatial Span Forwards	-0.41	0.86	0.37	0.94	-2.21	**.035**	-0.72
Delayed Matching to Sample	-1.09	0.55	0.47	0.64	-6.61	**.000**	-2.14
Letters Numbers Sequencing	-0.87	0.49	0.53	0.82	-4.99	**.000**	-1.60
Age & IQ							
Age (months)	100.90	17.76	108.86	20.65	-1.05	.304	-0.34
WASI FSIQ	86.20	11.36	104.00	11.67	-4.00	**.001**	-1.29
BPVS	90.80	13.40	100.57	11.13	-2.14	**.041**	-0.69
Other cognitive processes							
Stop Signal RT (inhibitory control)	-0.17	1.07	-0.02	0.78	-0.44	.666	-0.14
Intra-Extra Dimensional Errors (shifting)	0.12	0.61	0.22	0.83	-0.34	.734	-0.11
Stockings of Cambridge Problems Solved (planning)	0.18	1.10	0.04	0.92	0.35	.729	0.11
SST Median RT (processing speed)	-0.05	0.93	-0.03	0.93	-0.06	.954	-0.02
Parent Questionnaires							
Conners ADHD Inattention	82.10	13.81	83.33	8.11	98.50	.787	-0.05
Conners ADHD Hyperactivity-Impulsivity	87.30	6.46	83.90	10.32	78.50	.268	-0.23
Conners Oppositional Defiant	86.60	6.79	79.57	14.17	72.00	.173	-0.27
Conners Conduct Disorder	78.60	13.66	69.24	15.87	0.12	.120	0.52
Autism Quotient	4.20	2.82	4.29	2.70	-0.08	.936	-0.03
Movement ABC	19.10	17.458	17.67	15.525	0.82	.819	0.07
Strengths and Difficulties Questionnaire	26.60	6.38	21.90	6.07	1.98	**.057**	0.64
Maths							
WIAT MPS	82.70	11.47	99.90	10.04	-4.26	**.000**	-1.38
WIAT Numeracy	85.30	11.59	97.24	11.96	-2.62	**.010**	-0.85
WIAT Maths Fluency	86.40	12.70	95.52	14.23	-1.72	.095	-0.56
Factual Knowledge accuracy	-0.59	1.06	0.28	0.88	-2.33	**.027**	-0.78
Conceptual Understanding accuracy	-0.64	0.78	0.41	0.95	-2.95	**.006**	-0.99
Procedural accuracy	-0.68	0.53	0.51	0.73	-4.16	**.000**	-1.48
Procedural Efficiency RT (s)	0.10	0.60	0.23	0.90	-0.39	.703	-0.14

6.4 Discussion

This study explored the implications of cognitive heterogeneity for maths performance in children referred for ADHD diagnosis. Broadly, findings showed that the categorical diagnostic approach was not informative to children's maths outcomes. By contrast, the data-driven statistical approaches generated meaningful cognitive subgroups which could be differentiated on their intelligence and maths scores. This suggests that data-driven cognitive subtypes are more useful prognostic indicators of maths outcomes in ADHD than children's diagnostic status. The findings and implications of each analytical segment are discussed below, followed by an overarching discussion of their limitations.

6.4.1 EF Clusters

Cluster analysis using EF variables generated three distinct EF subtypes: (1) Low WM, (2) Low Visuospatial EF, and (3) Intact EF. Children in the Low WM cluster were distinguished from the other two groups by diminished performance on visuospatial WM and verbal WM updating tasks and had the lowest maths and intelligence scores when compared to the other two groups. This is consistent with previous studies showing that WM underpins children's maths achievement (Allen et al., 2019; Cragg et al., 2017; Calub et al., 2019; Friedman et al., 2018; Friso-Van Den Bos et al., 2013; Holmes et al., 2014) and extends this to more specific maths skills of factual, conceptual, and procedural maths components. Thus, children with WM updating difficulties may be at most need for maths intervention when compared to other children with ADHD. Notably, children in the Low WM cluster were also characterised by poorer performance on the delayed visuospatial memory task than the Intact EF cluster (g = -0.78). Maintaining relevant information across a delay is a necessary component of WM tasks (Daniel et al., 2016). As such, it cannot be ruled out that decay of stored information could have contributed difficulties in the Low WM cluster (e.g., decay of previously visited token locations on the spatial WM task).

The Intact EF cluster generally showed better performance on all EF tasks when compared to the other groups. This is consistent with the notion that EF profiles in ADHD are highly heterogeneous (Coghill et al., 2014; Kofler et al., 2019; Nigg et al., 2005; Sonuga-Barke et al., 2008) and confirms the existence of an ADHD group with comparatively intact EF performance (Roberts et al., 2017; Kofler et al., 2019). Children in this cluster showed the highest maths and intelligence scores. This is in line with previous research showing that children with better EF are higher achievers than children with lower EF performance (Roberts et al., 2017). Thus, children with high ADHD symptoms who show relatively intact EF performance compared to their peers may be at least need for maths intervention. The Intact EF cluster did not significantly differ from the other two groups on other cognitive tasks including visuospatial memory (i.e., storage, manipulation, and delayed recognition) and processing speed. Thus, problems in these other lower-level cognitive processes could be ruled out.

The Low Visuospatial EF cluster showed diminished performance on tasks containing visuospatial stimuli when compared to the other groups. Children in this cluster had substantially lower set shifting and planning scores than the other two groups and made greater visuospatial WM errors than the Intact EF group. Their relatively unaffected verbal WM raises the possibility that lower EF scores in this group are driven primarily by difficulties in visuospatial processing. However, when compared to the other two groups, children in the Low Visuospatial EF cluster did not significantly differ in their performance on other lower-level cognitive tasks taxing visuospatial processing. There was one exception – children in the Low Visuospatial EF cluster on average scored lower on the visuospatial STM storage task (*g* = -0.69) than the Intact EF cluster. Thus, it is possible that difficulties with storing relevant visuospatial information in STM compromised this cluster's performance on the other EF tasks (e.g., remembering which stimulus attribute should be attended to on the Intra-extra Dimensional shifting task).

In the context of maths, the Low Visuospatial EF group acted as an intermediate between the other two groups. Their attainment scores were not as high as the Intact EF cluster, but not as low as the Low WM cluster. This suggests that while visuospatial EF difficulties increase risk for difficulties in maths, these may not be as pronounced as those found in children with multimodal WM vulnerabilities. Both descriptively, and in terms of effect size magnitudes, children in the Low Visuospatial EF clusters scored lower than the Intact EF cluster on all maths component tasks. The only exception was the conceptual understanding task on which these two groups were comparable. This implicates visuospatial EF processes as important to children's maths abilities and suggests that conceptual reasoning may not be as dependent on visuospatial EF processes as other maths skills.

The lack of significant distinction between the groups on inhibitory control was consistent with a previous study showing inhibitory control is not useful for differentiating between neuropsychological ADHD profiles (Takács et al., 2014). However, it is unlikely that disinhibition was a cognitive characteristic common to all children, as children in the Low Visuospatial EF cluster showed lower scores on the inhibitory control task (also containing visuospatial stimuli) than the Intact EF group (*g*

= -0.71). Further work is necessary before inhibitory control is ruled out as an important subtyping mechanism. Unlike Roberts and colleagues (2017) this study did not find a poor shifting cluster and a distinct poor inhibitory control cluster. However, their study did not include assessments of verbal and visuospatial WM. The current findings imply that when WM processes are considered children with poor inhibitory control and cognitive flexibility appear to cluster together under a broader visuospatial EF vulnerability profile that is distinct from children with WM multimodal updating difficulties. This is consistent with the finding that updating as the most relevant EF factor for distinguishing amongst neuropsychological profiles of children with ADHD (Takács et al.,2014). Thus, those with WM updating difficulties form a distinct group who are at greater risk for maths difficulties than children with low inhibitory control and shifting difficulties.

One surprising finding was in relation to the lack of differentiation of the groups using planning scores. Children in the Low WM cluster were comparable in their planning scores to the Intact EF cluster. Planning involves monitoring, re-evaluating, and updating a sequence of planned actions, to achieve a goal and, as such, relies on the integrity of other EF processes such as WM (Best et al., 2009; Miyake et al., 2000). One possibility for why these two functionally distinct clusters did not differ in their more complex planning abilities is that children did not use a goal-oriented strategy which taxes the ability to manage goals and devise a sequence of subgoals. The desired goal state (i.e., what the stockings should look like) was perceptually available to children throughout the task. Thus, children may have opted for a less demanding perceptually oriented strategy, rather than a more demanding goal-management strategy (Miyake et al., 2000). In the perceptual strategy, children make moves that align the current state perceptually closer to the intended state, and so the involvement of more complex cognitive processes such as WM updating is minimised (Miyake et al., 2000). This strategy may have been selected because children had readily available cues which they could refer to at any point during the task to help them get a step closer to the desired state, and so they did not need to devise or update the pre-planned sequence in memory (Noyes & Garland, 2003). This could also help explain why the Low Visuospatial EF group had the lowest planning scores – their difficulties with visuospatial processing, such as fast decay of the accessible cues, could have hindered their ability to capitalise on the perceptual salience strategy.

6.4.2 Memory clusters

The second data-driven analytical strategy used children's memory scores to generate clusters. Two cluster subgroups were identified: Children in Cluster 1 showed lower performance on tasks assessing visuospatial STM, delayed visual recognition memory, and verbal WM than Cluster 2. Notably, the two clusters were comparable in their visuospatial WM scores. Thus, while both clusters show similar visuospatial WM profiles, a distinct group emerged with more pronounced difficulties in visuospatial memory storage and verbal WM. This is consistent with findings on ADHD-associated heterogeneity in memory profiles without concurrent processing (Gomez et al., 2014; Martinussen et al., 2005; Rhodes et al., 2012, Rhodes et al., 2004). The two memory clusters did not differ on inhibitory control, set shifting, and planning scores, ruling out the role of these other EF processes in the cluster membership.

