How Does Working Memory Training Work? Transfer, Strategies, and Neural Correlates in Children Aged 9-14 Years

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature: …………………………………………………………..

Abstract

Working memory predicts children's academic achievement at school and future prospects. Working memory training may offer generalised improvements; however, evidence has been mixed and is a source of controversial debate. Training has been shown to improve performance on working memory tasks, but it is unclear if this reflects increased capacity or a change in strategy. Training has been found to improve children's attention, maths, and reading, but rarely in studies with appropriate control groups. Very few controlled studies have investigated the neural correlates of working memory training in children, obscuring inferences about neural mechanisms.

Chapter 2 presents the most comprehensive investigation of the neural correlates of working memory training to date. Training is found to improve children's working memory performance, increase recruitment of the middle frontal gyrus, and increase connectivity within the posterior parietal cortex, but not change grey matter volume. It is concluded that repeated coactivation of fronto-parietal regions during training may increase executive or attentional control. However, strategy change may influence task-related brain activation.

Chapter 3 presents a randomised controlled trial of 'MetaCogmed', a novel working memory and metacognitive strategy training programme designed to facilitate transfer to academic outcomes. Working memory training alone is found to improve children's performance on tasks of working memory and mathematical reasoning. However, only the improvements in working memory were maintained three months later. MetaCogmed did not improve academic outcomes more than working memory training alone. It is concluded that working memory training may improve children's maths ability in the short-term when offered in addition to school, and that metacognitive training may require more time and activities to promote generalisation.

Chapter 4 presents a novel neuroimaging investigation of memory strategies in children. Grouping is found to be associated with decreased recruitment of the left middle frontal gyrus and increased recruitment of the left premotor cortex. It is suggested that grouping may afford an organisational advantage and more efficient use of working memory capacity compared to sequential rehearsal.

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Chapter 1: General Introduction

Cognitive training, sometimes known as brain training, has received massive commercial interest for its potential to enhance cognitive abilities, particularly for individuals with impairment in memory and attention (e.g. Klingberg et al., 2005). Lumosity is one company who offer a range of different online cognitive games that consumers train on over 10 weeks at regular intervals. They claim to have 85 million users worldwide (www.lumosity.com) and a report five years ago estimated their revenue at $24 million (Day, 2013). In 2016, an investigation by the Federal Trade Commission (FTC) concluded that Lumosity had made fraudulent claims about the effectiveness of the training and had exploited the fears of cognitive decline in their elderly consumers (Federal Trade Commission, 2016). The court found Lumosity guilty and ordered the company to reimburse their consumers for $2 million. Their current claims are more balanced, but still refer to research that was carried out by their employees with financial holdings in the company (Hardy et al., 2015).

This case study demonstrates how commercial cognitive training companies have financial conflicts of interest and can take advantage of their naïve or vulnerable consumers. Researchers with commercial conflicts of interest may be more likely to use inappropriate or inadequate methods to show their training product in a more positive light. These researchers and companies are also more likely to cherry pick findings from studies that support their training product, without careful evaluation of methodological rigour. Furthermore, companies may have a bias towards the research they support and they may withhold details about the training programme and data that restricts the advancement of science. Clearly, there is a demand for reliable and unbiased scientific research to inform educational and health practitioners, and members of the public. The fundamental questions are: Does cognitive training work? If so, how does it work? Furthermore, are there ways in which we can improve current training regimens? This thesis will investigate these questions within the context of working memory training, which is one of the most promising and most investigated forms of cognitive training.

1.1. Working Memory

Before discussing working memory training, it is necessary to define what working memory is. Broadly speaking, working memory is a system for retaining and manipulating information over a few seconds (Baddeley & Hitch, 1994). The multi-component model of working memory includes dissociable verbal and visuospatial short-term stores that are managed by a central executive (Baddeley & Hitch, 1974; Cowan, 1999; Oberauer, 2002). The phonological loop includes passive verbal storage and an articulatory control process that maintains information through sub-vocal rehearsal (Baddeley, 1983, 1992; Repovš & Baddeley, 2006). Speech input has direct access to the phonological loop, but information from other modalities can be recoded into a phonological form. The visuospatial sketchpad includes separate storage for visual and spatial information, which are maintained through rehearsal processes (Repovš & Baddeley, 2006). The short-term stores interact with long-term memory by storing representations of letters, words, or shapes, and by contributing to long-term learning (Baddeley, 2012). The central executive is a limited attentional system that is responsible for attending to the contents of working memory, dividing attention to multiple inputs, and switching between tasks (Baddeley, 2012). An additional component termed the 'episodic buffer' was later described, which provides short-term storage of multi-modal information integrated from a range of sources (Baddeley, 2000).

Working memory is also viewed as activated long-term memory, i.e. memory that is held in a highly accessible state, and a 'focus of attention' (Cowan, 1999; Oberauer, 2002). Activated long-term memory is subject to decay or interference, but it does not have a strictly limited capacity as do the short-term stores described in the multi-component model. The focus of attention has a limited capacity to attend to the contents of activated long-term memory, much like the central executive. Importantly, both models of working memory provide explanations for short-term memory, interactions with long-term memory, and executive/attentional processes.

Working memory has been operationalised using a range of tasks that make different demands on short-term memory and executive processes. Since working memory training is based on these tasks it is important to understand precisely what they are measuring. Simple span tasks, such as the word, letter or digit span, require short-term storage of a stimulus sequence (Conway et al., 2005). Complex span tasks, such as the reading (Daneman & Carpenter, 1980) or operation span (Turner & Engle, 1989), require short-term maintenance of a stimulus sequence whilst simultaneously performing a secondary task. For instance, the reading span requires participants to read a sequence of sentences and recall the final word of each sentence. Executive processes are required to maintain the memory of the final word of each sentence whilst reading each sentence and managing the interference. Finally, in an n-back task, a continuous sequence of stimuli are presented and participants are asked to match the current stimulus with the stimulus n-trials previous (Kirchner, 1958). This requires participants to maintain a subset of n-stimuli, and continuously update the contents of memory. Standardised assessment batteries are also used to provide an overall index of working memory capacity in relation to normative data from different age groups. For example, the Automated Working Memory Assessment (AWMA; Alloway, 2007) includes simple and complex span tasks, which measure short-term memory and working memory in the verbal and visuospatial domains.

Short-term memory involves the passive storage of information and, for the purposes of this thesis, it is assumed to be a facet of working memory, but no assumption is made regarding whether this system is supported by short-term stores or activated long-term memory (Baddeley & Hitch, 1974; Cowan, 1999; Oberauer, 2002). Working memory also involves executive processing of stored information and it is considered to be a core executive function that contributes to a range of complex thought processes, such as learning, planning, and problem-solving (Diamond, 2013; Miyake, Emerson, & Friedman, 2000). It is primarily for these reasons that working memory has become a popular target for cognitive training.

1.1.1. The Development of Working Memory and its Relationship with other Cognitive Abilities

Short-term memory capacity steadily increases through childhood and adolescence (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011). On average, children can correctly remember a sequence of five digits at the age of seven, which increases to six and a half digits at the age of fifteen (Isaacs & Vargha-Khadem, 1989). Similarly, performance on executively demanding working memory tasks steadily increases in childhood and, in children as young as six, performance on working memory tasks can be explained by three distinct but correlated factors, corresponding to the phonological loop, visuospatial sketchpad, and central executive of the multi-component model (Alloway, Gathercole, & Pickering, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004). This suggests that even at a young age, children's working memory has a similar structure to adults', although it has a more limited capacity.

Working memory capacity is associated with a wide range of cognitive abilities, including intelligence (Ackerman, Beier, & Boyle, 2005), inhibition (Redick, Calvo, Gay, & Engle, 2011), nonverbal reasoning (Kane, Hambrick, & Conway, 2005), reading comprehension (Daneman & Carpenter, 1980), and mental arithmetic (Hitch, 1978). However, of particular importance to children are the associations between working memory capacity and children's grades in Maths and English (Gathercole, Pickering, Knight, & Stegmann, 2004). In fact, working memory has been shown to be a stronger predictor of children's future academic attainment than IQ (Alloway & Alloway, 2010), which is a measure of general cognitive ability. Academic attainment is important for children as it predicts well-being (Quinn & Duckworth, 2007) and delinquency (Maguin & Loeber, 1996), as well as long-term outcomes such as income and unemployment (Office for National Statistics, 2013).

A study of mathematics skills in primary school children in Years 3 and 5 investigated the relative contribution of different components of working memory in mathematics skills (Holmes & Adams, 2006). Performance on an executively-demanding complex span task predicted performance on all mathematics tasks for both age groups, suggesting a significant role of executive components of working memory in maths skills, which may be related to general intelligence. The contributions of verbal and visuospatial short-term memory to mathematics were found to change with age. Specifically, visuospatial short-term memory uniquely predicted performance on different types of maths problems in Year 3 children, but it only predicted performance on difficult maths problems in Year 5 children. A corresponding developmental shift was found for verbal short-term memory, which did not predict mathematics performance in Year 3 but it did predict performance on easy maths problems in Year 5. It has been suggested that verbal short-term memory retains verbal codes for arithmetic (Houdé, 1997) and supports the direct retrieval of number facts and solutions from long-term memory (Dehaene & Cohen, 1997), therefore, older children may rely more on linguistic arithmetic and direct retrieval strategies. On the other hand, visuospatial short-term memory has been suggested to support the retention and calculation of numbers in a visuospatial form (Noël, Fias, & Brysbaert, 1997), analogous to a mental blackboard (Heathcote, 1994), and is particularly implicated in younger children's arithmetic (Houdé, 1997). The involvement of visuospatial short-term memory when older children solve difficult maths problems may reflect a reversion to simpler strategies when the solution cannot directly be retrieved from long-term memory (Siegler, 1996).

Similarly, components of working memory make different contributions to children's reading skills. A study in seven year olds found that word reading skills were predominantly predicted by phonological awareness, whereas performance on simple and complex span tasks only predicted a small but significant amount of variance in word reading scores (Leather & Henry, 1994). On the other hand, reading comprehension was equally predicted by phonological awareness and performance on complex span tasks, whereas performance on simple span tasks only explained a small amount of variance in reading comprehension scores. This suggests that executive components of working memory are particularly important in reading comprehension, but less so for basic word reading. Another study demonstrated that executive working memory capacity uniquely predicts children's reading comprehension between the ages of eight and eleven when controlling for word reading, vocabulary, and verbal IQ (Cain, Oakhill, & Bryant, 2004). Reading span was a stronger predictor of reading comprehension than an analogous task that involved reading sequences of digits and remembering the final digit of each sequence. As both working memory tasks were in the verbal domain and verbal skills were controlled for, it was suggested that the reading span better explains variance in reading comprehension because both tasks require sentence comprehension. Working memory was also associated with inference making and comprehension monitoring skills, suggesting that these skills may mediate relationship between working memory and reading comprehension. However, when working memory was controlled for both inference making and comprehension monitoring explained additional unique variance in reading comprehension.

Working memory is often impacted by atypical development. For example, working memory impairment is considered a core feature of Attention Deficit Hyperactivity Disorder (ADHD; Barkley, 1997). A meta-analysis showed that working memory is particularly impaired in children with ADHD, even when controlling for language and intellectual deficits (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005). Working memory is also substantially impaired in children with reading disability (Swanson, Zheng, & Jerman, 2009) and maths difficulties (Gathercole et al., 2016; Swanson, Jerman, & Zheng, 2008). This suggests that working memory may be an important determinant of children's attention, maths, and reading abilities. Increasing working memory capacity through cognitive training in childhood could, therefore, have considerable implications for children's academic attainment and prospects after school.

1.1.2. The Neural Correlates of Working Memory

Functional brain imaging has been used to identify neural systems involved in working memory and its development. Studies have shown that working memory predominantly activates fronto-parietal regions of the brain (d'Esposito et al., 1998; E. E. Smith & Jonides, 1999). A recent meta-analysis of 189 functional Magnetic Resonance Imaging (fMRI) experiments with adults, showed that working memory tasks commonly activate bilateral areas of the middle frontal gyrus and dorsolateral prefrontal cortex, inferior frontal gyrus, premotor cortex, medial supplementary motor area (SMA), anterior insula, intraparietal sulcus, superior parietal lobe, as well as areas of the visual cortex, cerebellum, thalamus, and basal ganglia (see Figure 1.1; Rottschy et al., 2012). The precise pattern of activation depends on task type, where verbal tasks show greater activation in left Broca's area, and visuospatial tasks show greater activation of the left SMA and bilateral dorsal premotor cortex. Visuospatial tasks can be further divided into memorisation of object locations versus memorisation of object identities. Object location tasks show greater activation in the bilateral dorsal premotor cortex, superior parietal lobe, precuneus, and right inferior parietal cortex, whereas object identity tasks show greater activation in the bilateral inferior frontal gyrus, left cerebellum, and left ventral visual cortex.