The two memory clusters could be differentiated using maths and intelligence scores. Specifically, children in Cluster 1 had lower intelligence and maths achievement scores than children in Cluster 2. In terms of more specific maths skills, children in Cluster 1 were less accurate in their factual knowledge, conceptual understanding, and procedural skill computations. This is in line with research showing substantial associations between visuospatial memory storage and maths attainment (Friedman et al., 2018; Friso-Van Den Bos et al., 2013) and extends this to more specific maths skills in ADHD. The findings of the memory cluster analysis therefore imply that difficulties with short term and delayed storage of visuospatial information can have negative consequences on children's maths performance.

Although previous work highlights the potential role of co-occurrences in children's memory profiles, such as ODD (Rhodes et al., 2012; Saarinen et al., 2015) and DCD (Martinussen et al., 2005), the current study did not find significant differences between these two groups on parent-rated questionnaires assessing these co-occurring symptoms. Nonetheless children in Cluster 1 showed increased emotional and behavioural difficulties on the SDQ ($g = 0.64$). Thus, it is possible that general predisposition to a negative affective state hindered children's performance on the tasks (De Meyer et al., 2019). However, given that no differences were found between the two clusters on any of the EF tasks, this was unlikely. The current findings therefore point to the potential existence of an ADHD subtype with broader memory difficulties who are greater risk for maths difficulties.

The finding that children could not be distinguished using their performance on visuospatial WM tasks is consistent with previous work showing visuospatial WM difficulties are present in a large proportion of children with ADHD (Kofler et al., 2020). Both visuospatial WM tasks placed substantial demands on the central executive, responsible for manipulating and updating information stored in memory. Thus, one possibility is that a common feature of children with ADHD difficulties is diminished performance in the central executive. However, given that the groups could be distinguished on verbal WM performance, which also taxed the central executive, it is unlikely that this can be explained on the sole basis of diminished central executive processing. A previous study found that only a third of children had visuospatial WM difficulties (Coghill et al., 2014). However, their sample size was over twice as large, and so it is possible that the smaller sample size used here led to higher probability for identifying children who all share similar profiles of visuospatial WM performance.

At first glance the lack of difference in visuospatial WM in the two memory clusters is counterintuitive to the findings of the EF clusters where the Low WM and Low Visuospatial EF could be distinguished from the Intact EF group by substantially lower visuospatial WM. However, as previously mentioned the Intact EF group were also characterised by higher delayed visual recognition memory (when compared to the Low WM cluster) and better visuospatial STM storage scores (when compared to the Low Visuospatial EF cluster). Thus, it is possible that the lower-level memory processes were driving these group differences in the EF clustering approach. Furthermore, while the EF clusters were generated using scores on a visuospatial WM task with updating demands, the memory cluster analysis included an additional visuospatial WM task without updating demands. As such, it could have provided a more accurate characterisation of the homogenous visuospatial WM profiles.

6.4.3 ADHD symptoms and clinical outcomes of clusters

A common finding to both clustering approaches was that children were comparable in their inattention and hyperactivity/impulsivity symptoms. Kolfer and colleagues (2018) found that children with greater WM difficulties showed higher ADHD symptoms than those without WM difficulties. However, the mean parent rated inattention and hyperactivity/impulsivity scores in that study were lower (i.e., < 70) than the current study (i.e., > 80). It is possible that children included in the current study generally had higher ADHD-associated difficulties. Another study by Roberts and colleagues (2017) did not find differences in inattention but were able to show that the poor set-shifting/speed cluster had higher hyperactivity-impulsivity symptoms, as indicated by parent interview > 6 symptoms counts, than other EF subtypes. This different finding could be attributed to the difference in the way in which ADHD symptoms were assessed as the current study relied on the more comprehensive Conners DSM-5 ADHD T-scores.

Another commonality in both clustering techniques was the finding that clusters were comparable in rates of clinical ADHD diagnosis. This implies that diagnostic ADHD classification systems and are not informative to establishing neuropsychological and academic profiles. Further, in both approaches the clusters did not significantly differ on co-occurring disorder symptoms. Consistent with previous work, this implies that cognitive vulnerabilities cut across different developmental disorder symptoms (Astle et al., 2019). Furthermore, co-occurrences appear to be the rule rather than the exception (Elia et al., 2008; Reale et al., 2017). Yet, many studies continue to rely on a ‘pure’ ADHD approach, excluding children with other neurodevelopmental disorders from participating. The current findings therefore suggest that rather than excluding children with concurrent disorders, future work should focus on capitalising on the rich data that children can provide and instead using data-driven cognitive profiles as methods for grouping children into homogenous and meaningful groups. Such approaches will be especially important for developing academic interventions that are based on children’s neurocognitive profiles.

6.4.4 Diagnostic subgroups

The categorical approach compared children with a confirmed clinical ADHD diagnosis to those who did not meet criteria for a clinical ADHD but nonetheless scored high on ADHD symptoms (i.e., subclinical ADHD). Findings showed that the two groups were comparable in their intelligence scores, as well as in their performance on EF and memory tasks. In relation to maths, children who ended up receiving an ADHD diagnosis actually showed better accuracy on factual retrieval and conceptual understanding, as well as scoring higher on the problem-solving achievement subtest than children with subclinical ADHD. Thus, these findings suggest that arbitrary diagnostic ADHD categories do not appear to successfully differentiate between children with varying levels of cognitive functioning and are not informative to children's maths outcomes.

Much of the neurodevelopmental literature focuses on comparing children with and without a clinical diagnosis on cognitive and academic outcomes. However, such categorical approaches are limited in their assumptions of functional homogeneity in disorders such as ADHD. Furthermore, the categorical approach overlooks equally debilitating academic difficulties found in children with subthreshold ADHD symptoms (Karalunas & Nigg, 2020) – rates of whom were comparable in both cluster analysis techniques. Research consistently shows that even children who fall short of the criteria necessary for a clinical ADHD diagnosis are at higher risk for academic adversities (Czamara et al., 2013; Hong et al., 2014; Marcus & Barry, 2011). Children with this type of 'subclinical ADHD' show persistent levels of under-attainment in numeracy (May et al., 2020). Despite this, existing literature continues to rely on categorical approaches to group children based on diagnostic outcomes. As demonstrated in the current study, a dimensional characterisation of cognition in children with high ADHD difficulties is more informative to children's maths outcomes than arbitrary diagnostic categories. Future neurodevelopmental research should therefore explore cognitive, rather than diagnostic, subtypes when exploring academic difficulties. This will also enable the developmental of appropriate maths interventions irrespective of children's diagnostic status.

6.4.5 Limitations

One of the main limitations of this study is the small sample size. While it benefits from the use of a large battery of cognitive assessments, the small sample size limited the number of criterion variables which could be entered at the cluster identification stage. EF subtypes are subject to wide speculation in ADHD theory, to the extent that some researchers suggest refining DSM-5 diagnostic ADHD subtypes with EF subtype profiles (Roberts et al., 2017). Thus, it was important to address EF classifications when assessing an ADHD sample. Comparatively less attention has been given to children's memory profiles, and in particular memory without concurrent processing. Lower-level memory processes have previously been implicated in ADHD (e.g., Rapport et al., 2008; Rhodes et al., 2005; 2012) and in children's maths performance (Bull et al., 2008; Gathercole et al.,2006; Passolunghi et al., 2014; Swanson & Kim, 2007). Thus, it was equally important to explore memory subtypes and their implications to maths profiles in the alternative cluster analysis approach. While the current study reports the EF and memory cluster analyses separately, future work using larger samples would benefit from including all cognitive scores as criterion variables under a single cluster analysis when exploring their implications to maths. Another possibility would be to use existing datasets to explore whether the clusters can be confirmed. This would enable a more holistic approach to subtyping cognitive profiles in ADHD. Furthermore, larger samples would help increase the amount of within-group heterogeneity that can be accounted for. Although the small sample size limited the number of criterion variables that was incorporated into the analysis, the number of variables entered in each of the analyses was considered in line with previous recommendations (Formann, 1984). Furthermore, cluster analysis has been used with small neurodiverse samples (e.g., Little et al., 2013) and in ADHD research (e.g., Nuñez, et al.,2020; Roberts et al., 2017).

Although the findings implicate verbal WM difficulties as increasing risk for maths difficulties in ADHD, this should be interpreted with caution. The verbal WM task required processing of numbers and letters which may have been generally easier for children with higher academic abilities. Although assessing verbal WM without reliance on stimuli words and letters is difficult, future research would benefit from exploring verbal WM performance in tasks without digit processing to, at the very least, rule out the confounding effects of numerical abilities. Furthermore, verbal STM was not assessed here. Previous work points to difficulties in verbal STM in ADHD (Martinussen et al., 2005 Rhodes et al., 2012) and as predictive of children's maths performance (Bull et al., 2008). Further work is necessary to explore the implications of data driven verbal STM profiles to children maths performance.

It is also important to note that the interpretation of performance of the clusters relied on their performance relative to the other ADHD clusters. Thus, while there were relatively 'intact' clusters, these were not compared to neurotypical controls. Furthermore, other behavioural (e.g., maths anxiety) domains were not assessed here. Thus, it cannot be ruled out that these unassessed domains affected children's cluster membership. These factors are shown as important to children's maths performance (Passolunghi et a, 2016) and so would benefit from being considered in future work.

6.4.6 Conclusions

The current study supports existence of cognitive heterogeneity in ADHD. To the best of the authors knowledge this is the first study to comprehensively investigate cognitive heterogeneity in a clinically referred ADHD sample, whilst concurrently considering its implications for children's maths skills. Evidently, grouping children based on diagnostic categories is not informative to these functional outcomes. By contrast, grouping children using data-driven cognitive scores generates distinct profiles in maths performance that are meaningful both in terms of children's attainment and more specific maths skills. This highlights the utility of data-driven cognitive profiles for differentiating between children with variable maths abilities, and cautions against use of dichotomous diagnostic categories where grouping children in neurodevelopmental research. Assessing children's cognitive functioning will be especially informative to identifying children who are in most need for intervention and tailoring appropriate intervention to their needs.

7 Chapter 7: General discussion

This thesis provides the first detailed investigation of cognition, behaviour, and maths in children referred for clinical ADHD evaluation. This chapter highlights the key findings of the research and their practical implications, followed by a discussion of the strengths and limitations, as well as directions for future research.

7.1 Summary and implications of findings

7.1.1 Cognitive and maths performance in children with ADHD (Chapter 2)

Chapter 2 investigated existing literature on the association between cognitive processes and maths performance in children with a clinical ADHD diagnosis. A previous review (Tosto et al., 2015) had found evidence for a negative association between ADHD symptoms and maths performance. The stronger finding in relation to symptoms of inattention pointed to the potential role of higher-order cognitive processes responsible for attention control. Thus, the review in the present thesis sought to delve deeper into this idea by systematically exploring existing research which specifically investigating the relationship between cognitive task performance and maths in ADHD. The review found that verbal WM and visuospatial WM showed particularly strong associations with children's maths attainment scores, highlighting the importance of WM to maths. However, very few studies (N = 4) directly addressed the association between cognition and maths in ADHD. The few studies that did meet inclusion criteria assessed limited and often different cognitive processes (memory, inhibition, and/or processing speed), limiting definitive conclusions and highlighting a gap in research in this area. This raises concerns around the availability of evidence to inform appropriate decision making by practitioners and policymakers when it comes to maths interventions (Simms et al., 2019). Although at first glance the lack of research was surprising, in hindsight it could reflect the novelty of exploration of the relationship between cognition and maths in children more generally (Allen et al., 2019). Furthermore, much of the excluded literature used ADHD-vs-control designs to compare performance on cognitive and maths tasks, without addressing the association between key domains of interest. Using ADHD-vs-control approaches exaggerate homogeneity in ADHD, which can become counterintuitive to developing suitable educational interventions. Years of research has now established that ADHD can put children at greater risk for maths difficulties when compared to neurotypical controls (Tosto et al., 2015). What is less frequently addressed, but arguably more important, are the mechanisms that are associated with maths difficulties in this population and the characteristics which distinguish children with ADHD with and without educational difficulties. Effective and theoretically oriented interventions will depend on future research addressing such heterogeneity.

7.1.2 Cognitive correlates of maths performance of children referred for ADHD evaluation (Chapter 4)

In Chapter 4 children with high ADHD symptoms and referred for clinical ADHD evaluation were tested on a large battery of tasks tapping into higher order EF processes and other lower-level cognitive processes that were previously implicated in maths. Children were recruited from the CAMHS waiting list, regardless of whether or not they ended up receiving a clinical diagnosis. This allowed for the assessment of children's cognitive function while they were still drug naïve. Another novelty of Chapter 4 was the exploration of key maths component skills thought to contribute to broader maths attainment levels – factual knowledge, conceptual understanding, and procedural skill. Although the role of these domain specific maths skills in broader attainment were previously explored in a neurotypical population (Cragg et al., 2017), these had not been comprehensively investigated in children with ADHD. However, since these findings cannot indicate causal pathways, these are only suggested hypotheses for future work.

The results of Chapter 4 showed that cognition, but not behavioural ADHD symptoms, generated strong associations with maths performance across the board. Although some research shows that ADHD symptoms uniquely predict mathematics underachievement, cognitive factors tend to mediate this association (Antonini et al., 2016; Barry et al., 2002; Gremillion & Martel, 2012; Greven et al., 2014; Hart et al., 2010; Mayes et al., 2020; Rogers et al., 2011). This suggests that the relationship between maths and ADHD symptoms could be an artefact of underlying cognitive difficulties. The current findings support this notion and imply that researchers should focus on identifying cognitive signatures of maths difficulties, rather than behavioural characteristics.

Chapter 4 was the first study to provide a detailed account of domain general and domain specific mechanisms associated with maths attainment in ADHD. Similar to studies in neurotypical samples the factual, conceptual, and procedural domain specific skills were significantly related to children’s broader maths attainment scores (e.g., Cowan & Powell, 2014; Cragg et al., 2017). Thus, all three domain specific maths skills are essential to successful acquisition of more complex maths processes found in standardised achievement tests.

Chapter 4 also demonstrated differential patterns of associations between cognitive processes and maths. Perhaps some of the strongest evidence was found in relation to *working* and *storage* aspects of memory which showed substantial associations with all maths attainment subtest scores and, albeit to a lesser extent, with the domain-specific maths component skills. This is in line with a previous meta-analysis (Friso-van den Bos et al., 2013) which found that WM components are more strongly related to broad maths test scores of primary school children than more specific arithmetic assessments. Standardised achievement tests, which simulate national curriculum assessments, employ a variety of maths skills including retrieval of numerical facts, reasoning about numerical concepts, and solving procedural computations (Van de Weijer-Bergsma, et al., 2015). Thus, it is not surprising that the relationship between verbal and visuospatial memory processes with maths attainment is amplified under circumstances where multiple numerical skills are employed.

Other key EF processes namely, inhibition, cognitive flexibility and planning did not emerge as important to maths as memory processes. As the EF tasks in the current thesis did not contain numerical stimuli, this supports the notion that associations between other EFs and maths are likely domain specific (Cragg et al., 2017). Furthermore, it complements the notion that when compared to WM other EF processes may not be as important (Cragg et al., 2017). In the context of ADHD, the lack of meaningful relationship between EF processes and maths is important as EF deficits are central to prominent models of the disorder and are frequently affiliated with behavioural manifestations in the classroom (e.g., being impulsive and struggling to stay on task). The current findings thereby suggest that children with ADHD who show memory storage and WM difficulties could be at increased risk for maths difficulties.

Importantly, the patterns of associations between cognition and maths skills were not uniform across the factual, conceptual, and procedural domains. For example, while factual knowledge and procedural skill components showed meaningful associations with virtually all visuospatial and verbal memory domains, conceptual understanding was exclusively associated with verbal aspects of memory. This differential role of verbal and visuospatial memory processes will have important implications for the type of intervention that may be most useful for the child and the modality in which it is delivered (i.e., visuospatial vs verbal). To illustrate, children with factual retrieval difficulties may primarily benefit from both verbal and visuospatial interventions aimed at increased practice for factual fluency. Examples could include enhancing associations between spatial representations of numbers (e.g., training children to recognise which pairs of numbers add to 10; Jay et al., 2019). This could be particularly useful for children who are still mastering less mature visuospatial representations and strategies (e.g., number lines, finger counting, visuospatial digits; van der Ven et al., 2013). Further mastery of phonological codes can be encouraged by rote rehearsal and encouragement of verbalising methods such as solving spatially presented sums out loud. Eventually this will help children shift from less mature visuospatial solution strategies which tax WM (e.g., finger counting), to more efficient phonologically oriented factual fluency.

Based on the current findings that conceptual understanding is more closely related to verbal memory, children with poor conceptual reasoning may primarily benefit from phonologically oriented intervention strategies such as, for example, talking through or writing down their reasoning behind problem solving. However, it is important to note that there is evidence to show that spatially oriented interventions using visualisation strategies and spatial objects also result in improvements in conceptual understanding (Simms et al., 2019).

For children who struggle with more complex procedural skill, it may be useful to allow the child to devise step by step solution reasoning plans that they can work through, and in doing so reduce the amount of information which has to be held and monitored 'online'. Children can also be encouraged to highlight important information and make notes as they go to minimise interference in WM, allowing the child to focus on successfully solving the problem. There is some evidence to show that drawing out strategical 'schemas' and using these graphic diagrams to solve the problem can improve children's maths performance (Griffin & Jitendra, 2008; Poland & van Oers, 2007; Sulak, 2010; Simms et al., 2019)

7.1.3 Cognition and maths in children with ADHD with and without co-occurring movement difficulties (Chapter 5)

Evidence for high co-occurrence rates with other developmental disorders raised important questions about how these potentially affect children's cognitive and maths performance. Despite evidence for diminished visuospatial memory processing in DCD, which is frequently implicated in maths, and high rates of co-occurrence of DCD in ADHD, little research has addressed functional outcomes of their co-existence. As such, Chapter 5 examined the cognitive and maths profiles of children with and without co-occurring motor difficulties indicative of DCD. Findings showed that children with ADHD + co-occurring motor difficulties were generally comparable to their ADHD-only counterparts on key EF processes, memory, and processing speed. However, a key differentiating characteristic of children with concurrent ADHD + co-occurring motor difficulties was the substantially poorer performance on visuospatial WM without updating requirements (i.e., concurrent storage and manipulation of temporarily stored visuospatial information). This implies that co-occurring DCD symptoms increase children's risk for diminished ability to manipulate visuospatial content in memory. This carries important implications for clinical practice as it suggests children with concurrent DCD can be identified by more pronounced difficulties in visuospatial WM manipulation tasks. Furthermore, it suggests that children with concurrent DCD would benefit from remediation strategies that support manoeuvring of visuospatial information.

Despite these differences in this very specific cognitive domain, Chapter 5 showed that children with and without concurrent DCD were largely comparable in their maths attainment scores and domain-specific maths skills. This again echoes the idea that behavioural disorder symptoms are not informative to children's maths outcomes. At first glance this could be interpreted as visuospatial WM as not being important for maths performance. However, as demonstrated in Chapter 4, visuospatial WM shows substantial associations with range of maths skills. A more plausible explanation is that grouping children using diagnostic categories (i.e., ADHD vs ADHD + co-occurring motor difficulties) exaggerated homogeneity of maths performance. This parallels recent advances in the literature which show that diagnostic categories are not informative to academic outcomes (Astle et al., 2019; Gathercole et al., 2018). Indeed, Chapter 5 pointed to the notion that cognitive correlates of maths performance in ADHD with and without concurrent DCD were generally comparable.