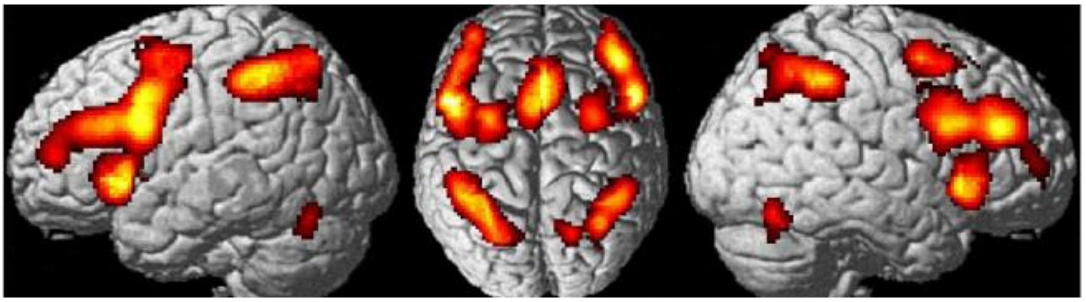

Figure 1.1. Bilateral fronto-parietal network activated across working memory studies. Reprinted from "Modelling the Neural Correlates of Working Memory: A Coordinate-Based Meta-Analysis", by C. Rottschy et al., 2012, Neuroimage

In children, working memory activates similar regions of the brain. However, activation is typically more distributed and reduced in fronto-parietal regions compared to adults (Geier, Garver, Terwilliger, & Luna, 2009). As children's working memory matures, brain activity becomes more localised to core working memory regions (including the dorsolateral prefrontal cortex and parietal regions) and more functionally integrated with regions involved in response preparation and execution (Scherf, Sweeney, & Luna, 2006). Older children also show greater activation of the superior frontal cortex and intraparietal sulcus compared to younger children, and this activation correlates with increased working memory capacity (Klingberg, Forssberg, & Westerberg, 2002a). Working memory development is also associated with structural changes in the brain. Maturation of white matter in the fronto-parietal network correlates with children's performance on visuospatial working memory tasks (Nagy, Westerberg, & Klingberg, 2004; Vestergaard et al., 2011), and can predict children and young adults' working memory capacity two years later (Darki & Klingberg, 2015). Together, this research demonstrates how the development of working memory is closely related to the structural and functional maturation of the fronto-parietal network.

In more recent years, neuroscience has primarily provided evidence for state-based models of working memory, which suggest that information is maintained through the internal allocation of attention to semantic, sensory, or motoric representations rather than through dedicated short-term stores (see D’Esposito & Postle, 2015, for a review). In one study, participants were asked to make judgments about pictures of famous people, famous locations, and common objects in order to elicit perceptual and semantic or episodic representations during fMRI (Lewis-Peacock & Postle, 2008). In a second fMRI session, participants completed a paired-associates task using the same stimuli. A pattern classifier trained on the neural activation for each category of pictures in session one successfully decoded the neural activation in the delay period of the paired-associates task according to the category of picture. Therefore, brain activation associated with maintaining a stimulus in its absence matched the brain activation associated with perception and long-term representations when the stimulus was present. These findings provide evidence that the maintenance of information over a short period of time can be explained by activated long-term memory (Cowan, 1999; Oberauer, 2002). Similar techniques have also established that the maintenance of particular visuospatial patterns can be decoded from activation in the occipital and parietal cortices (Christophel, Hebart, & Haynes, 2012), suggesting that maintenance of a visual pattern is associated with the same neural activation as perception.

In their review, d’Esposito and Postle (2015) highlighted five neural mechanisms that contribute to working memory. First, persistent neural activity in sensory areas maintains representations during a delay period and in the prefrontal cortex it serves to guide behaviour. However, persistent neural activity is not necessarily present for unattended items in memory (Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012), which may instead be maintained through rapid shifts in synaptic weights (Itskov, Hansel, & Tsodyks, 2011). Second, the prefrontal cortex holds abstract representations of stimulus information, rules, categories, and stimulus-response mappings, whereas activation in lower-level sensory areas is more stimulus specific. Third, top-down signals from the prefrontal cortex can modulate activity in sensory areas. For example, participants who were instructed to remember faces when shown pictures of faces and visual scenes showed increased activation of the fusiform face area, whereas activation was suppressed when participants were instructed to remember visual scenes (Gazzaley, Cooney, McEvoy, Knight, & D’esposito, 2005). Fourth, synchronous activity between remote regions of the brain is critical to working memory, for example sustained synchronised activity in the alpha, beta, and gamma bands has been observed in the delay period of a visual working memory task, which was dependent on memory load and associated with performance (Palva, Monto, Kulashekhar, & Palva, 2010). Finally, neurotransmitters such as dopamine modulate working memory function. Research in monkeys has shown that depletion of dopamine in the prefrontal cortex impairs working memory performance to a similar degree as prefrontal lesions (Sawaguchi & Goldman-Rakic, 1991).

1.2. Working Memory Training

Since the turn of the millennium working memory capacity has been the target of training interventions (Klingberg, Forssberg, & Westerberg, 2002b), given its role as a core executive function that predicts other cognitive abilities and outcomes (see Section 1.1.1.). Training programmes typically involve intensive and prolonged practice on one or multiple working memory tasks. For example, single n-back training entails practice on typical n-back tasks (Jaeggi et al., 2010), and dual n-back training entails practice on a dual n-back task, which requires updating two simultaneous streams of information from separate modalities (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). Cogmed is a widely available commercial working memory training programme that entails practice on 12 gamified simple and complex span tasks (Klingberg et al., 2005). Cogmed is typically performed for 30-45 minutes a day, 5 days a week, for 5 weeks; similar to other training programmes (Harrison et al., 2013; Jaeggi et al., 2008). The difficulty of the tasks adapts according to the individual’s performance, which means that the difficulty increases if the individual is performing well and decreases if the individual is performing poorly. The adaptive difficulty is thought to optimise learning and adherence by operating at a level that is constantly challenging for the individual (Diamond & Lee, 2011; although see von Bastian & Eschen, 2016), but not too difficult as to be discouraging (Shinaver, Entwistle, & Söderqvist, 2014). Children are given feedback on their performance and encouraged to beat their high scores. Other training programmes have incorporated practice on working memory tasks with instruction in strategies to complete these tasks more effectively (St Clair-Thompson et al., 2010; Witt, 2011).

Typically during the course of working memory training, the majority of children improve on the tasks with practice, demonstrating a practice effect (Klingberg, n.d.). However, practice effects can be highly task-specific and so this does not necessarily mean that there has been an improvement in working memory capacity. In order to assess improvements in working memory researchers must evaluate children's performance on untrained working memory tasks to establish whether there has been 'near-transfer' (Perkins & Salomon, 1992). This will determine whether the skills and strategies learned during training will transfer to novel tasks. Studies should also determine whether there has been 'far-transfer', i.e. improvements in other cognitive and behavioural domains that are related to working memory.. This is important to determine whether training has generalisable benefits on ecologically valid measures such as academic achievement. The magnitude of transfer may depend on how distal the transfer task is to the training task and so it may be expected that the greatest improvements will be seen on the training tasks, followed by the near-transfer tasks, and the smallest improvements may be seen on far-transfer tasks dependent on how closely associated working memory is with the measured construct. However, it is also important to consider that transfer effects will depend on an individual task's sensitivity to training effects, therefore, it is possible that a far-transfer effect can be shown without a near-transfer effect when the tasks differ in their sensitivity.

Working memory training studies may utilise a number of measures to assess near- and far-transfer. Tasks should be appropriately selected based on their theoretical association with working memory capacity such that improvements on these tasks can be qualified as transfer effects. It is also important that studies either run a small number of tests on the measures of most interest or use an appropriate control for multiple comparisons to reduce the chance of false-positive results in typical null hypothesis significance testing. Composite scores of multiple working memory tasks (e.g. Astle, Barnes, Baker, Colclough, & Woolrich, 2015) or latent variables may be used to limit the number of significance tests (e.g. Redick et al., 2013). Whilst significant effects can be interpreted as transfer, it is difficult to determine whether non-significant effects reflect absence of transfer or a lack of power. Therefore, replication of significant findings is important and meta-analyses can examine whether non-significant effects in studies with small samples actually reflect a small true effect or no effect.

To reliably assess near- or far-transfer it is vital to compare the training to an appropriate control group. A passive or waitlist condition will control for test-retest effects, maturation effects, historical effects (e.g. schooling in between testing sessions), and regression to the mean (Shipstead, Redick, & Engle, 2010). However, it does not control for differences in expectation that may arise from the Placebo and Hawthorne effect. These expectation effects can be large (Stewart-Williams & Podd, 2004) and, therefore, active control conditions are essential. The ideal active control should equate for all of the nonspecific effects of training but not train working memory. For example, Cogmed has often been compared to the non-adaptive version, which includes the same training tasks but the difficulty remains at a span of two for the duration of the programme (e.g. Klingberg et al., 2005). As this difficulty is well below most children's working memory capacity, it is unlikely that much learning will take place. However, there is some evidence that children with impaired working memory capacity, may benefit from this low level training (Dunning, Holmes, & Gathercole, 2013). The choice of control group has important implications for the interpretation of findings and, therefore, it is important to consider the control group when evaluating the evidence for working memory training.

1.2.1. Evidence for Working Memory Training across Populations

The evidence for working memory training has been summarised in numerous reviews and meta-analyses (Au et al., 2014; Karbach & Verhaeghen, 2014; Melby-Lervåg & Hulme, 2013; Morrison & Chein, 2011; Schwaighofer, Fischer, & Bühner, 2015; Shinaver et al., 2014; Shipstead, Hicks, & Engle, 2012; Shipstead et al., 2010; Simons et al., 2016; Soveri, Antfolk, Karlsson, Salo, & Laine, 2017; von Bastian & Oberauer, 2014), and the conclusions drawn have been a source of controversial debate (Au, Buschkuehl, Duncan, & Jaeggi, 2016; Melby-Lervåg & Hulme, 2016). Two comprehensive meta-analyses including a range of working memory training programmes, participants, and settings, have shown moderate to large near-transfer effects that are maintained five to eight months later (Melby-Lervåg & Hulme, 2013; Schwaighofer et al., 2015). Concerning measures of far-transfer, both meta-analyses reported small but significant improvements in nonverbal reasoning, which were not maintained six months later. Small short-term improvements were also reported for 'verbal ability' (verbal comprehension and reasoning; Schwaighofer et al., 2015) and inhibition, as measured by the Stroop task (Melby-Lervåg & Hulme, 2013). In both analyses, there were no significant improvements in academic achievement, namely word reading and mathematical abilities.

An important consideration when evaluating the efficacy of working memory training is the type of control group used. While all of the studies included in the meta-analyses discussed above utilised a control group, many of these were passive waitlists rather than active training (e.g. Jaeggi et al., 2008). Furthermore, type of control group was found to significantly moderate short-term far-transfer to nonverbal reasoning, such that studies with active controls had a mean effect size of zero (Melby-Lervåg & Hulme, 2013). Randomisation is also an important methodological consideration, as this eliminates any bias in group allocation and equates for baseline differences. Although randomisation was not quite a significant moderator of far-transfer to non-verbal reasoning (p = 0.06), the average effect size of studies with random allocation to conditions was also close to zero (d = 0.04). This demonstrates that studies with more rigorous experimental designs failed to find improvement in non-verbal reasoning. Far-transfer to inhibition and verbal ability were not moderated by control group or randomisation, suggesting that these effects may be more reliable. However, these improvements were small and short-term only.

Near-transfer was not significantly moderated by type of control group or randomisation (Melby-Lervåg & Hulme, 2013) suggesting that these are robust effects. However, near-transfer was moderated by training programme and the age of participants. Cogmed had the largest near-transfer effects (*d* = 0.86-1.18) compared to n-back training (*d* = 0.79) and Jungle Memory (*d* = 0.32-0.45 Alloway & Alloway, 2008), suggesting that it may be the most effective working memory training programme. There was significant near-transfer for all participant groups, however, the largest effects were seen in young children (*d* = 0.46-1.41), defined as 10 years old or younger, and the smallest effects were seen in older children (*d* = 0.26-0.45), defined as 11-18 years old. Larger effect sizes were also evident for typical adult and child samples (*d* = 0.57-0.91) as opposed to 'learning disabled' samples (*d* = 0.47-0.56), although this difference was not significant. Overall, these findings suggest that near-transfer effects vary according to the sample and training programme, and far-transfer effects can vary according to methodological rigour. The following sections will provide a more current and thorough examination of the evidence for working memory training in children.