7.1.4 Data-driven profiles of cognitive performance in ADHD: implications for maths (Chapter 6)

The role of cognitive processes in maths was further substantiated in Chapter 6. At this stage information regarding most children's diagnostic outcomes became available, which enabled a group comparison based on confirmed clinical diagnoses. First, children were grouped using categorical diagnostic outcomes (i.e., clinical ADHD vs subthreshold ADHD) and were compared on maths, intelligence, and parent-rated symptoms. Thereafter, an alternative data-driven cluster analysis was used to identify homogeneous subgroups based on children's scores on tasks assessing (1) EF, and (2) memory. The EF oriented clustering strategy generated three ADHD subtypes which could be distinguished on their maths performance. The Low WM group showed the lowest maths performance while the Intact EF group had the highest math scores. The Low Visuospatial EF group acted as somewhat of an intermediate between the other groups. Together these findings implied that diminished WM updating, and to a lesser extent visuospatial EF, increases children's risk for maths difficulties. However, as demonstrated by effect size magnitudes the Intact EF group showed better performance on some of the other lower-level visuospatial memory tasks that may have contributed to their higher EF abilities. Thus, an alternative memory-oriented cluster analysis was also explored. This was particularly important as Chapter 4 clearly showed stronger associations between memory variables and children's maths when compared to the EF score. The memory clustering technique identified a distinct subgroup with substantially lower scores on verbal WM, visuospatial STM, and delayed storage of visuospatial information. Contrary to the EF clustering approach, the memory cluster analysis did not find differences between the clusters on visuospatial WM. The cluster with broader memory difficulties also scored substantially lower on both the most achievement tests and on the more specific maths skills. Collectively, these findings point to lower-level memory storage for visuospatial information and verbal WM as key to identifying homogenous subgroups of children with high ADHD symptom difficulties who struggle with maths.

Collectively, both cluster analysis techniques implicated the role of verbal WM as key to subtyping children with different maths profiles. However, the numerical stimuli in the verbal WM task may have confounded these findings. Furthermore, storage for verbal information without concurrent processing was not assessed and so it is unclear whether working or storage aspects of verbal memory was the key distinguishing characteristic. As shown in in Chapter 3, the little literature that does exist (i.e., Alloway, 2011; Friedman et al., 2018; Miranda-Casas et al., 2012) generally does not show strong associations between verbal STM and children's maths attainment once age and IQ are accounted for. However, the findings in a smaller subsample of children in Chapter 4 showed that non-executive immediate and delayed verbal recognition memory generated some of the strongest associations with children's maths performance.

A common finding across both EF and memory clustering strategies was that children in the data-driven cognitive groups did not differ on ADHD symptoms, rates of clinical ADHD diagnosis, nor on symptoms of other frequently co-occurring disorders including ODD, autism, and movement difficulties. This implies that children's cognitive profiles are not related to different neurodevelopmental disorder symptoms. Thus, cognitive profiles rather than diagnostic labels could be more informative for developing suitable maths remediation strategies.

7.2 Strengths, limitations, and future directions

Included below is a discussion of some of the strengths, as well as the consideration of their respective limitations. Additionally, recommendations and future directions are provided.

7.2.1 Participant inclusion

A major strength of this thesis was the recruitment of a clinically referred sample on the waiting list to be evaluated for suspected ADHD. All children were drug naïve at the time of testing. Recruiting children in this fashion provided a unique opportunity to test children prior to any pharmacological treatment. Stimulant treatment of ADHD has previously been shown to yield improvements in cognitive and academic functioning (Hawk et al., 2018; Kortekaas-Rijlaarsdam et al., 2019; Leo & Cohen, 2003; Rhodes et al., 2006; Vaidya et al., 1998). By recruiting children from the waiting list, the current thesis was able to form conclusions without any confounding effects of stimulant treatment (DuPaul et al., 2004; Efron et al., 2014). Further, this study capitalised on the benefits of the dimensional approach to disorder manifestations. Specifically, not all children ended up receiving an ADHD diagnosis, but all children had symptoms that had led them being referred by a health or education professional and they had also been assessed as having difficulties sufficient to merit waiting-list placement by CAMHS. In doing so the current finding can be generalised to children with both clinical and subthreshold ADHD difficulties. Children with subthreshold ADHD show persistent levels of academic difficulties and may equally benefit from remediation efforts as their diagnosed peers (Czamara et al., 2013; Hong et al., 2014; Karalunas & Nigg, 2020; Marcus & Barry, 2011; May et al., 2020).

The use of a clinical sample is not without its limitations. Plausibly, the current recruitment method was subject to a referral bias and may restrict inferences surrounding the broader ADHD population. Referral to CAMHS is generally sought out by parents or schools, which likely occurs as a result of a notable degree of concerns around the child’s educational, emotional, and/or behavioural functioning. From the perspective of heterogeneity, argued throughout this thesis, it is very much possible that high achieving children with ADHD are missed by clinical informants. Recruitment of participants via schools/community routes could have generated data from children who are missed by such clinic referrals, but ultimately will have compromised the essence of clinical requirements of ADHD diagnoses (Rowland et al., 2015). Arguably, it is the children who demonstrate some degree of clinical suspicion that would benefit most from psychoeducational interventions which can be guided by the current findings. Having said that, environmental changes and increased demands associated with transition to high school can be critical for children with ADHD with evidence pointing to exacerbation of ADHD symptoms and related difficulties (Langberg et al., 2008; Thompson et al., 2003; Zendarski et al., 2016). Thus, it is possible that some children missed by the present recruitment method may go on to raise clinical suspicion in the high school transition period.

The General Introduction chapter particularly touched upon issues around higher prevalence rates of ADHD in boys, which could be attributed to under-recognition and referral biases in girls. The discrepancy in ADHD rates between boys and girls tends to be higher in clinical samples than in community samples (Young et al., 2020). Thus, it is possible that the current sample was subject to similar issues surrounding this referral bias. Nonetheless, just under a third of the current sample were girls, which is an improvement from previous research where even lower proportions of girls are reported (e.g., Alloway, 2011) or where girls are completely excluded (e.g., Friedman et al., 2018). While the exploration of different sex profiles was beyond the scope of this thesis, future work should move away from stereotypes driven by all-male ADHD research and explore the behaviour, symptoms, and co-occurrences profiles of girls (Young et al., 2020).

Another factor which could be considered a limitation is the lack of control group as this may challenge the internal validity of the findings. Karalunas and Nigg (2020) argue that although comparisons of ADHD with control groups can be informative for identifying ADHD-specific characteristics, it is more favourable to move away from such approaches and instead focus on identifying features and mechanisms for clinical subgroups, as observable characteristics are likely to cluster together in informative ways even without such comparisons. An abundance of research over the years demonstrated behavioural, cognitive, and educational disadvantages in children ADHD when compared to their neurotypical peers. Yet, after decades of such research we are still far from understanding the etiological mechanisms behind academic difficulties in ADHD and developing suitable intervention methods that have long-lasting benefits (Kofler et al., 2017; Luo et al. 2019). Not only does case-control approach risks magnifying within group homogeneity, as discussed throughout this thesis, but it is also inherently biased on focusing primarily on the negative aspects of the disorder while overlooking the strengths that many children with ADHD have. Crucially, these strengths can provide invaluable information into why some children with ADHD struggle academically whilst others do not, thereby informing appropriate remediation strategies.

The wide age-range of participants may also be regarded as a potential limitation as it may have confounded the results in various parts of the thesis. There is evidence to show that the nature of the relationship between cognition and maths varies with age. For example, Holmes and Adams (2006) found that verbal STM (phonological loop measure) was more strongly related to children's arithmetic performance before age was controlled for. Their study also found that verbal STM was a unique predictor of older children's (Year 5; mean age of 9 years 10 months) performance on easier arithmetic tasks, but not that of younger children's (Year 3; mean age 8 years 1 month). This was interpreted to suggest that younger children are still reliant on visuospatial memory processing, whilst older children are employing more mature phonologically based retrieval strategies. Arguably, visuospatial processing is particularly important for early mathematics learning during which children rely heavily on visuospatial number representations in preserving information in STM. As children get older, they likely shift to spontaneous verbal rehearsal/retrieval of critical maths information via verbal STM. Thus, even with 1 year gap in age there is evidence for different patterns of relationship. The current thesis uses a much wider age range group and may therefore be subject to confounding effects of age. However, it is worth mentioning that limiting the age-range of this clinically recruited sample would have resulted in fewer children being eligible to participate.

One way that this thesis tried to overcome the confounding effects of age was by using maths tasks that varied in difficulty for children in different year groups. Furthermore, the standardised assessments of maths attainment and IQ (i.e., WIAT, WASI, and BPVS) overcome these issues by providing detailed breakdowns of standardisation techniques based on the child's age in years and months. However, as mentioned in the General Methodology chapter, the average number of days between the testing sessions was 15 days, ranging anywhere between 1-53 days between sessions. It is possible that this gap could be problematic, since the point at which children received the cognitive assessments may have been in some cases situated at a different (albeit proximal) point of their developmental trajectory.