1.2.2. Evidence for Working Memory Training in Typically Developing Children

A recent meta-analysis of 26 studies, including 1601 typically developing children aged 3-16 years, demonstrated significant improvements on working memory tasks, which were maintained three to six months later (Sala & Gobet, 2017b). Near-transfer in the short-term was not significantly moderated by the type of control group used or randomisation, suggesting that these effects are reliable. However, too few studies have investigated long-term near-transfer to afford analysis of potential moderators. Some studies with active control groups have shown evidence of long-term near-transfer (Henry, Messer, & Nash, 2014; Karbach, Strobach, & Schubert, 2015), whereas others have not (Hitchcock & Westwell, 2017; Studer-Luethi, Bauer, & Perrig, 2016). Thus, long-term near-transfer in typically developing children requires further investigation. In the meta-analysis, far-transfer was small but significant for mathematics in the short-term, and nonsignificant for literacy/word decoding, science, fluid intelligence, crystallised intelligence, and cognitive control (Sala & Gobet, 2017b). Importantly, all far-transfer effects were non-significant when considering studies with randomisation and active control groups (*n* = 13), suggesting that there is little evidence of far-transfer in the most methodologically rigorous studies.

Only two studies have formally investigated academic outcomes in typically developing children following Cogmed. The most informative was a recent cluster-randomised controlled trial of 148 children with a mean age of 12 years (Hitchcock & Westwell, 2017). Classes were randomised to receive Cogmed, non-adaptive Cogmed, or lessons as usual. Verbal working memory was assessed on the forwards and backwards digit span and letter-number sequencing sub-tests of the Wechsler Intelligence Scale for Children (Wechsler, 2003). Far-transfer was assessed on measures of maths ability and reading comprehension. All assessments were conducted before training, immediately after training, and three months after training. The results of mixed models analysis indicated that there were no significant differences between the Cogmed group and the non-adaptive or passive control groups over time. Furthermore, the results of Bayesian analyses indicated moderate to strong evidence for the null hypothesis on measures of reading and maths. This suggests that Cogmed does not improve academic achievement in the short- or medium-term. However, the absence of near-transfer contradicts previous findings in studies of Cogmed (Melby-Lervåg & Hulme, 2013) and working memory training in typically developing children (Sala & Gobet, 2017b). This may be because Cogmed training tasks are predominantly visuospatial, whereas only verbal working memory was assessed.

The only other study included 40 Swedish children aged 9-10 years, who were assigned to receive a short programme of Cogmed (approximately half the training time) or lessons as usual (Söderqvist & Bergman-Nutley, 2015). Children were assessed before training and 24 months after training on a reading and spelling test, as well as a timed maths test. The Cogmed group showed significantly greater improvements in reading and spelling but not maths compared to the control group. These results may suggest that Cogmed improves reading and maths in the long-term. However, this finding should be treated with caution because the comparison group did not adequately control for expectations, differences between the groups were close to the significance threshold, the direction of change in each group was unclear, and there was no assessment of training effects in the short-term.

There is currently limited available evidence and contradictory findings for the effects of Cogmed and working memory training in typically developing children. Much of the literature has investigated working memory training in children with learning difficulties, including children with poor academic attainment, poor working memory, or ADHD. These studies have typically examined whether training can ameliorate working memory deficits and improve performance at school. Findings from this literature will be reviewed in the following sections as these outcomes are also very pertinent to typically developing children.

1.2.3. Evidence for Working Memory Training in Children with Poor Working Memory and Academic Attainment

Working memory training has been investigated as a means to improve academic outcomes in children with poor attainment and learning difficulties. Holmes & Gathercole (2014) recruited 50 children aged 9-11 years with low academic performance to receive Cogmed. Training improved Maths and English grades when compared to matched controls who did not participate in any training. Working memory training has also been found to improve numeracy in five year old children, when compared to a passive control group (Kroesbergen, van ’t Noordende, & Kolkman, 2014). Only one study has compared working memory training to an active control group in children with poor attainment. This study examined the Jungle Memory programme (Alloway & Alloway, 2008), where children train on three simple and complex span tasks involving memory for letters, words, and numbers, as well as mental rotation and arithmetic (Alloway, Bibile, & Lau, 2013). Ninety-four children aged 10-11 years received either 24 sessions of Jungle Memory, eight sessions of Jungle Memory, or no intervention. Twenty-four sessions of Jungle Memory was associated with greater improvements in working memory and vocabulary compared to eight sessions of Jungle Memory or the passive control group, and these effects were maintained eight months later. However, there were no relative improvements in the academic measures of spelling and maths. This suggests that Jungle Memory may have improved children’s vocabulary, however neither the low-intensity training or passive control group appropriately controlled for expectations because there were large differences in training and contact time. Overall, there is some preliminary evidence that working memory training may ameliorate poor academic attainment, but this needs to be confirmed in appropriately controlled studies.

Working memory training may be an effective intervention to improve academic outcomes in children with poor working memory. Holmes, Gathercole, and Dunning (2009) assigned 42 children aged 8-11 years with working memory scores in the bottom 15th percentile to receive Cogmed or the non-adaptive control. Near-transfer was assessed on the AWMA (Alloway, 2007) and a school based working memory task that required children to remember and follow a set of simple instructions (see Gathercole, Durling, Evans, Jeffcock, & Stone, 2008). Far-transfer was assessed to word reading, mathematical reasoning, verbal IQ, and performance IQ. Compared to non-adaptive training, Cogmed improved performance on the visuospatial short-term memory, visuospatial working memory, verbal working memory and following instructions tasks, but not on the verbal short-term memory tasks. Six months later, near-transfer effects were maintained and mathematical reasoning had significantly increased in the Cogmed group. However, there was no significant evidence of immediate far-transfer to mathematical reasoning, verbal IQ, performance IQ, or word reading in comparison to the non-adaptive control group. The authors suggested that children’s maths ability only improved in the long-term because increased working memory capacity improved their ability to learn, and so this required time to take effect. However, the analysis of long-term outcomes lacked a control group, there was no randomisation, and the groups significantly differed in their visuospatial short-term memory at baseline.

A randomised controlled trial with a larger sample of 94 children aged 7-9 years with poor working memory aimed to replicate the finding that Cogmed improved children’s maths ability long-term (Dunning et al., 2013). As above, the same pattern of near-transfer was found on the AWMA and following instructions tasks compared to non-adaptive training, however only the improvement in verbal working memory was maintained 12 months later (Dunning et al., 2013). Regarding far-transfer, written expression was improved in the short-term; however, no significant improvements were found for mathematical reasoning, number operations, word reading, reading comprehension, sentence recall, rhyme recall, visual scanning, sustained attention, verbal IQ, or performance IQ. Similar results were reported by another research group in a study of 111 7-year old children with poor working memory and maths (Ang, Lee, Cheam, Poon, & Koh, 2015). They found that Cogmed and updating training only improved performance on working memory tasks that were similar to the specific training programme. Neither training programme resulted in far-transfer to numerical operations when compared to an active control group who trained on similar games which did not tax working memory.

The long-term academic outcomes of Cogmed for children with poor working memory was recently evaluated in a large randomised controlled trial with 452 children aged six to seven years (Roberts et al., 2016). Regular Cogmed sessions at school improved performance on one of four near-transfer tasks (visuospatial short-term memory) six and 12 months after training, but it did not improve children's maths or reading more than school as usual. In fact, at the two year follow-up maths scores in the Cogmed group were significantly worse than the control group, suggesting that taking children out of class to complete their training was detrimental to their learning. One limitation of this study is that the researchers did not examine immediate outcomes when the effects of training may be largest, and so it was not possible to determine whether working memory training was effective in the short-term. Regardless, the long-term decline in maths scores suggests that current working memory training programmes should only be considered in addition to typical education, and should not replace lessons.

Working memory impairment is considered a core feature of ADHD (see section 1.1.1.) and research has sought to ameliorate this impairment with training. In a randomised controlled trial of 85 children with ADHD, Cogmed significantly improved performance on three out of four tasks from the AWMA, relative to a non-adaptive control (Chacko et al., 2014; note, one of these effects did not survive correction for multiple comparisons). However, there were no improvements in ADHD symptoms, as rated by teachers and parents; sustained attention and impulsivity, as measured by the A-X Continuous Performance Test (Halperin, Sharma, Greenblatt, & Schwartz, 1991); or academic achievement, as measured by the word reading, sentence completion and maths computation subtests from the Wide Range Achievement Test (WRAT4-PMV; Roid & Ledbetter, 2006). Similar results were reported in a meta-analysis, including this study and five others, that found significant near-transfer but no far-transfer to parent or teacher rated ADHD symptoms (Cortese et al., 2015). A more recent randomised controlled trial of 65 children with ADHD also found no improvement in parent-rated ADHD symptoms, but did find a significant improvement in teacher-rated ADHD symptoms six months post-training, relative to a non-adaptive control (Bigorra, Garolera, Guijarro, & Hervas, 2016). The study also reported some improvements in parent and teacher ratings of working memory, monitoring, and metacognition. However, these questionnaire findings should be treated with caution as there was no correction for almost 100 statistical comparisons, which would have greatly inflated the chance of false positives.

1.2.4. Summary

The evidence presented here suggests that training reliably improves children's performance on working memory tasks (Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2017b). There is some evidence that these effects are maintained long-term; however, further investigation is required in typically developing children because this has only been examined in a few appropriately controlled studies. The effects of training are moderated by the age of participants and type of training programme, suggesting that younger children may benefit the most and that Cogmed produces the largest effects (Melby-Lervåg & Hulme, 2013). Meta-analyses have shown that there is some evidence that working memory training improves children's academic achievement compared to a passive control group (e.g. Holmes & Gathercole, 2014; Titz & Karbach, 2014), but these effects are minimal when only considering studies with active control groups and randomisation (Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2017b). Similar conclusions have been drawn in a recent review (Redick, Shipstead, Wiemers, Melby-Lervåg, & Hulme, 2015) and randomised controlled trials (Hitchcock & Westwell, 2017; Roberts et al., 2016).

1.3. The Neural Correlates of Working Memory Training

Neuroimaging techniques have been used to investigate how working memory is enhanced through training and the mechanisms of transfer. It is currently unclear the extent to which training related improvements in working memory are due to increased capacity or the acquisition of more effective strategies (von Bastian & Oberauer, 2014). Increased capacity may occur from neuroplastic changes in the working memory network that are induced by repeated demands on cognitive resources that exceed current capacity (Lövdén et al., 2010). Evidence of changes in brain structure and increased resting connectivity after working memory training would broadly support this hypothesis. Alternatively, performance on working memory tasks may be improved by the acquisition of strategies and a more efficient use of working memory (von Bastian & Oberauer, 2014), which would not necessitate changes in brain structure or resting connectivity. Changes in brain activity during a task may be explained by either capacity or strategy. Increased activation may reflect a stronger neural response or additional neuronal recruitment, whereas decreased activation may reflect increased neural efficiency as a result of a more precise neural response (Kelly, Foxe, & Garavan, 2006). Finally, a pattern of activation increases and decreases may reflect increased recruitment of task-specific areas and decreased attentional control, or a change in strategy (Kelly et al., 2006).

Discovering whether working memory training results in a change in capacity or strategy is important because these two hypotheses make different predictions about the extent of far-transfer. A change in working memory capacity would be expected to generalise to related cognitive capacities that depend on the same neural systems (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008), whereas a change in working memory strategy would only be expected to narrowly generalise to similar tasks (see Lustig, Shah, Seidler, & Reuter-Lorenz, 2009, for a review). Currently, the strategy hypothesis provides a better explanation for why there is an apparent lack of far-transfer in the most methodologically rigorous working memory training studies (see Dunning & Holmes, 2014). However, it should be noted that these two hypotheses are not mutually exclusive; it may be the case that training leads to changes in both capacity and strategy.

As discussed in Section 1.1.2., working memory activates a bilateral fronto-parietal network and the development of working memory capacity is associated with functional and structural changes in this network (Darki & Klingberg, 2015; Scherf et al., 2006). It has been suggested that neurodevelopmental changes in working memory may be similar to changes induced by training (Klingberg, 2010). However, there are very few studies that have investigated the neural correlates of working memory training in children and the majority of research has focussed on adults. A review of working memory training in adults six years ago highlighted a range of neural correlates, including changes in brain activity (e.g. Olesen, Westerberg, & Klingberg, 2004; Schneiders, Opitz, Krick, & Mecklinger, 2011), functional connectivity (e.g. Lewis, Baldassarre, Committeri, Romani, & Corbetta, 2009), grey (e.g. Takeuchi et al., 2011) and white matter volume (e.g. Takeuchi et al., 2010), and dopaminergic function (e.g. McNab et al., 2009), but concluded there was no clear pattern of change to suggest evidence for a specific neural mechanism (Buschkuehl, Jaeggi, & Jonides, 2012). Due to a paucity of studies at the time, the review also included studies that trained domains other than working memory, such as perceptual learning and mirror reading, which may be associated with different neural correlates. The following sections will review working memory training studies with children and adults published in more recent years, investigating changes in brain activation on working memory tasks, functional connectivity, and grey matter volume.

1.3.1. Brain Activation

Only one study has examined changes in brain activation following working memory training in typically developing children. Ten 12-year old children trained on a forwards and backwards object span task for 25 minutes, two to three times a week, for six weeks (Jolles, Van Buchem, Rombouts, & Crone, 2012). The children performed significantly better on a digit span task after training, but they were no better than an age-matched control group who received no training. Brain activation during the object span was recorded using fMRI before and after training. There was no direct comparison of brain activation over time. However, before training children showed no significant activation when completing the task in the scanner, and after training children showed significant activation of the right dorsolateral prefrontal cortex, left superior parietal cortex, and left occipital lobe. Interpretation of these neuroimaging findings is severely limited by the absence of an analysis over time and in comparison to the control group.

Another study recruited 18 neurotypical adolescents and 18 adolescents with ADHD to receive Cogmed (Stevens, Gaynor, Bessette, & Pearlson, 2016). Brain activity was recorded during a visuospatial working memory task using fMRI. Cogmed improved working memory capacity and ADHD symptoms, as rated by children and their parents. Increases in activations were broadly observed in a number of frontal and temporal areas across task phases, and parietal areas during the encoding phase. In addition, there were fewer significant differences in brain activity between the ADHD and neurotypical groups after training. These findings imply that Cogmed can alter brain function associated with working memory and potentially ameliorate brain abnormalities related to ADHD. However, as all of the participants completed Cogmed, it is not possible to discount the potential confounding effects of task practice, maturation, and expectation. In addition, the authors only analysed group differences in brain activity before and after training, rather than comparing the effect of training on each group individually. This is important because the neural mechanisms of working memory training may differ for children with ADHD, given that they have atypical neural function (Cortese et al., 2012).

Change in working memory related brain activity has also been investigated in 7-12 year old children who were born very prematurely (Everts, Wapp, Ritter, Perrig, & Steinlin, 2015). Children either received 240 minutes of training on three adaptive working memory tasks, 240 minutes of instruction and adaptive practice in memory strategies, or no intervention over a five week period. Brain activity was recorded during a visuospatial working memory task using fMRI. Both working memory training groups showed significant improvements in working memory capacity, whereas the control group did not. The memory strategy group demonstrated decreased activation in bilateral frontal regions, the working memory training group showed decreased activation in right frontal and parietal regions, and there was no significant change in the control group. However, no direct comparisons were made between the training groups and control group, which would have highlighted training-specific changes in working memory capacity and brain function. In addition, the activations were thresholded at $p < 0.01$ (uncorrected) and 20 contiguous voxels, which is very liberal and likely to produce false-positives.

Given the limitations of child studies, it is informative to address adult studies which are more numerous and, in some cases, better controlled. A meta-analysis of fMRI experiments found that working memory training was associated with reduced activity in the bilateral superior frontal gyrus, bilateral middle frontal gyrus, and right inferior parietal lobule, as well as increased activity in the right inferior frontal gyrus (Li et al., 2015). A similar pattern of activation was apparent when only considering studies that employed a comparison group, where working memory training decreased activity in the right inferior parietal lobule and right middle frontal gyrus, and affected activity in the putamen. These results demonstrate that working memory training is predominantly associated with functional changes in the fronto-parietal network. However, the meta-analysis comprised of only eight controlled studies, which included studies with brief practice on working memory tasks. In addition, there was no analysis of activation increases because only three controlled studies reported increases in activation. A review (Klingberg, 2010) highlighted that brief practice is often associated with decreases in activation whereas longer training, more typical of working memory training programmes, is associated with both increases and decreases in activation. Therefore, increases in activation may be of particular importance to understand the neural mechanisms of working memory training over time, as opposed to brief practice.

As discussed in Section 1.2.1., Cogmed is associated with large near-transfer effects and it is, therefore, an optimal training programme to investigate the neural correlates of increased working memory capacity. Cogmed studies in adults have investigated activation change using a visuospatial working memory task during fMRI (Brehmer et al., 2011; Olesen et al., 2004; Westerberg & Klingberg, 2007). Two studies recruited small samples of young adults ($N < 10$) to receive Cogmed, finding significant near-transfer and widespread increases in activation across fronto-parietal regions after training (Olesen et al., 2004; Westerberg & Klingberg, 2007). This included activation in the middle frontal gyrus, inferior parietal cortex, superior parietal cortex, and the caudate. However, both of these studies lacked a control group, which limits interpretation. A randomised controlled trial of 23 older adults found that Cogmed increased performance on one of four untrained working memory tasks, compared to non-adaptive training (Brehmer et al., 2011). Reduced activity was observed in the right dorsolateral prefrontal cortex, right superior temporal cortex, and bilateral lingual gyrus, relative to the control group. Interestingly, the studies with young adults reported increased activation whereas the study of older adults reported decreased activation, which may mean the neural correlates of working memory training vary with age.

The few studies that have been conducted with children have suggested that working memory training changes activation in frontal and parietal regions of the brain (Everts et al., 2015; Jolles et al., 2012; Stevens et al., 2016). However, research needs to establish whether the activation changes observed in typically developing children are specific to working memory training. To date, studies have failed to analyse the effects over time and/or in comparison to a control group. Brain activity may change over time simply because the child becomes more practised on the fMRI task, requiring less effortful monitoring, control, and error detection processes, and more familiar with the task structure and timings (Poldrack, 2000). Furthermore, there may be effects of maturation or expectation. These issues can be mitigated by using an appropriate control group. Controlled studies with adults have also reported changes in fronto-parietal activity, which may be moderated by the type of training and age of participants.

1.3.2. Functional Connectivity

The brain is comprised of distinct networks, which are functionally related regions of the brain that are simultaneously co-activated at rest (S. M. Smith et al., 2012). These networks can be examined using functional connectivity analysis, which computes the temporal correlations between remote neural events (Friston, 1994, 2011). As working memory activates a bilateral fronto-parietal network (Rottschy et al., 2012), training may affect functional connectivity between these regions. An advantage of this technique is that findings cannot be explained by change in working memory strategy or task performance, because brain activity is typically measured at rest.

At present, the effects of Cogmed on functional connectivity has only been investigated in one sample of children (Astle et al., 2015). In this study, 33 typically developing children aged 8-11 years were randomly assigned to receive adaptive or non-adaptive Cogmed. Children's working memory was measured using four tasks from the AWMA, and resting brain activity was measured using Magnetoencephalography (MEG). Compared to non-adaptive training, Cogmed increased working memory capacity and increased functional connectivity between the right fronto-parietal network and left lateral occipital cortex. In addition, increases in working memory capacity (across groups) correlated with increased connectivity between the fronto-parietal network and two other regions: the left superior parietal cortex and left inferior temporal cortex. Similar results were obtained in a connectivity analysis of the same sample of children as they completed a visuospatial working memory task (Barnes, Nobre, Woolrich, Baker, & Astle, 2016). Cogmed increased coupling between slower cortical rhythms in the fronto-parietal network and shorter oscillatory activity in the inferior temporal cortex, and this coupling correlated with improvement on the task. These findings suggest that training enhanced connectivity within and between the fronto-parietal network, which may have effectively enabled increased working memory capacity.

Only one other study has investigated how working memory training affects functional connectivity in typically developing children (Jolles, Van Buchem, Crone, & Rombouts, 2013). Fifteen young adults and nine 12-year old children trained on a forwards and backwards object span task for 25 minutes a day, three days a week, for six weeks. Before and after training, participants completed the same task during fMRI. Performance on the task increased and response times decreased over time, demonstrating practice effects. No changes in functional connectivity were observed in the children, which may be due to limited power owing to the small sample. In adults, increased functional connectivity was observed between the right middle frontal gyrus and other regions of the fronto-parietal network, including the bilateral superior and middle frontal gyri, as well as the anterior cingulate and paracingulate gyrus. In addition, improvement on the task was correlated with increased functional connectivity between the right middle frontal gyrus and superior parietal cortex. The findings in adults also suggest that working memory training may enhance connectivity within the fronto-parietal network. However, this study is limited by the absence of a control group and measures of near-transfer.

Takeuchi et al. (2013) improved upon this design with a larger sample and a control group. Sixty one healthy young adults were assigned to receive either adaptive working memory training or no intervention. Training consisted of practice on visuospatial, auditory, and dual modality working memory tasks for approximately 20-60 minutes per day, for 27 days. Participants completed assessments of cognitive function and resting-state fMRI scans before and after the training period. Training increased performance on the training tasks and increased working memory capacity more than controls, as assessed by near-transfer tasks. Training significantly decreased functional connectivity between the external attention network (right posterior parietal cortex and right lateral prefrontal cortex) and default mode network (medial prefrontal cortex), compared to controls. The authors suggest that the training-related changes in connectivity may be the result of changes in the externally-oriented lateral prefrontal cortex, which regulates activity in regions of the internally-oriented default mode network (Greicius, Krasnow, Reiss, & Menon, 2003). However, as the control group was passive and there was no correlation between neural change and near-transfer, this finding could be the result of other non-specific effects of the training.

1.3.3. Brain Structure

Neuroimaging techniques have also been used to examine how working memory training influences the structure of the brain (e.g. Takeuchi et al., 2013). However, this question has yet to be examined in any sample of children. In adults, voxel-based morphometry (VBM) has been used to analyse how training effects grey matter volume. As described in Section 1.3.2., Takeuchi and colleagues (2013) found that adaptive working memory training increased working memory capacity and decreased functional connectivity between the external attention network and default mode network. The authors also reported increased grey matter volume in widespread fronto-parietal regions, as well as the left middle temporal gyrus, caudate, and cerebellum, compared to controls. However, the control group received no intervention and the changes in grey matter volume did not significantly correlate with improvement in working memory performance. Therefore, it is difficult to interpret the cause of these neural changes.

In a placebo controlled study, Takeuchi and colleagues (Takeuchi et al., 2011) randomly assigned young adults to receive adaptive mental arithmetic training, non-adaptive mental arithmetic training, or no intervention. The training tasks were designed to tax working memory, and adaptive training did indeed increase performance on an untrained letter span task compared to non-adaptive training. Adaptive training also decreased grey matter volume in the bilateral dorsolateral prefrontal cortex, right inferior parietal lobule, left paracentral lobule, and left superior temporal gyrus. Improvement on the letter span task was only associated with decreased grey matter volume in the left superior temporal gyrus. This suggests that the training reduced grey matter volume in fronto-parietal and other regions; however, it is difficult to interpret whether these changes are due to increased working memory because the participants trained mental arithmetic rather than working memory per se, and only one task was used to infer change in working memory capacity.

Cogmed is assumed to train working memory more specifically, and has been investigated in comparison to an active control group (Metzler-Baddeley, Caeyenberghs, Foley, & Jones, 2016a). This study investigated changes in grey matter structure and volume, by analysing cortical thickness. Forty young adults were randomly assigned to receive adaptive or non-adaptive Cogmed. Compared to non-adaptive training, Cogmed increased working memory capacity but there were no differential effects of training on cortical thickness across the two groups. Some changes were observed within the adaptive Cogmed group, including increased cortical thickness in the right caudal middle frontal cortex, increased volume in the left pallidum, and reduced thickness in the right insula. However, the absence of differential effects of training suggests that these changes in grey matter may be due to other factors, rather than increased working memory capacity.

1.3.4. Summary

Current evidence suggests that working memory training is associated with activation changes in fronto-parietal regions of the brain. Three studies have examined changes in children's brain activation, finding both increased (Jolles et al., 2012; Stevens et al., 2016) and decreased fronto-parietal activation over time (Everts et al., 2015). However, these studies employed different training protocols and either lacked a control group or failed to find significant differences compared to controls. Thus, there is only preliminary evidence for changes in children's fronto-parietal activity, which has yet to be rigorously tested in typically developing children. Working memory training in adults has also been associated with increases and decreases in fronto-parietal activation. Cogmed has more frequently been associated with increased activation in children (Stevens et al., 2016) and young adults (Olesen et al., 2004; Westerberg & Klingberg, 2007). However, the only controlled investigation of Cogmed reported decreased activation of the dorsolateral prefrontal cortex in older adults (Brehmer et al., 2011).