7.2.2 Sample size

Like in previous clinical ADHD research the sample size used here was small (e.g., Alloway, 2011; Friedman et al., 2018; Kaufmann & Nuerk, 2008; Miranda et al., 2012; Passolunghi et al., 2005). Although larger sample sizes have been reported (e.g., Antonini et al., 2016; Gremillion & Martell, 2012; Roberts et al., 2017) these typically include community/school recruited samples. However, due to the limited sample size, and large number of constructs assessed, it was not statistically sound to conduct what would be considered more powerful statistical analyses from which pathways of causality could be inferred. Inevitably, any research study will be subject to a quality over quantity trade-off. Clinical samples, and even more so drug naïve ADHD samples, are notoriously difficult to recruit but nonetheless allow for rich disorder-specific data to be collected. Recruitment of a larger sample but smaller number of measures may have allowed for more powerful statistical conclusions but would have compromised the richness of data and in-depth characterisation of children's difficulties presented here.

Specifically, the data collected and processed as part of this thesis was used by the wider research team towards developing a comprehensive clinical report for each participant which included their maths achievement profiles, intellectual functioning, parent-rated ADHD and co-occurring symptoms, as well as behavioural observations made during testing. Many of the children were still on long waiting lists for their ADHD evaluation when their clinical reports were sent to CAMHS. Thus, the large magnitude of data collected for each child benefited children's clinical evaluations, further referrals, and treatment. Additionally, three hours of testing per child spread across multiple visits, coupled with the large number of tasks and questionnaires, provide a comprehensive picture of each child's individual profile. It also provided the researcher with ample opportunity to build rapport with each participant, which has been shown to predict better cognitive tasks engagement in children with ADHD under demanding experimental settings (Gidron et al., 2020).

It is highly unlikely that this process would have been possible if a large sample of children was recruited. Nonetheless, the author recognises that small sample sizes increase likelihood of Type 2 error (i.e., null results due to lack of statistical power; Forstmeier et al., 2017). Although this thesis attempted to address these issues by using appropriate statistical mitigation, the current work requires replication using a larger sample of children – where resources allow. Any replication efforts and intervention developments should, nonetheless, focus on collecting a large body of cognitive, academic, and clinical data. It is also recommended that as much as reasonably practicable, an individual-oriented intervention approach (rather than whole group methods) should be taken. The first step of such strategies should be identifying difficulties presented by each child, which can then be used to guide the most optimal method of intervention that is suited to their needs.

7.2.3 Measures

The large battery of measures used in the current thesis is another important strength as it promoted a detailed and transparent representation of the sample. Many previous studies in this research area do not report on the socioeconomic status of participants (e.g., Antonini et al., 2016; Gremillion & Martell 2012; Holmes et al., 2014; Miranda et al., 2012). Here, information in relation to children’s socioeconomic background was collected using the SIMD. The current sample comprised participants from a range of different backgrounds which increases generalisability to a wider ADHD population. This again highlights the benefits of using a clinically referred sample as it helps avoid volunteer biases inherent to community identified cases (Miller et al., 2018). However, it is important to mention that the SIMD reflects the level of deprivation of participants area of residence, rather than their individual socioeconomic score and should therefore be interpreted with this limitation in mind (Clelland & Hill, 2019).

The broad range of parent questionnaires used is another advantage of the current work. All parents completed the 110-item Conners 3-P ADHD questionnaire which reflected the level and type of ADHD symptom manifestation. Notably, the majority of children included here scored high on both inattention and the hyperactivity-impulsivity subscales, which indicates that the findings mainly generalise to children with ADHD-Combined subtype difficulties. Previous studies show that symptoms of inattention, present in both the Inattentive and Combined ADHD subtypes are more closely related to maths difficulties than hyperactivity impulsivity (Tosto et al., 2015). Children with the predominantly Inattentive subtype, who are at the greatest risk for educational difficulties, were underrepresented here. However, this questionnaire was not diagnostic, and the specific subtype diagnoses were in the majority of cases not provided by CAMHS. Furthermore, as emphasised in this thesis cognitive dimensions rather than behavioural ADHD symptoms are key to informing children's maths outcomes.

To receive a diagnosis of ADHD functional impairments must be present in two settings, typically at home and at school (Alder et al., 2015). Thus, the gold-standard to diagnosing ADHD occurs via parent reports of the child's behaviour at home combined by teacher reports of the child's behaviour at school. Indeed, teacher corroboration of difficulties was one of the key inclusion criteria for the systematic review (Chapter 3). This is because community-oriented approaches using parent and/or teacher questionnaires are linked to high false positives of ADHD (Coghill & Seth, 2015; Sayal et al., 2008). The remaining experimental chapters of this thesis overcame this issue by recruiting a clinically referred sample of children who have been referred by health or education professionals and who are further assessed as showing functional difficulties that merit waiting list placement. Moreover, teacher corroboration of difficulties is a fundamental part of the CAMHS information gathering stage (Coghill & Seth, 2015) and so children in this sample who ended up receiving an ADHD diagnosis (i.e., just over half of the sample) will have undergone teacher corroboration of high ADHD difficulties. The remaining participants can be deemed as subthreshold ADHD.

ADHD frequently coexists with at least one, and in many cases more than one, disorder (e.g., Kadesjo & Gillberg, 2001; Liu et al., 2017; Rasmussen & Gillberg, 2000; Zajic et al.,2018). The current thesis used a range of questionnaires to assess frequently co-occurring disorder symptoms, as well as getting information from the clinical team regarding co-occurring ASD diagnosis. This helped maximise external validity and generalisability of the findings to the clinical reality of children with ADHD (Kofler et al., 2019). Rather than excluding children based on co-occurrences, the overarching stance of this thesis was to embrace their complexity. As emphasised throughout this thesis, much of the existing ADHD research excludes children with other neurodevelopmental disorders from participating. Such ‘pure’ ADHD approaches are useful for informing disorder-specific manifestations, but seldom reflect the clinical realities of children with neurodevelopmental disorders to whom co-occurrences are the norm rather than the exception. Furthermore, failure to screen for co-occurring disorder symptoms can contribute to inconsistent findings across the ADHD literature. This thesis cautions against ‘pure’ ADHD approaches and highlights the importance of screening for a range of frequently co-occurring disorders when developing remediation strategies. However, it is important to note that there was no clinical confirmation of a DCD diagnosis in the present thesis. DCD is diagnosed by a different service than CAMHS and so obtraining further diagnostic information other than ASD/ADHD was beyond the scope of the study.

If research primarily focuses on identifying difficulties that are exclusive to ADHD profiles, or fails to screen for relevant co-occurrences, then this could cause a disconnect between research and practice by misguiding subsequent intervention formulation efforts. Indeed, positive effects of high-quality interventions ‘fade-out’ due to the attenuating effects of underlying individual differences in factors such as cognitive skill – which are not targeted by initial intervention efforts (Bailey et al., 2016). As such, more tailored methods are necessary for identifying and addressing mechanisms that render learners at greater risk for mathematics difficulties in order to achieve more effective and resilient interventions. Limited resources can make such a holistic approach challenging; however, the existing compilation of academic interventions shows little promising effects. The quality of evidence for the efficacy of maths interventions in primary school children is generally low (Simms et al., 2019), and although positive effects are reported in children with maths difficulties, these are only moderate and short lived (Benavides-Varela et al., 2020). Similar challenges apply to cognitive training interventions (e.g., Cogmed), which are seldom successful in transferring benefits to academic domains (Gray et al., 2012; van der Donk et al., 2015; Yanwen, 2020). The close association between cognition and maths indicates that the most optimal methods of interventions are likely to be those that not only identify which maths skill(s) the child struggles with, but also which cognitive processes and modalities need to be embedded within intervention efforts.

However, not all co-occurrences were considered in the present work. For example, psychiatric disorder such as bipolar disorder, anxiety, and depression were not comprehensively examined. Children with these psychiatric disorders are at higher risk for maths learning difficulties than those without (Mayes & Calhoun, 2006). Although the SDQ provided a general measure of children's emotional well-being, and some items on the Conners 3-P indicated that investigation for anxiety and/or depression may be necessary, a more comprehensive characterisation of other psychiatric symptoms would be beneficial. Rates of maths anxiety (i.e., negative affect towards doing maths) were also not assessed here. Maths anxiety is negatively related to math performance in children and so would benefit from being considered in future work (Passolunghi et a, 2016; Xin, 1999). Another co-occurring disorder not assessed for was dyslexia. Maths difficulties frequently co-occur with reading, writing, and spelling difficulties, and have been linked to similar cognitive mechanisms (Boada et al., 2012; Child et al., 2018; Gremillion & Martel, 2012; Willcutt et al., 2013). Maths difficulties may be exacerbated by reading difficulties (Jordan, 2007; Jordan et al., 2003). The current thesis implicated verbal aspects for memory as particularly important for maths, but it is possible that these results were confounded by children's reading and writing difficulties. Future work should therefore screen for co-occurring reading and writing difficulties when exploring sources of maths performance heterogeneity in ADHD.

The current study also benefited from including a large battery of cognitive tests which assessed EF, memory, and processing speed. However, other theoretically important cognitive aspects of performance, such as reaction time variability (RTV) and delay aversion were not explored. RTV has been hypothesised to indicate lapses in attentional processing during task performance and may underpin behavioural difficulties such as staying on task in the classroom (Hervey et al., 2006; Antonini et al., 2013). Furthermore, it has been shown that RTV can vary as a function of demands and length of tasks (Gooch et al., 2012). Thus, it cannot be ruled out that children's performance on both the cognitive and maths tasks was affected by high cognitive load and consequent lapses in attention (Epstein et al., 2010; Tamm et al., 2012). The effects of RTV on cognitive and educational domains may be of interest to future research. Delay aversion is another important theoretical aspect of cognitive performance not assessed here. Motivational style difficulties (i.e., motivation to escape/avoid negative affect associated with delays) associated with reward processing are frequently found in ADHD (Sonuga-Barke, et al., 1992; Sonuga-Barke et al., 1996; Nigg 2001; Rubia et al., 1999; Rubia, & Smith, 2001). Plausibly, children's desire to avoid negative affect associated with difficulties on completing the tasks, could have affected their performance. One example of this could be rushing or refusing to complete a maths task, reflecting preference for small and immediate rewards. However, a previous study of adolescents with ADHD found that only EF difficulties, but not delay aversion, mediated the association between ADHD symptoms and maths skills (Thorell, 2007). Based on the current thesis it cannot be ruled out that delay aversion affected children's performance on both the cognitive and maths assessments. Future work may wish to focus on the way in which delay aversion affects younger children's performance.