Working memory training has been found to increase functional connectivity within the fronto-parietal network in adults (Jolles et al., 2013) and in children (Astle et al., 2015; Barnes et al., 2016). However, this has only been examined in one sample of children, and the few studies that have been conducted with adults lacked an active control group. Furthermore, no studies have examined how working memory training influences the structure of the brain in childhood. Adult studies employing active control groups have either reported no differential effects of training on brain structure (Metzler-Baddeley et al., 2016a) or reported reduced grey matter volume in fronto-parietal and other regions that are associated with adaptive mental arithmetic training (Takeuchi et al., 2011). Future research will need to clarify whether working memory training leads to structural changes in the brain. Finally, the majority of published studies have examined functional and structural changes in isolation, rather than taking a broader approach to examining neural correlates. One study reported both increases in grey matter volume and changes in connectivity in the lateral prefrontal cortex; however, this was only observed in comparison to a waitlist control group (Takeuchi et al., 2013). Therefore, these changes may not be the result of increased working memory through training, but could be due to the placebo effect or other processes such as improved attention or planning, which are required to complete the training.

1.4. Facilitating Far-Transfer from Working Memory Training

Near-transfer is frequently reported in working memory training studies and this is often associated with changes in the fronto-parietal network; however, there is a lack of convincing evidence for far-transfer (see Sections 1.2. and 1.3). This has led to the suggestion that working memory training may primarily promote the acquisition of strategies that can only be used on structured working memory tasks (Dunning & Holmes, 2014; Randall & Tyldesley, 2016). A study by Dunning and Holmes (2014) showed that working memory training promotes the use of working memory strategies. After 10 sessions of Cogmed, young adults performed better on the near-transfer tasks and reported using grouping more frequently than those in the non-adaptive control group. Grouping is an effective strategy to remember a stimulus sequence by dividing it into groups and rehearsing the sequence with pauses in between the groups (Ryan, 1969a; Wickelgren, 1964). Therefore, grouping could at least partially explain the improvements on the near-transfer tasks. However, it would be difficult for a child to apply such a strategy frequently at school, as school tasks are inherently more varied than working memory tasks. This has been demonstrated in a study measuring working memory capacity, working memory strategies, and reading comprehension in 148 young adults (Bailey, Dunlosky, & Kane, 2008). Working memory capacity significantly predicted reading comprehension and use of memory strategies significantly predicted performance on the working memory task. However, memory strategies did not predict reading comprehension. This suggests that working memory strategies are task-specific, and that whilst other cognitive tasks make demands on working memory, they afford different strategies. Therefore, the strategies learnt during working memory training, such as grouping, are unlikely to promote far-transfer to measures of academic achievement. Children may benefit from being taught when this strategy can be used in school tasks, but more generalised benefits may be achieved from teaching children metacognitive strategies that are applicable in a wide variety of contexts.

1.4.1. Metacognitive Interventions in Education

Metacognition broadly concerns thinking about one's own thinking (Flavell, 1979). It can be divided into metacognitive knowledge and metacognitive regulation (Schraw, 1998; Schraw & Dennison, 1994). Metacognitive knowledge describes what one knows about their own cognitions and cognitions in general, factors that influence them, and cognitive strategies. Metacognitive regulation describes the attentional control of cognition, planning how to complete a task, monitoring for errors, and evaluating performance. In the education literature, metacognitive strategy interventions typically instruct children how to plan, monitor, and evaluate in a domain of interest, such as reading comprehension (Mason, 2004) or mathematical reasoning (Mevarech & Kramarski, 2003). In a meta-analysis of 74 educational interventions, instruction of metacognitive strategies was found to be the most effective at improving academic performance in primary schools (Dignath & Büttner, 2008). Metacognitive reflection, i.e. teaching children how and when to use strategies, was found to be the most effective at improving academic performance in secondary schools. Metacognition has also been linked with the transfer of knowledge and skills from one domain to another (Fisher, 1998a). For example 'Thinking Science', a science intervention where teachers use questions to scaffold students' metacognition, has been shown to improve Maths and English grades more than controls who received education as usual (Adey & Shayer, 1993). Further, these improvements were significantly larger for the children that showed greater improvements on the near-transfer measure of science reasoning. These findings demonstrate evidence that metacognitive interventions in school produce generalizable academic benefits.

1.4.2. Combined Working Memory and Metacognitive Training

Metacognitive strategy instruction has been combined with working memory training to facilitate the far-transfer of skills and behaviour. One study randomised 100 8-12 year old children with ADHD to receive either Cogmed or the 'Paying Attention in Class' (PAC) programme, which includes training on three paper-based working memory tasks, psychoeducation about attention, planning, and memory strategies, and simulation of classroom situations (van der Donk, Hiemstra-Beernink, Tjeenk-Kalff, van der Leij, & Lindauer, 2015). Before and after training, children completed assessments of working memory, attention, planning, inhibition, word reading, spelling, and arithmetic, and parents rated their children's executive function. Counter to predictions, PAC did not improve far-transfer measures of academic attainment or executive function significantly more than Cogmed. In fact, Cogmed induced significantly greater near-transfer, suggesting that the working memory training in PAC may not have been as effective. Without significant near-transfer the intervention may be unlikely to induce far-transfer, as this undermines the proposed mechanisms of training. Metacognitive strategy instruction might be more likely to facilitate far-transfer if it was combined with Cogmed, which reliably improves working memory. Unfortunately, the absence of a control group in this study precludes any interpretation about the specific effects of PAC on metacognition, planning, and academic achievement.

In a randomised controlled trial of 64 eight year old children with Special Educational Needs (SEN), Cogmed was combined with metacognitive strategy training and compared to Cogmed alone and a waitlist control (Partanen, Jansson, Lisspers, & Sundin, 2015). The metacognitive group received three additional group sessions each week that focused on labelling elements of the training tasks, formulating goals, identifying strategies and pitfalls, sharing planning and execution strategies, and relating the training tasks to school or leisure time. Only the metacognitive group showed improvements in working memory capacity compared to the waitlist control, but not Cogmed alone, and there were no differences in maths, reading, and nonverbal reasoning. This suggests that for children with SEN, Cogmed may only improve working memory capacity if accompanied by metacognitive strategy training, which may facilitate engagement in the training. However, this effect is confounded by the additional contact time that this group received and, as discussed earlier, improvements relative to a waitlist control should be treated with caution. A further consideration is whether eight year old children with SEN have the appropriate insight to engage with the metacognitive intervention. Indeed, it may have been more feasible to foster far-transfer if the children were given maths and reading exercises to practise applying the strategies they had learnt.

One study investigated how children's reading can be supplemented with working memory and metacognitive training in school (Carretti, Caldarola, Tencati, & Cornoldi, 2014). Typically developing children aged 9-11 years completed 22 one-hour training sessions during school time. Children were taught how to identify goals, use reading strategies, monitor their comprehension, and predict the content of the reading based on the genre. The children also trained on three working memory tasks of increasing difficulty. These children showed significant improvements in working memory, reading comprehension, and self-reported metacognition compared to the control group who, in the same number of training sessions, only completed reading comprehension exercises. This study demonstrates how a diverse training schedule targeting basic cognitive functions, task-specific skills and strategies, and general metacognitive strategies may be optimal for improving academic outcomes. However, it is unclear from this study whether the improvement in reading comprehension was the result of working memory training, instruction in reading strategies, instruction in metacognitive strategies, or a combination of the three.

Metacognitive strategy training has also been used in paediatric neurorehabilitation research to help children manage their attention and memory difficulties. Strategies are designed to help children approach, engage, and evaluate tasks. Some specific examples include: repeating instructions, goal setting, predicting task difficulty, motivational self-talk and rewarding oneself (Butler & Copeland, 2002; Sohlberg, Harn, MacPherson, & Wade, 2014). The Amsterdam Attention and Memory Training programme for Children (AMAT-C; van't Hooft et al., 2005) combines training on memory and attention tasks with strategy training that specifically targets learning strategies and the completion of school tasks. The AMAT-C has been shown to improve working memory, sustained attention, and selective attention in children with acquired brain injury (van't Hooft et al., 2005). Similarly, the Cognitive Remediation Programme (CRP) was developed for childhood cancer survivors who suffer neuropsychological impairment following chemotherapy (Butler & Copeland, 2002). The CRP has been shown to improve self-reported metacognitive strategy use, parent-reported attention and academic achievement (Butler et al., 2008). These childhood interventions show promise, however they have yet to be rigorously tested against active control groups.

1.5. Memory Strategies

Working memory training reliably improves children's performance on working memory tasks (see Section 1.2); but it is unclear whether training is increasing capacity, the effective use of strategies, or both (von Bastian & Oberauer, 2014). Studies in adults have shown that strategy-use is significantly associated with performance on a range of memory tasks, including: working memory tasks (Bailey et al., 2008; Bailey, Dunlosky, & Kane, 2011; Dunlosky & Kane, 2007), short-term memory tasks (Bailey et al., 2011), and free recall and paired associates tasks (Bailey et al., 2008). These findings suggest that strategy-use significantly contributes to measures of memory capacity, which may be explained by two hypotheses (Dunlosky & Kane, 2007). The strategy-as-cause hypothesis states that some individuals are generally more strategic than others and this leads to differences in performance across a range of tasks. Alternatively, the strategy-as-effect hypothesis states that individuals are similarly strategic on easy tasks, but that a high working memory capacity affords the production and implementation of effective and effortful strategies on demanding novel tasks.

There is some empirical evidence in support of the strategy-as-effect hypothesis (Dunlosky & Kane, 2007). Studies have shown that instructions to use an imagery strategy to remember lists of word pairs improves recall for children aged 6-7 years (Pressley & Levin, 1977), but not children aged 4-6 years (Guttmann, Levin, & Pressley, 1977). This suggests that the effective use of imagery requires some cognitive capacity, which is not sufficiently developed in young children. It has also been shown that higher working memory capacity predicts the ability to implement effective strategies (Dunlosky & Thiede, 2004). Adults were instructed to remember six word pairs from a list of 30 and to choose a small number of the easiest pairs for restudy. Individuals with high working memory capacity effectively implemented the strategy they had been instructed to use, whereas individuals with low working memory capacity selected approximately half of the word pairs for restudy. These findings suggest that working memory capacity affords the use of more effective strategies.

1.5.1. Accounts of Strategy in Models of Short-term Memory

Models of short-term memory have provided accounts for strategic processes. For example, verbal information in the phonological loop is maintained by sub-vocal rehearsal (Baddeley, 1992). Speech input has direct access to the phonological loop, but information from other modalities can be strategically recoded into a phonological form. Sub-vocal rehearsal can be disrupted by articulatory suppression, whereby an unrelated word is repeatedly articulated whilst attempting to remember and retrieve a list of words (Baddeley, Lewis, & Vallar, 1984). Similarly, recall is worse for words with more syllables (i.e. the word-length effect) because they take longer to articulate in sub-vocal rehearsal (Baddeley et al., 1984). These findings suggest that rehearsal is important process to maintain information over a short period of time.

Grouping has also been investigated experimentally. The temporal grouping effect describes a common observation where memory is improved when a stimulus sequence is separated into distinct groups by introducing a longer pause in between presentations (Hitch, Burgess, Towse, & Culpin, 1996; Ryan, 1969a, 1969b). This has been suggested to be an effect of rehearsal (Ryan, 1969b) and is consistent with the observation that the effect is reduced under articulatory suppression for visual stimuli (Hitch et al., 1996). However, articulatory suppression may interfere with the recoding of visual stimuli into an auditory form (Baddeley et al., 1984). Indeed, the temporal grouping effect persists for auditory stimuli under articulatory suppression (Frick, 1989) and is insensitive to the word length effect (Hitch et al., 1996). This suggests that temporal grouping is not an effect of rehearsal (Frankish, 1985, 1989), and that the temporal presentation of stimuli may be a contributing factor. However, the phonological loop, consisting of the store and sub-vocal rehearsal, does not provide a sufficient specification for this effect. Interestingly, studies have also shown that items grouped by voice or spatial location are more easily remembered (Frankish, 1989; Frick, 1989; Parmentier et al., 2006), suggesting that grouping is a domain-general phenomenon.

A connectionist model of short-term memory may provide a better account for temporal grouping because it distinguishes between the representation of items, representation of phonemes, and contextual timing signals (Burgess & Hitch, 1996, 2006). According to this model, the timing signal and phonemic components independently contribute to the representation of items in short-term memory. Under conditions of temporal grouping, a first set of timing signals codes for the order of a stimulus within the sequence and a second set of timing signals codes for the order of a stimulus within its group (Hitch et al., 1996). Therefore, this proposal also accounts for characteristic errors in grouping (Ryan, 1969b), where stimuli are confused between groups that share the same within-group position because they share the same within-group timing signal.