It is also worth mentioning the problem of task impurity, that is, cognitive tasks are seldom 'pure', and this can complicate interpretations around causal cognitive processes in ADHD (Conway et al., 2005). Cognitive processes inherently rely on the successful operation of other, closely related cognitive domains. Thus, diminished performance on one task (e.g., cognitive flexibility) could actually be attributed to difficulties with another associated domain (e.g., inhibition or visuospatial memory). To illustrate, on the Intra-Extra Dimensional assessment of set shifting children must remember which dimensional rule applies at each trial, attend to relevant visuospatial stimuli, whilst concurrently suppressing selection of a stimuli relevant to a previously learned rule. Thus, successful performance is likely navigated by other cognitive competencies such as inhibition or visuospatial memory. One way to remedy this issue in future work is to use a latent variable approach which aims to capture the domain of interest by using more than one task to measure it and isolating common variance attributable to each subdomain (Kofler et al., 2019; Miyake & Friedman, 2012).

Another strength discussed throughout this thesis is the assessment of children's maths performance beyond just general achievement tests. Although the factual, conceptual, and procedural maths components were previously assessed in a neurotypical population (Cragg et al., 2017), these had not been examined in ADHD.

However, due to the small sample size it was not possible to conduct a mediation analysis, and future research would particularly benefit from exploring the extent to which cognitive mechanisms mediate the relationship between diagnostic status and the different maths skills.

Notably, many of the previous intervention attempts produce negligible or short-lived effects. One possibility for this is a mismatch between child's baseline difficulties and the type of intervention that is administered to them (Burns, 2011; Burns et al., 2010). Given that there are individual differences across the factual, conceptual, and procedural components (Cragg et al., 2014; Dowker, 2015; Gilmore et al., 2017; Gilmore & Papadatou-Pastou, 2009) either of the three components may result in low attainment scores. Therefore, the current findings caution against the sole use of broad attainment scores to inform maths interventions as there is a risk that the remedy strategy will be misaligned with the underlying skill that children struggle with (Sussman & Wilson, 2018). Not only is this detrimental to children's maths outcomes, but it can also result in wasted resources. Rather, it is important to move away from "one size fits all" approaches and instead identify the skill(s) that the child struggles with before devising and applying a tailored intervention. It is therefore important that future research examining sources of maths difficulties consider the componential nature of maths abilities rather than relying on broad attainment tests to group children into intervention groups. However, the author recognizes that lack of resources may not allow for this approach and it is therefore highlighted as a potential model approach to be employed as far as is reasonably practicable.

7.2.4 Missing data

A major limitation of the current thesis was the large proportion of incomplete data – around 40% of children in the current study had missing data on at least one of the cognitive or maths measures. Missing data is a common challenge in paediatric clinical, education, and psychological studies (Enders, 2003; Larkins et al., 2019). Children with developmental disorders may experience a range of behavioural and functional difficulties which impact their ability to complete assessments (Rhemtulla & Little, 2012; Nicholson et al., 2017). Missing data under such circumstances provides invaluable insight into the causes behind inability or refusal to complete tasks. In line with recommendations (Dong & Peng, 2013) the General Methodology chapter addressed the proportion and mechanisms of missing data prior to making decisions on how to address it. Furthermore, each experimental chapter addressed incomplete data on the cognitive and maths assessments as a function of the relevant subgroupings involved. Children who cannot complete tasks are frequently excluded from analyses, but arguably represent the population at most need for educational intervention. Therefore, future work should consider addressing potential reasons for missing data in the context of the sample.

7.3 Conclusions

The current thesis provides the first comprehensive investigation of maths performance in a specific population – clinically referred, medication naïve, children with high symptoms of ADHD. Furthermore, the way in which cognitive dimensions can be informative to children's maths outcomes were explored. Cognitive processes, and more specifically, verbal, and visuospatial aspects of memory functioning show strong associations with maths skills in ADHD. Furthermore, grouping children on the basis of categorical diagnostic labels (i.e., ADHD vs subthreshold ADHD, and high ADHD with and without co-occurring DCD) provides little insight on children’s maths outcomes. Rather, cognitive dimensions appear to be fundamental to informing children’s maths outcomes. Collectively, these findings point to substantial heterogeneity in ADHD both in terms of cognitive functioning and co-occurring symptoms. A dimensional characterisation of ADHD, which defines difficulties on a continuum of frequency and/or severity, is therefore more favourable than the use of dichotomous diagnostic categories. Specifically, future efforts should focus on (1) embracing clinical complexities and heterogeneity inherent to ADHD and other co-occurring neurodevelopmental disorders, (2) going beyond broad attainment tests when assessing children’s maths performance, and (3) focusing on cognitive dimensions rather than categorical labels or symptoms to explore causal risk factors for maths difficulties. Lastly, it is highly recommended that one-size-fits all approaches to interventions are avoided, and instead efforts should be made to assess and target individual needs of each child. The current work should be considered in light of both its strengths and limitations, and rather than make definitive theoretical conclusions, can help inform future research on educational difficulties in ADHD, as well as other neurodevelopmental disorders.

8 Chapter 8: References

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9 Appendices

9.1 Appendix A – PRISMA Checklist

From: Moher et al. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Systematic Reviews 4(1).

Section/topic	**#**	**Checklist item**	**Reported on page # of manuscript**
TITLE			
Cognitive and mathematics performance in children with attention deficit hyperactivity disorder (ADHD): A systematic review	1	Identify the report as a systematic review, meta-analysis, or both.	1
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3-9
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	9
METHODS			

Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	9
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	10-13
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	13
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	14
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	14-16
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	16-17
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	16-17
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	17-18
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	18
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	18
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	33
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A
RESULTS			

Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	15-16
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	19-20
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	20; 23-25
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	25-28
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	N/A
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	N/A
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	28-32
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	32-33
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	33-34
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data), role of funders for the systematic review.	34

9.2 Appendix B – Title and abstract screening checklist

Adapted from: Polanin, J. R., Pigott, T. D., Espelage, D. L., & Grotpeter, J. K. (2019). Best practice guidelines for abstract screening large-evidence systematic reviews and meta-analyses. Research Synthesis Methods, 10(3), 330-342.

Reviewer instructions: Examine titles and abstracts to remove obviously irrelevant reports (generally be over-inclusive at this stage).

<u>Citation, Title, and Abstract Screening</u>

1. Does the **citation** indicate publication on or after 1992?

   ☐ Yes: continue screening
   ☐ No: stop screening

2. Does the **title or abstract** use English?

   ☐ Yes: continue screening
   ☐ No: stop screening

3. Does the **title or abstract** indicate that children with ADHD were included?

   ☐ Yes: continue screening

   -Key words: Attention deficit hyperactivity disorder, hyperkinetic disorder, hyperkinetic syndrome, attention deficit, attentional disorder, hyperactivity, children

   ☐ b. No: stop screening
   - For example: the study clearly focuses on adult ADHD

4. Does the **title or abstract** indicate that mathematics was assessed?

   ☐ Yes: continue screening
   ☐ No: stop screening

<u>Abstract Screening</u>

5. Does the **abstract** indicate that a 4-12 aged sample was studied?

   ☐ Yes or Unsure/Unclear: continue screening
   ☐ No: stop screening

-For example: the study **only** samples adults

6. Does the **abstract** indicate that children had ADHD diagnosis?

☐ Yes or Unsure/Unclear: continue screening

-Key words: Attention deficit hyperactivity disorder, hyperkinetic disorder, hyperkinetic syndrome, attention deficit, attentional disorder, hyperactivity, clinic, clinical diagnosis, formal diagnosis

☐ b. No: stop screening

7. Does the **abstract** indicate that mathematics was studied?

☐ Yes or Unsure/Unclear: continue screening

-Key words: math, arithmetic, numeracy, number, calculation, academic achievement, standardized achievement test, learning

☐ b. No: stop screening

8. Does the **abstract** indicate that at least one of the cognitive domains of interest was studied?

☐ Yes of Unsure/Unclear: continue screening

-Key words: Cognition, attention, executive functions, executive control OR inhibition, inhibitory control, interference control, cognitive flexibility, set shifting, working memory, planning, problem solving, organization, memory processing speed, cognitive processing, cognitive functioning, IQ, intellectual ability
N.B. This should be an objective measure of cognition (e.g., BRIEF questionnaire excluded)

☐ b. No: stop screening

9. Does the **abstract** indicate that the study uses a quantitative design?

☐ Yes or Unsure/Unclear: continue screening

-Key words: regression, covariate, modeling, structural equation modeling, mean, standard deviation, correlation, variance

☐ b. No: stop screening

-For example: qualitative only, ethnography, action research, social observation, focus groups, case study research, reviews

Decision: **Should this article be included for full test review?**

☐ **Yes**, all screening questions answered Yes or Unclear

☐ **No**, at least one answers definitely “No”

9.3 Appendix C – Observation sheet

Attention and concentration:

- Does the child show good eye contact? Does the child fidget/move around a lot that is not typical for their age? Is the child engaged with the tasks/the session? Are they generally distracted or beyond where they are not looking at the stimuli? If not engaged, what specific tasks?

Attitude towards testing:

- Is it easy/difficult to build rapport? Is the child eager to speak/mention any hobbies/interests? Do they cope well with success/failure in tasks? In what ways?

Affect/Mood:

- How is the child's mood? Happy? Annoyed? Does the child require a lot of prompts/motivating to continue the tasks, more so than a typical of a child of that age?