The connectionist model suggests that temporal grouping effects are caused by the temporal presentation of items (Hitch et al., 1996). However, this does not account for the strategic use of grouping where the temporal presentation of items is held constant. In a series of experiments, young adults were initially instructed to recall sequences of digits without instruction and then instructed to rehearse the sequences in groups (Farrell, 2008; Farrell, Wise, & Lelièvre, 2011). Participants recalled more correct sequences after the instructions, suggesting the strategy was effective. However, this effect is confounded by practice and expectation because all participants completed the grouping condition second and there was no control group. A controlled study failed to find a significant effect of grouping instruction (Ryan, 1969a), but this may be due to limited power as there were only 10 participants per condition. A suitably powered between-subjects study found that grouped rehearsal was more effective than single-item rehearsal (Wickelgren, 1964). However, grouping was not compared to sequential rehearsal, which is the most common strategy on short-term memory tasks (Morrison, Rosenbaum, Fair, & Chein, 2016). Furthermore, grouped rehearsal always included twice as many repetitions compared single-item rehearsal. During single item rehearsal participants were instructed to rehearse each item once after presentation (e.g. “1, 2, 3, 4”); whereas for grouped rehearsal, participants were instructed to rehearse each item once after presentation and then to rehearse them once again in their groups (e.g. “1, 2, 1-2, 3, 4, 3-4”). Therefore, it is currently unclear whether individuals benefit from instructions to rehearse items in groups, when compared to a sequential rehearsal.

1.5.2. Development of Memory Strategies

In children the word-length effect and temporal grouping effect have been used to investigate the development of memory strategies. The word-length effect has been shown for spoken words at the age of four years; however, this does not emerge for picture stimuli until the age of eight years (Hitch, Halliday, Dodd, & Littler, 1989). This suggests that sub-vocal rehearsal is present at an early age, but that other modalities are not strategically recoded into a phonological form to facilitate rehearsal until the age of eight. In a series of experiments, Towse, Hitch, & Skeates (1999) investigated the temporal grouping effect in typically developing children between the ages of four and eight years. They demonstrated that eight year old children consistently remembered more items (letters or numbers) when they were temporally grouped during visual or auditory presentation, whereas younger children did not. This may suggest that eight year old children have the capacity to use grouping; however, it is not clear whether children can strategically use grouping at the age. The effects of instructing children to use grouped rehearsal has yet to be investigated in any published report.

Studies using think-aloud procedures have suggested the development of rehearsal and grouping is somewhat later. A study of free recall of category words showed that eight year olds typically repeated one word at a time as it was presented, 10 year olds rehearsed several words at the same time, and 13 year olds rehearsed related category words together at the same time (Ornstein, Naus, & Liberty, 1975). All age groups were able to sort the words according to their categories and recalled more words when they were presented in their categories rather than a random order. However, only 13 year old children were able to spontaneously chunk, which was associated with improved recall performance. Another study of free recall demonstrated similar development of memory strategies. One-item repetition was used by 52% of eight year olds and 37% of 10 year olds, sequential rehearsal was used by 17% of 8 year olds and 46% of 10 year olds, and elaboration or association strategies, such as chunking, were used by only 8% of 8 year olds and 9% of 10 year olds (Lehmann & Hasselhorn, 2007). Furthermore, sequential rehearsal significantly correlated with recall.

Research suggests that it is possible to teach children to use memory strategies after a brief instruction. In one study, children were shown 12 picture cards belonging to three categories in a mixed four by three array (Schleepen & Jonkman, 2012). They were told that they would need to remember the items and that they could move the cards however they liked. This was repeated for a different set of picture cards with the instruction that it might be easier for them to remember the items if they placed them in groups which belong together. Children aged eight or nine years did not spontaneously sort the items according to their groups in the first task, but after instruction the children showed better sorting, more instances of grouped rehearsal, and better recall. Children aged six to seven years did not benefit from the instruction, whereas children aged 10 to 12 years spontaneously grouped but increasingly so with instruction.

1.5.3. The Neural Correlates of Memory Strategies

Children develop more effective strategies with age, which may reflect a strategic allocation of resources to certain regions within the working memory network. This has yet to be tested in children; however, some studies have highlighted the neural correlates of working memory strategies in adults. Henson, Burgess, & Frith (2000) used a subtraction fMRI procedure to examine brain activation associated with storage, rehearsal, and grouping in six healthy young adults. Sequences of six letters were visually presented and followed by a probe. Rehearsal was examined by comparing recognition of a six letter sequence to recognition of a single letter, and revealed increased activation in the left middle frontal gyrus, bilateral superior parietal lobe, and bilateral middle occipital lobe. Grouping was examined by comparing sequence recognition to recognition of a temporally grouped sequence. Grouping increased activation in the right inferior frontal gyrus and decreased activation in the left middle frontal gyrus and thalamus. These strategies predominantly recruited core frontal and parietal regions of the working memory network, however rehearsal was also associated with large clusters of activation in the visual cortex, which may reflect greater visual attention directed towards the sequence probe compared to the letter probe. Indeed this was not the case in a subsequent study where letter strings were presented aurally, rather than visually (Logie et al., 2003). Six young adults were instructed to subvocally rehearse random strings of five letters, compared to rehearsal of A-B-C-D-E. Rehearsal of items in short-term memory was associated with recruitment of core regions of the working memory network; specifically, greater activation in the left inferior parietal lobe, left inferior frontal gyrus, and left middle frontal gyrus.

The neural correlates of grouping has also been investigated in a larger sample of 23 adults more recently (Kalm, Davis, & Norris, 2012). Letters were aurally presented in continuous sequences and temporally grouped sequences during fMRI. Participants were instructed to verbally recall the sequences in order. At a span of six, grouping decreased activation in the left middle frontal gyrus, bilateral superior temporal gyrus, left premotor cortex, and left insula. At a span of nine, grouping increased activation in the left inferior parietal lobe and left premotor cortex. These findings also implicate fronto-parietal regions, but suggest that grouping may be moderated by load, particularly when comparing recall for items above and below capacity.

A series of experiments by Bor and colleagues investigated the neural processes of chunking in adults. This strategy is very similar to grouping, in that it requires the division of stimuli into smaller groups, but these groups are also associated with meaningful representations in long-term memory (G. A. Miller, 1956). In a corsi-block task, stimulus sequences that formed shape patterns were significantly easier to remember than random sequences and recruited greater activation in the lateral prefrontal cortex, inferior parietal lobe, and fusiform gyrus (Bor, Duncan, Wiseman, & Owen, 2003). Mathematically structured sequences of numbers (of the form 8, 6, 4, 2, 3, 5, 7, 9) were significantly easier to remember than random sequences and recruited greater activation in the bilateral areas of the prefrontal cortex, parietal cortex and temporal cortex (Bor, Cumming, Scott, & Owen, 2004; Bor & Owen, 2007). Similarly, overlearned sequences of four numbers that were combined to make eight digit sequences were significantly easier to remember than random sequences (Bor & Owen, 2007). This chunking strategy was associated with greater activation in the left lateral frontal cortex, bilateral parietal cortex, medial parietal cortex, and left hippocampus. Overall, these findings demonstrate that strategic encoding of verbal and visual information elicits consistent recruitment of lateral prefrontal and lateral parietal regions. These findings cannot be attributed to task difficulty because although chunking facilitated more efficient storage it was associated with an increase rather than decrease in activity.

1.6. Thesis Aims

Working memory training studies in typically developing children have provided reliable evidence of near-transfer (Sala & Gobet, 2017b), but there is limited evidence to infer whether this associated with changes in the brain. There is currently no published investigation of how working memory training influences the structure of children's brains, and studies that have investigated changes in brain activation have lacked appropriate control groups and/or analyses (Everts et al., 2015; Jolles et al., 2012; Stevens et al., 2016). Chapter 2 will describe a broad investigation of the neural correlates of working memory training in typically developing children aged 10-14 years using MRI techniques to examine change in brain activation, functional connectivity, and grey matter volume, in comparison to a non-adaptive control group. Specifically, the study will investigate Cogmed as this has been associated with large near-transfer effects, suggesting it is an effective working memory training programme. Near-transfer will be measured using eight simple and complex span tasks from the AWMA. Brain activation will be measured using fMRI as children complete simple and complex span tasks. Functional connectivity will be measured using resting-state fMRI and grey matter volume will be measured using VBM. This study will provide a novel examination of training-related changes in children's brain activation and structure, and afford greater spatial resolution to examine changes in functional connectivity than previous investigations using MEG (Astle et al., 2015). Furthermore, the study affords a novel examination of how changes in brain activation, functional connectivity, and grey matter volume may potentially interrelate.

Despite good evidence for near-transfer following working memory training, far-transfer effects have remained elusive in studies with active control groups and randomisation (Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2017b). Combined working memory and metacognitive training has shown some promise at improving children's academic outcomes (Butler et al., 2008; Carretti et al., 2014). However, very few studies exist, and only one study has investigated this type of intervention in typically developing children (Carretti et al., 2014). Furthermore, previous studies have either lacked an active control group (Butler et al., 2008; van't Hooft et al., 2005; van der Donk et al., 2015), not controlled for contact time between the groups (Partanen et al., 2015), or manipulated more than one factor at a time (Carretti et al., 2014). Chapter 3 will describe a randomised controlled trial of combined working memory and metacognitive strategy training where these two factors are varied independently. Ninety-five typically developing children aged 9-14 years will either receive 'MetaCogmed' (i.e. Cogmed and metacognitive training), Cogmed alone, or visual search training, over the course of half a term after-school. Near-transfer will be measured using four tasks from the AWMA and far-transfer to academic achievement will be measured using two subtests of the Wechsler Individual Achievement Test-II (WIAT-II; Wechsler, 2011): reading comprehension and mathematical reasoning. This will be the first investigation of MetaCogmed and the most rigorous investigation of whether metacognitive training facilitates far-transfer from working memory training.

An alternative approach to improving children's working memory is instruction in strategies that make more efficient use of current capacity. Grouping is associated with greater performance on memory tasks and is increasingly used after working memory training. This suggests that it is an effective strategy that may moderate near-transfer effects of training. At the age of eight children can remember more items when they are temporally grouped (Towse et al., 1999). Temporal grouping in adults is associated with decreased recruitment of the left middle frontal gyrus (Henson et al., 2000; Kalm et al., 2012), and both grouping and chunking are associated with increased activation of the inferior parietal lobe (Bor et al., 2004, 2003; Bor & Owen, 2007; Kalm et al., 2012). The temporal grouping effect may be a product of the timing of stimulus presentation, rather than a strategic reorganisation and rehearsal process. However, no study has examined whether children can strategically use grouping on ungrouped sequences, if they would benefit from being taught to group, and what neural processes are associated with this strategy. Chapter 4 will describe an fMRI study investigating these questions in a group of 50 typically developing children aged 11-14 years.

Chapter 2: How does working memory training work? Investigating the neural correlates of working memory training in children.

2.1. Introduction

This chapter describes an extensive investigation of the neural correlates of working memory training, utilising multiple neuroimaging techniques in a single sample of typically developing children. Evidence suggests that working memory training improves performance on near-transfer tasks, but there is debate regarding the mechanisms of transfer (see Section 1.3; von Bastian & Oberauer, 2014). Training may increase capacity, which implies changes in the neural systems that support working memory. Alternatively, training may promote the acquisition and practice of strategies that can be transferred to tasks with similar structure to the training tasks. This implies a more efficient use of working memory capacity, without necessitating changes in the brain. To date, published studies have investigated the neural correlates of working memory training in only five independent samples of children and only two these employed a control group (see Section 1.3 for a review). Therefore, it is currently unclear how working memory training might influence the structure and function of children's brain, which may provide valuable insights into the mechanisms of training. This chapter will investigate whether Cogmed in typically developing children is associated with changes in task-related brain activation, functional connectivity, and grey matter volume in comparison to an active control group. This section will summarise the relevant literature reviewed in Chapter 1 and justify the present investigation.

A meta-analysis demonstrated that Cogmed is associated with larger near-transfer effects than other existing working memory training programmes (Melby-Lervåg & Hulme, 2013). Cogmed studies have reported large near-transfer effects on composite scores of the AWMA in typically developing children (Astle et al., 2015), children with poor working memory (Dunning et al., 2013; Holmes et al., 2009), and children with ADHD (Holmes et al., 2010). Near-transfer has also been reported on individual AWMA tasks. This includes the Dot Matrix (Chacko et al., 2014), which is a simple span measure of visuospatial short-term memory, and the Odd-One-Out (Bergman Nutley et al., 2011), which is a complex span measure of visuospatial working memory that requires active maintenance in the face of competing processing. These findings suggest that Cogmed is associated with reliable near-transfer effects in children, which can be detected using an individual task or battery of tasks from the AWMA.

Working memory activates bilateral fronto-parietal regions of the brain (Rottschy et al., 2012), which have also been implicated in working memory training. Previous studies have provided preliminary evidence that Cogmed increases activation of the middle frontal gyrus in children (Stevens et al., 2016) and adults (Olesen et al., 2004; Westerberg & Klingberg, 2007). Increased activation of the superior parietal lobe has also been associated with working memory training in children (Jolles et al., 2012) and Cogmed in adults (Olesen et al., 2004; Westerberg & Klingberg, 2007). However, these studies have lacked control groups and, therefore, it has yet to be determined whether these effects are specific to Cogmed. Conversely, a meta-analysis of controlled working memory training studies in adults found decreased recruitment of the middle frontal gyrus (Li et al., 2015). However, this also included studies with short practice on working memory tasks, which were largely associated with decreases in activation, whereas working memory training programmes were associated with both increases and decreases in activation.

Previous neuroimaging investigations of Cogmed in children (Stevens et al., 2016) and adults (Olesen et al., 2004; Westerberg et al., 2007) have measured the neural correlates of visuospatial short-term memory using tasks similar to the Dot Matrix. However, no previous study has investigated how Cogmed might affect brain activation on a complex span task. This may provide an interesting insight into the mechanisms of transfer because complex span tasks are more strongly associated with measures of other cognitive functions (see Engle & Kane, 2004, for a review). Cogmed has been found to improve children's performance on the Odd-One-Out, suggesting that this may be a suitable task to identify the neural correlates of working memory training.

Only one study has examined whether Cogmed is associated with changes in resting-state functional connectivity using MEG (Astle et al., 2015). Increased functional connectivity was observed within the dorsal attention network, which comprised of the frontal eye fields and superior parietal lobes. In addition, increased functional connectivity was found between a fronto-parietal network, consisting of the right lateral prefrontal cortex and posterior parietal cortex, and the left lateral occipital cortex. These findings suggest that Cogmed in childhood is associated with increased functional connectivity within fronto-parietal networks of the brain. It was suggested that the repeated and demanding co-activation of fronto-parietal regions during training may have increased functional connectivity and afforded greater attentional capacity. However, the spatial resolution of MEG is somewhat limited and fMRI may provide a more precise anatomical localisation of changes in functional connectivity.

There are no published investigations that have examined the association between working memory training and structural changes in children's brains. Furthermore, only one study in adults has investigated whether Cogmed is associated with structural changes in the brain (Metzler-Baddeley et al., 2016a). Cogmed was associated with no significant changes in grey matter volume or cortical thickness compared to non-adaptive training. However, a larger study found that adaptive mental arithmetic training, which was found to improve working memory, reduced grey matter volume in bilateral fronto-parietal regions of the brain compared to non-adaptive training (Takeuchi et al., 2011). This suggests that adaptive training may be associated with structural changes in the brain; however, this has yet to be established in children.

The present study will examine whether working memory training in children is associated with changes in brain activation on a simple and complex span task, resting-state functional connectivity, and grey matter volume, in comparison to a non-adaptive control. This will be the first investigation to examine whether working memory training is associated with changes in the structure of children's brains and the first to examine changes in children's brain activation compared to an active control. Furthermore, this will be the first study to combine these neuroimaging measures within a single sample. This will afford a novel evaluation of the relationship between different functional and structural changes in the brain associated with working memory training. The study will inform whether the effects of working memory training have a neural basis and how these relate to the cognitive mechanisms of transfer.

Children aged 10 to 14 years were recruited for the study for theoretical and practical reasons. Firstly, evidence suggests that younger children benefit more from working memory training than older children (Melby-Lervåg & Hulme, 2013). It has been suggested that training early in development may lead to broader transfer across cognitive domains (Wass, 2015; Wass, Scerif, & Johnson, 2012) because working memory is associated with a more distributed neural network in early childhood (Scherf et al., 2006). Furthermore, whilst white matter volume steadily increases through childhood and adolescence, grey matter volume increases until late childhood and decreases in adolescence (Giedd et al., 1999, 2015). Decreases in grey matter volume are thought to reflect synaptic pruning (Huttenlocher, 1979), which may occur during a period of neurodevelopment which is particularly sensitive to adapting to experience of the environment. Pilot work sought to establish whether children as young as eight years old could tolerate being in the MRI scanner and to what extent they moved their heads during scanning. Fourteen children aged 8-15 years were recruited to pilot the MRI procedure; all four children under the age of 10 made a large number of head movements whereas only one child over the age 10 made a large number of head movements. Head movements limit the spatial localisation of MRI and, therefore, it was decided that children should be at least 10 years old to take part in the study. The age group of the sample overlaps with previous working neuroimaging investigations of working memory training (e.g. Astle et al., 2015; Jolles et al., 2012), but it is narrower than some studies that have sampled over a larger age range (Everts et al., 2015; Stevens et al., 2016).

2.1.1. Hypotheses

1. Working memory training has been shown to improve performance on working memory tasks in typically developing children (Sala & Gobet, 2017). It is predicted that Cogmed will improve performance on the AWMA significantly more than the non-adaptive control group.

2. Working memory training has been associated with activation changes in the bilateral middle frontal gyrus and superior parietal lobe in children (Jolles et

al., 2012; Stevens et al., 2016) and adults (Li et al., 2015; Olesen et al., 2004; Westerberg & Klingberg, 2007). Therefore, it was predicted that Cogmed would increase or decrease activation within these regions relative to the control group, but no prediction was made regarding the direction of the effect because there have been mixed results.

3. Cogmed has been shown to increase functional connectivity within fronto-parietal networks of the brain in typically developing children compared to a non-adaptive control group (Astle et al., 2015). Therefore, it was also predicted that Cogmed would increase functional connectivity within fronto-parietal networks of the brain compared to the control group.

2.2. Method

2.2.1. Participants

Fifty-two typically developing children aged between 10 and 14 years (*M* = 12.02, *SD* = 1.25) were recruited from the Exeter and Devon area. Only right handed children without the presence of a developmental disorder or brain injury were recruited for the study. The sample included 29 girls (55.8%) and 23 boys (44.2%), and the majority were attending secondary schools (69.2%). All participating children provided written assent and their parent/guardian provided written consent. The study was approved by the University of Exeter Ethics Committee (Ref: 2015/676).

2.2.2. Behavioural Assessments

Working memory capacity was assessed before and after the training using eight tasks from the Automated Working Memory Assessment (AWMA; Alloway, 2007). This included two measures of verbal storage (Digit Recall and Word Recall), two measures of verbal working memory (Backwards Digit Recall and Listening Recall), two measures of visuospatial storage (Mazes Memory and Block Recall), and two measures of visuospatial working memory (Mr. X and Spatial Span). There is good test-retest reliability for these measures ranging from r = 0.64-84 and, in-line with the multi-component model of working memory (Baddeley & Hitch, 1974), factor analyses support the notion of distinguishable visuospatial and phonological storage components, and a central executive (Alloway et al., 2006). Performance on the eight tasks were averaged for each individual to form an overall composite score of working memory.

IQ was assessed to characterise the sample at baseline using the two sub-tests version (FSIQ-2) of the Wechsler Abbreviated Scale of Intelligence-II (WASI-II; Wechsler, 2011). This includes a measure of crystallised intelligence (Vocabulary) and a measure of fluid intelligence (Matrix Reasoning). The FSIQ-2 has excellent internal consistency ($\alpha = 0.93$), test-retest reliability ($r = 0.87$-0.95), and interrater reliability (r = 0.94-0.99; McCrimmon & Smith, 2013). In addition, the FSIQ-2 has good internal structure, high concurrent validity with other measures of IQ ($r = 0.71$-0.92), and it distinguishes children with intellectual disability from typically developing children (McCrimmon & Smith, 2013).

2.2.3. Randomisation and Instruction

Following baseline assessment, 50 children were randomly assigned to either the experimental or control condition, with equal numbers in each group. Two children were excluded before randomisation because they could not tolerate being in the scanner. Children assigned to the experimental condition completed an adaptive working memory training programme, and children assigned to the control condition completed a non-adaptive working memory training programme. Parents/Guardians and children were instructed on how to use their respective training programme and practised for approximately 10 minutes until they were confident of how they would login and use the programme at home. A member of the research team was assigned as the child's coach, which involved weekly emails to the family in addition to any help and support as required. A parent/guardian also agreed to be the child's training aide, which involved organising training times, managing rewards, and offering encouragement. Training aides were given guidance on how to best support their child's training. Children were given guides on how to perform the training tasks and a booklet to timetable their training sessions, record their goals, and acknowledge mutually agreed rewards with their parent/guardian. The booklet also included a training agreement that the child, training aide, and coach were requested to sign. Training was completed for approximately 30-45 minutes a day, five days a week, for five weeks and all participating children were instructed to complete 20-25 training sessions, for which they would be rewarded with a £20 Amazon voucher and a small stationery reward for every five sessions completed.

2.2.4. Adaptive Working Memory Training

Children assigned to adaptive working memory training completed Cogmed RoboMemo (Cogmed RM) according to the standard protocol[1] (see https://www.cogmed.com/rm for full details). Cogmed RM includes a battery of 12 simple and complex span games that include both visuospatial and verbal stimuli, which were practised on rotation, eight games per session. The difficulty of the training tasks was adapted on a trial-by-trial basis according to the individual's performance. The number of items to remember would increase after a succession of correct responses and the number of items to remember would decrease after a succession of incorrect responses. High scores were recorded for each task and their performance was converted into coins that children could use to play the Robo Racing game at the end of each training session. The graphics were thematically based around a robot, with each task involving different aspects of the robot.

2.2.5. Non-Adaptive Working Memory Training

Children assigned to non-adaptive working memory training completed an online training programme developed around a verbal updating working memory task (Roberts & Adlam, unpublished). This training task was chosen because it shares a number of characteristics with the non-adaptive version of Cogmed, which was discontinued shortly before the commencement of the study. At the beginning of each session, children were first required to

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[1] It should be noted that Cogmed RM is a commercial product owned by Pearson who reserve the right to publically provide details of the training tasks, including the number of trials, task timing, and structure of the adaptive difficulty. Furthermore, these details may be subject to change as the product is developed in future.

memorise a list of seven words. Their memory was then assessed on a cued and free recall test and children could only proceed to the updating training after perfect performance. At the beginning of each trial of the training task, three words from the list were presented in three separate boxes for 5s (see Figure 2.1). Children were then required to update their memory of the words in accordance with two of three consecutive updating sub-tasks (see Figure 2.1: d-f). The sub-tasks required replacement of the target word with one that was either one or two words further down the original list or from one of the other boxes. Finally, a word from the original word list was presented in one of the boxes and children were asked if it was the correctly updated word for that box. Children were given 10 seconds to respond ‘Yes’ or ‘No’, before it was marked incorrect. Half of the trials required a ‘Yes’ response and half of the trials required a ‘No’ response. Difficulty was fixed throughout; children were required to remember three words and had to perform two consecutive updating tasks on each trial.