Unusual behaviours:

- Behaviours such as spinning around in circles, continuous tapping of hands/feet? Any other behaviours that would not be typical for the child's age?

Any distractions:

- Distractions that you would think would invalidate the data. If so, please name the distractions as well as the specific tasks that were implicated.

Any other notes:

- This could include notes helpful for the next visit (e.g., a pet name, needing a lot of breaks), for the research team (e.g., issues/points you want to query with the project team) or for CAMHS (e.g., demonstrating signs of autism, concerns about house/family).

Reasons for potential data exclusion (with reasons):

9.4 Appendix D – Intercorrelations between maths variables

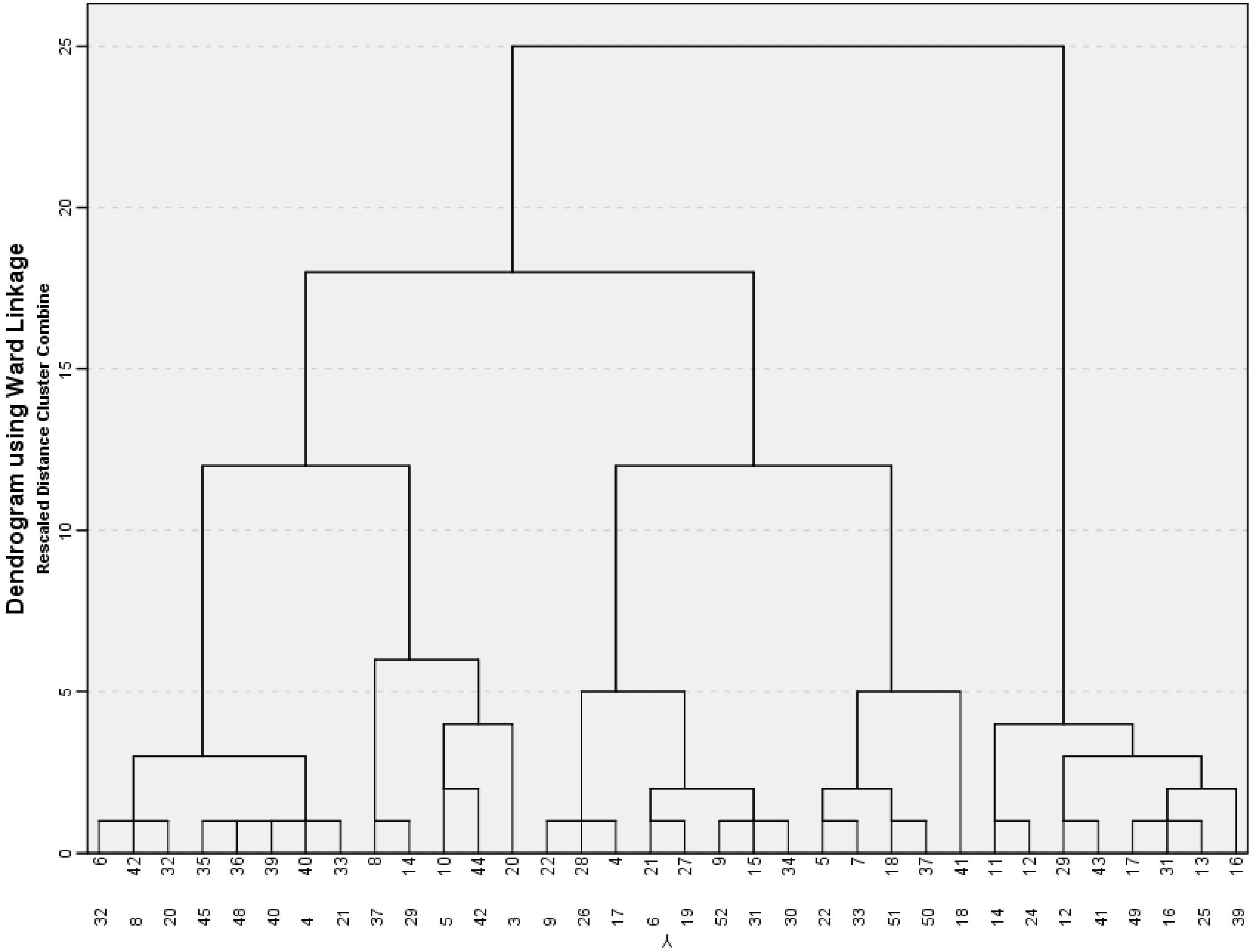
	Age	FSIQ	Maths Problem Solving	Numeracy	Maths Fluency	Factual Knowledge Accuracy	Conceptual Understanding Accuracy	Procedural Skill Accuracy	Procedural Skill RT
Age	-								
FSIQ	.031	-							
Maths Problem Solving	.046	.660**	-						
Numeracy	-.208	.412**	.668**	-					
Maths Fluency	-.119	.411**	.681**	.630**	-				
Factual Knowledge Accuracy	-.002	.384*	.565**	.636**	.501**	-			
Conceptual Understanding Accuracy	.148	.502**	.625**	.459**	.343*	.481**	-		
Procedural Skill Accuracy	.076	.454*	.733**	.605**	.555**	.492**	.445*	-	
Procedural Skill RT	-.069	.052	.373*	.491**	.511**	.538**	.164	.547**	-

9.5 Appendix E – Intercorrelations between cognitive and ADHD symptom variables

	Age	ADHD-I	ADHD-H	FSIQ	SSTS SRT	IED	SWM Errors	SWM Strategy	LNS	SOC	SSP-R	SSP-F	DMtS	VRM-I	VRM-D	SST MRT
Age	-															
ADHD-I	.046	-														
ADHD-H	.106	.318*	-													
FSIQ	.031	.200	.102	-												
SSTSSRT	.015	.075	.111	.251	-											
IED	-.016	-.052	-.087	.132	.083	-										
SWM Errors	-.049	.025	.182	.256	.051	.337*	-									
SWM Strategy	.046	.080	.346*	-.168	-.011	-.403*	-.209	-								
LNS	.275	.090	.107	.763**	.244	-.005	.274	-.024	-							
SOC	.024	.150	-.069	-.036	.059	.218	.149	-.075	-.150	-						
SSP-R	-.040	.164	-.020	.302	.227	.512**	.307	-.214	.155	.003	-					
SSP-F	.013	.083	-.083	.089	.103	.405**	.440**	-.212	.048	.007	.455**	-				
DMtS	.030	-.081	-.126	.415**	.208	.125	.113	-.098	.559**	-.232	.136	.292	-			
VRM-I	-.016	-.063	-.320	.547**	.389	.267	.268	-.238	.719**	.248	.485*	.203	.166	-		
VRM-D	-.095	.188	-.055	.244	.072	.123	.110	.217	.396	.089	.384	.334	.093	.570**	-	
SSTMRT	-.011	.283	.159	.320*	-.075	.098	.406*	-.221	.055	.145	.345*	.069	-.064	.031	.070	-

ADHD-I = Inattention; *ADHD-H* = Hyperactive/Impulsivity; *FSIQ* = WASI Full Scale IQ; *SSTSSRT* = Stop Signal Task Stop Signal Reaction Time; *IED* =Intra-Extra Dimensional; *SWM* =Spatial WM; *LNS* =Letter Number Sequencing; *SOC* =Stockings of Cambridge; *SSP-R* =Spatial Span Reverse; *SSP-F* =Spatial Span Forward *DMtS* = Delayed Matching to Sample; *VRM-I*=Verbal Recognition Memory-Immediate; *VRM-D*= Verbal Recognition Memory Delayed; *SSTMRT* =Stop Signal Task Median RT

9.6 Appendix F – Dendrogram of emerging EF clusters



9.7 Appendix G – Agglomeration schedule for EF clusters

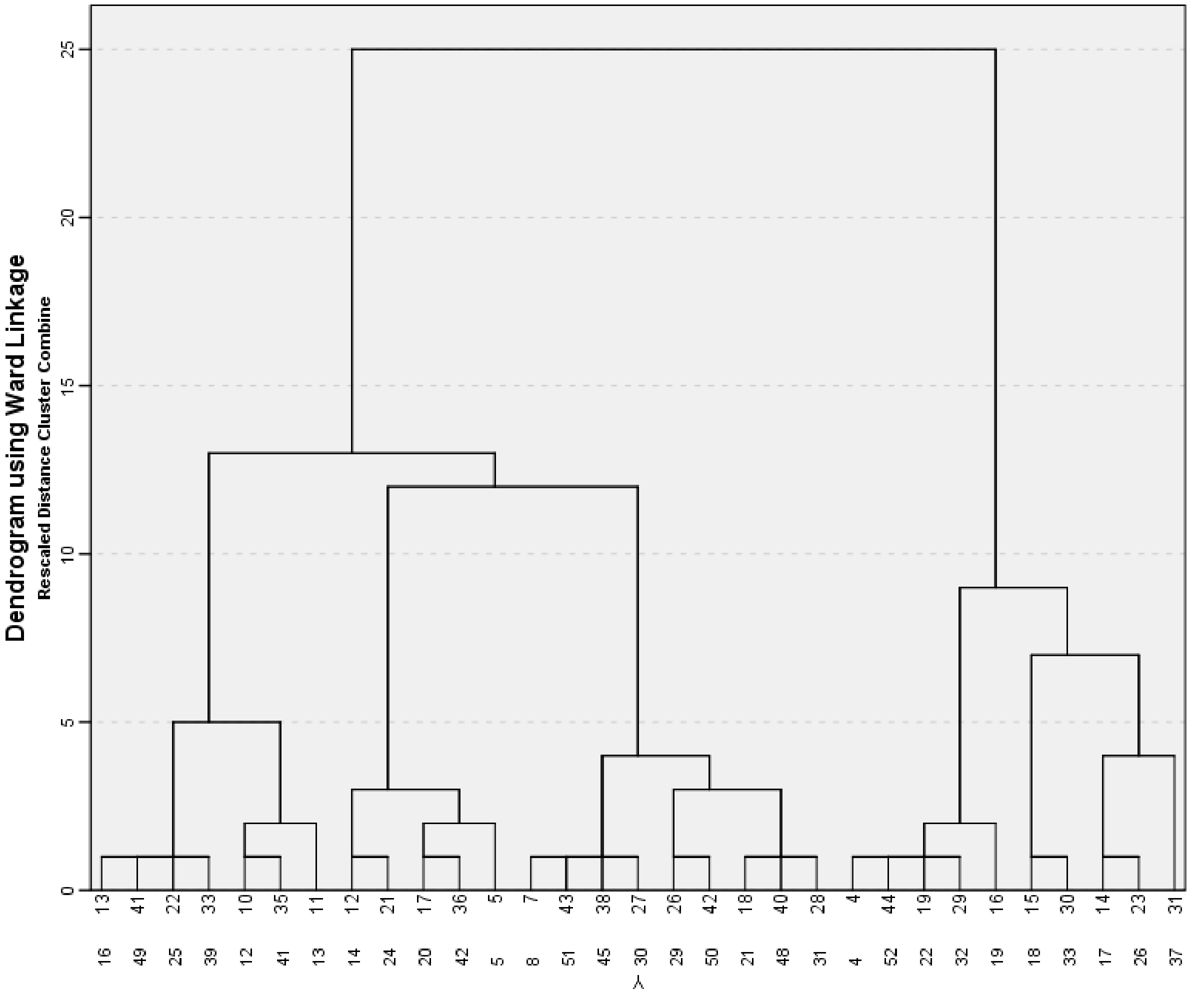
Step	No of clusters	Last step	Coefficients of this step	Change
33	2	137.774	106.401	31.372
32	3	106.401	83.966	22.435
31	4	83.966	69.262	14.704
30	5	69.262	55.225	14.037
29	6	55.225	47.889	7.337
28	7	47.889	42.307	5.582
27	8	42.307	36.862	5.445
26	9	36.862	31.764	5.098
25	10	31.764	27.066	4.698
24	11	27.066	23.266	3.800
23	12	23.266	20.405	2.861
22	13	20.405	17.963	2.442
21	14	17.963	15.772	2.191
20	15	15.772	13.891	1.881
19	16	13.891	12.451	1.440
18	17	12.451	11.052	1.399
17	18	11.052	9.781	1.272
16	19	9.781	8.593	1.188
15	20	8.593	7.545	1.048
14	21	7.545	6.582	0.964
13	22	6.582	5.810	0.772
12	23	5.810	5.095	0.714
11	24	5.095	4.411	0.684
10	25	4.411	3.740	0.671
9	26	3.740	3.098	0.642
8	27	3.098	2.475	0.623
7	28	2.475	1.877	0.598
6	29	1.877	1.316	0.562
5	30	1.316	0.994	0.321
4	31	0.994	0.696	0.298
3	32	0.696	0.403	0.294
2	33	0.403	0.191	0.212
1	34			

9.8 Appendix H – Significance values and effect sizes for univariate EF cluster contrasts

	1 vs 2		1 vs 3		2 vs 3	
	p	*g*	*p*	*g*	*p*	*g*
Criterion EF variables						
Stop Signal RT	.582	0.33	.467	-0.38	.086	**-0.71**
Intra-Extra Dimensional Errors	**.036**	**0.82**	.444	**-0.55**	**.002**	**-1.41**
Spatial WM Between Search Errors	.987	0.05	**.000**	**-1.73**	**.000**	**-4.04**
Verbal WM Scaled Score	**.004**	**-1.18**	**.000**	**-2.29**	.097	**-0.73**
Stockings of Cambridge Problems Solved	**.000**	**1.52**	.882	0.25	**.005**	**-1.30**
Age & IQ						
Age (months)	.414	-0.24	.888	-0.01	.907	0.24
WASI FSIQ	.066	**-1.09**	**.001**	**-2.16**	.218	**-0.52**
BPVS	.893	-0.25	.069	**-0.90**	.215	**-0.56**
Other cognitive processes						
Delayed Matching to Sample	.472	-0.41	.077	**-0.78**	.5111	-0.37
Spatial Span Forwards	.947	0.17	.545	-0.40	.285	**-0.69**
Spatial Span Reverse	1.00	-0.02	.526	-0.46	.564	-0.41
SST Median RT	1.00	0.02	.938	-0.19	.921	-0.20
Co-occurrences						
Conners ADHD Inattentive	.879	-0.21	.568	-0.41	.911	-0.26
Conners ADHD Hyperactive-Impulsive	.995	0.06	.894	-0.30	.799	-0.29
Conners ODD	.801	0.26	.998	-0.07	.767	-0.31
Conners CD	.462	0.46	.878	0.25	.940	-0.18
Autism Quotient Total	.969	0.13	.732	0.42	.918	0.20
Movement ABC Checklist Total	.497	-0.42	.956	0.18	.321	**0.58**
Strengths and Difficulties Questionnaire Total	.929	0.17	.242	**0.72**	.504	0.47
Maths						
WIAT Mathematics Problem Solving	.083	-0.85	**.003**	-1.75	.196	-0.67
WIAT Numeracy	.766	-0.27	**.007**	-1.42	**.028**	-1.07
WIAT Maths Fluency	.531	-0.49	**.008**	-1.25	.067	-0.86
Maths Factual Component Accuracy	.463	-0.48	**.035**	-1.16	.295	-0.67
Maths Conceptual Accuracy	.126	-0.77	**.029**	-1.51	.676	-0.36
Maths Procedural Accuracy	.657	-0.36	**.012**	-1.80	**.067**	**-0.89**
Maths Procedural Efficiency RT (s)	.437	0.48	.453	-0.67	**.033**	**-1.04**

1= Low WM cluster; 2= Low Visuospatial EF cluster; 3= Intact EF cluster

9.9 Appendix I – Dendrogram of emerging memory clusters



9.10 Appendix J – Agglomeration schedule of memory clusters

Step	No of clusters	Last step	Coefficients of this step	Change
30	2	135.418	100.255	35.163
29	3	100.255	82.689	17.566
28	4	82.689	66.449	16.240
27	5	66.449	54.151	12.298
26	6	54.151	45.146	9.005
25	7	45.146	38.733	6.413
24	8	38.733	33.053	5.680
23	9	33.053	27.997	5.057
22	10	27.997	24.246	3.750
21	11	24.246	20.700	3.546
20	12	20.700	18.330	2.370
19	13	18.330	16.276	2.054
18	14	16.276	14.483	1.793
17	15	14.483	13.035	1.448
16	16	13.035	11.682	1.353
15	17	11.682	10.517	1.165
14	18	10.517	9.353	1.163
13	19	9.353	8.266	1.087
12	20	8.266	7.207	1.059
11	21	7.207	6.175	1.032
10	22	6.175	5.161	1.014
9	23	5.161	4.243	0.918
8	24	4.243	3.381	0.863
7	25	3.381	2.701	0.679
6	26	2.701	2.059	0.642
5	27	2.059	1.490	0.569
4	28	1.490	0.954	0.536
3	29	0.954	0.504	0.450
2	30	0.504	0.134	0.369
1	31	0.134		0.134

9.11 Appendix K – Non-completers results

9.11.1 EF variables

Ten children had a missing value on at least one cognitive criterion measures. Non-completers were younger *t* (42) = -2.56, *p* = .017 (*M* = 91.10, *SD* = 12.20), than those with complete EF data (*M* = 104.35, *SD* = 20.21) and had lower parent reported birthweight *t* (42) = -2.39, *p* = .021 (*M* = 3041.44, *SD* = 513.12) than completers (*M* = 3585.73, *SD* = 637.86). Non-completers were rated by parents as having higher ADHD-Hyperactive/Impulsive symptoms on the Conners 3-P *t* (41.97) = 2.10, *p* = .042 (*M* = 87.80, *SD* = 2.86), than completers (*M* = 83.74, *SD* = 9.99). Children with incomplete data had higher parent-rated autism traits on the AQ-10 *t* (42) = 1.97, *p* = .055 (*M* = 5.90, *SD* = 3.51), than children with complete EF data (*M* = 4.00, *SD* = 2.40). Completers and non-completers did not differ on the remaining assessments of IQ, maths, or parent ratings (all p's > .05).

9.11.2 Memory variables

Thirteen children had a missing value on at least one cognitive criterion measure. Non-completers were younger *t* (42) = -2.82, *p* = .007 (*M* = 89.54, *SD* = 12.27) than those with complete cognitive data (*M* = 106.29, *SD* = 19.83) and had lower parent reported birthweight *t* (42) = -2.70, *p* = .010 (*M* = 3070.85, *SD* = 164.50). Non-completers scored lower on the WIAT Mathematics Problem Solving subtest *t* (42) = -1.75, *p* = .042 (*M* = 87.46, *SD* = 8.16) than children with complete observations (*M* = 94.36, *SD* = 13.18). Non-completers also had lower scores on maths procedural component task accuracy *t* (29) = -2.74, *p* = .010, (*M* = -1.08, *SD* = 0.64) and efficiency *t* (29) = -3.54, *p* = .001, (*M* = -1.31, *SD* = 0.61) than completers (*M* = 0.16, *SD* = 0.86 and *M* = 0.19 *SD* = 0.81, respectively). Non-completers were rated by parents as having lower ODD scores *t* (16.29) = -2.54, *p* = .022 (*M* = 66 .85, *SD* = 19.68), than completers (*M* = 81.84, *SD* = 12.60). Completers and non-completers did not differ on the remaining assessments of IQ, maths, or parent ratings (all p's > .05).