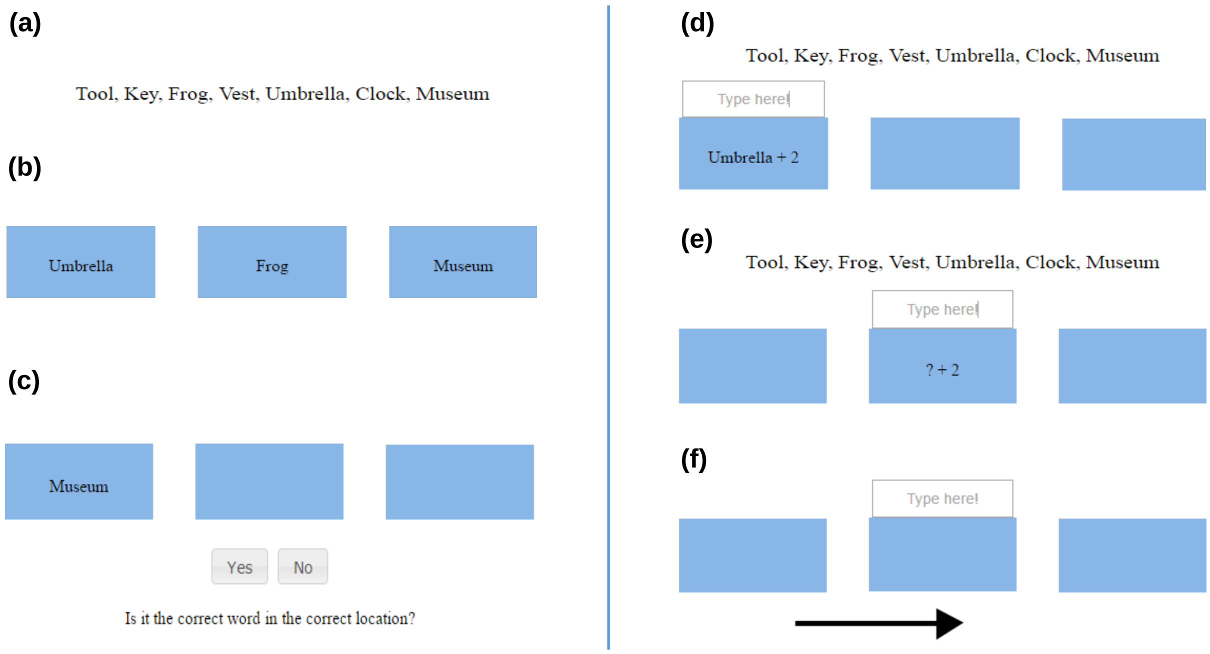

Figure 2.1. Components of the online updating training task: (a) the word list is learnt at the beginning of the training session but is also shown during the updating sub-tasks; (b) at the start of the trial, three words are presented in Boxes 1-3 (left to right) for 5s; (c) following two updating sub-tasks, a word is shown in one of the boxes and children must decide if it is the correct word; (d) updating sub-task 1 presents '+1' or '+2' next to one of the words, indicating replacement with the word that is one or two forward in the word list - here the contents of Box 1 ('Umbrella') should be replaced with the word that is two forward in the list ('Museum'); (e) updating sub-task 2 presents '+1' or '+2' next to a question mark in one of the boxes, indicating replacement with the word that is one or two forward in the word list - here the contents of Box 2 ('Frog') should be replaced with the word that is two forwards ('Umbrella'); (f) updating sub-task 3 requires replacement of the contents of Box 2 ('Umbrella') with the contents of the Box 1 ('Museum'), as indicated by the arrow. In the event that the '+1' or '+2' in sub-tasks 1 or 2 indicates replacement of a word beyond the end of the list, children were instructed to start again at the beginning of the list.

2.2.6. MRI Acquisition

Functional images were acquired at the Exeter MR Research Centre using a 1.5T Phillips Gyroscan magnet, equipped with a Sense coil. A T2*-weighted echo planar sequence was used (TR=3000ms, TE= 45ms, flip angle 90º, 35 transverse slices, 2.5 x 2.5 x 3.5mm). Participants completed one scanning session before training and one after training. Each session included two runs of the Dot Matrix task, three runs of the Odd-One-Out task, one run of resting-state, and a structural scan. One hundred and twenty six scans were collected for each run of the Dot Matrix, 106 scans were collected for each run of the Odd-One-Out, and 120 scans were collected for the resting-state. The standard volumetric anatomical MR image was acquired using a 3D T1-weighted pulse sequence (TR = 25ms, TE = 4.2ms, flip angle = 30˚, 0.9 x 0.9 x 0.9mm).

2.2.7. fMRI Tasks

Children completed two working memory tasks in the scanner before and after training. The Dot Matrix task (see Figure 2.2) was adapted from the AWMA (Alloway, 2007) and is comparable to tasks used in other neuroimaging investigations of Cogmed in adults (Brehmer et al., 2011; Olesen et al., 2004; Westerberg & Klingberg, 2007). Four to six red dots were sequentially presented on a 4x4 grid for 900ms each, with no inter-stimulus interval (ISI). The dot locations were pre-randomised, meaning that they were consistent for each participant and each session. The dot locations were never repeated within a trial. After a randomised delay of 1000-3500ms, a probe dot was

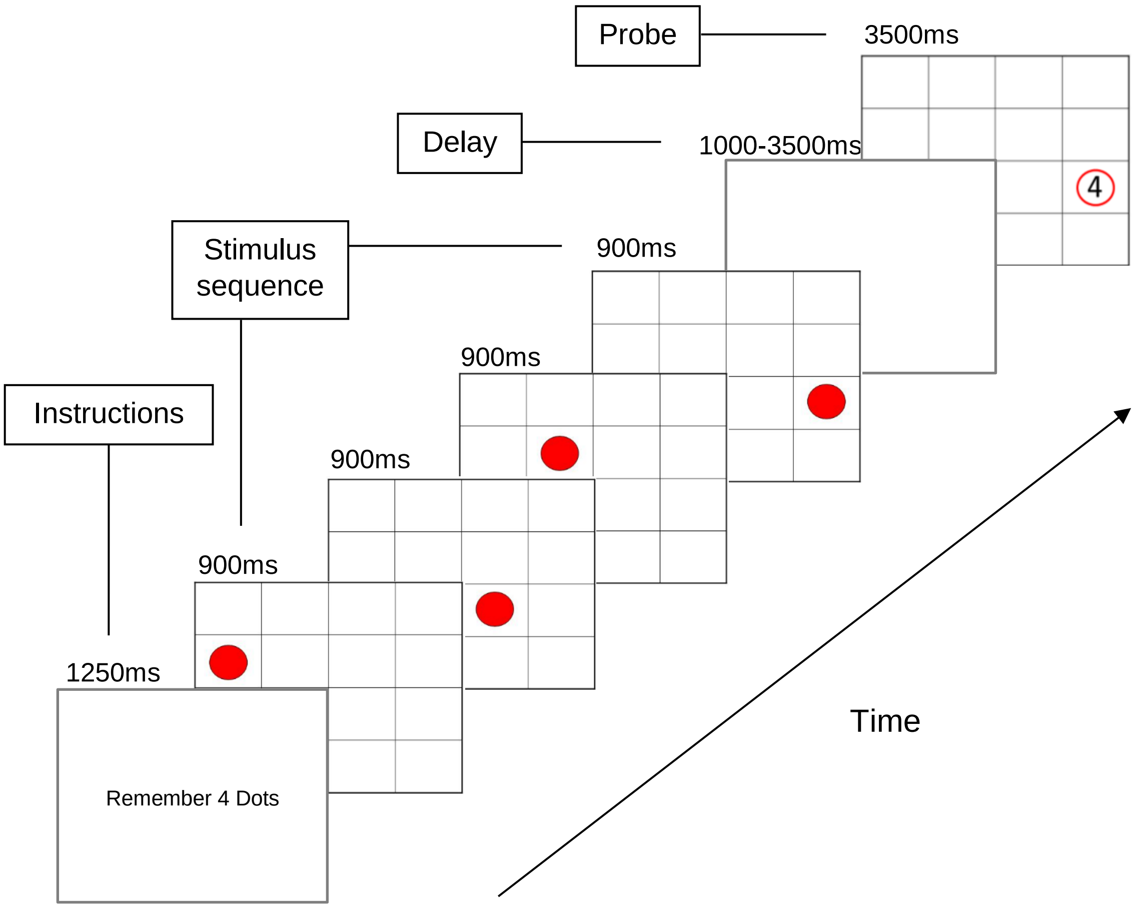

Figure 2.2. Procedure and timings for the Dot Matrix task. An example of a correct probe trial at span four is presented. At the start of each trial, instructions regarding how many stimuli to remember were briefly presented for 1250ms. In the encoding phase, four to six red dots were displayed sequentially on a 4x4 grid for 900ms per stimulus. The stimulus sequence was followed by a randomised delay between 1000 and 3500ms. Finally, a probe was presented for 3500ms and children judged if it was presented in the same location and order as one of the dots from the sequence

presented in the grid with a number from one to six within it, indicating the serial order of the probe. Participants were required to indicate if the probe was in the correct location and order as one of the previously presented dots by pressing the left button for ‘yes’ and right button for ‘no’. The task consisted of 54 trials across two runs, 18 of each span length. Half of the trials required a correct response and half required an incorrect response. Furthermore, approximately half of the incorrect trials presented lures (*n* = 13), i.e. probes that were in the same location as a previously presented dot but in a different order.

The Odd-One-Out task (see Figure 2.3) was also adapted from the AWMA (Alloway, 2007) but has never been used before in published neuroimaging investigations of working memory training. Three to five sets of adjacent shapes were presented sequentially for 2500ms with a 200ms ISI. Each set contained three shapes, two were the same and one was different (or ‘odd’). After a 1500ms delay, children were asked to recall the position of one of the odd-one-outs by pressing the appropriate ‘left’, ‘middle’ or ‘right’ button within 4000ms. This was indicated in text by reference to the 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, or 5^{th} odd-one-out from the sequence. The task consisted of 48 trials across three runs, 16 of each span length. Correct responses were equally distributed across the three locations.

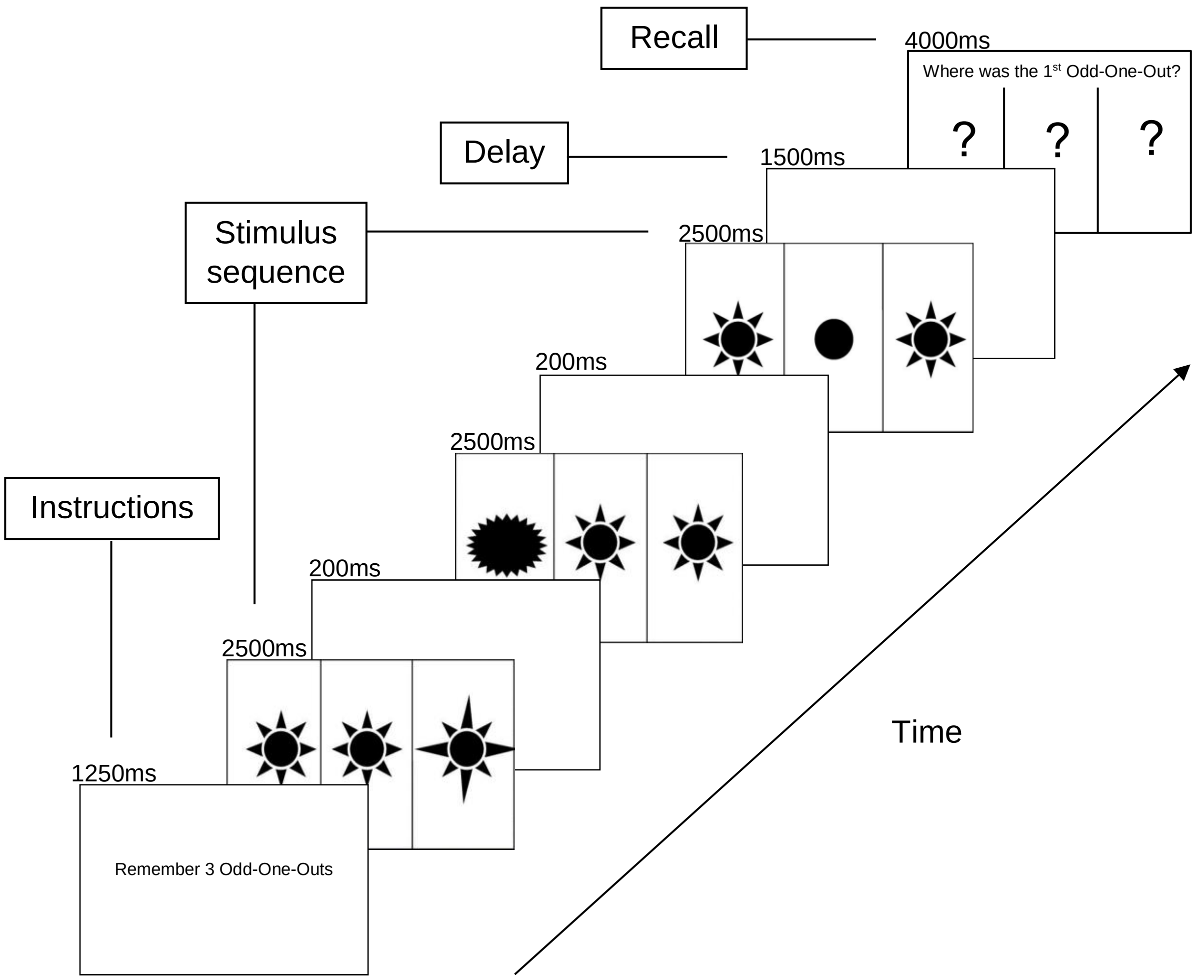

Figure 2.3. Procedure and timings for the Odd-One-Out task. An example of a trial at span three is presented requiring retrieval of the position of the first stimulus. At the start of each trial, instructions regarding how many stimuli to remember were briefly presented for 1250ms. In the encoding phase, three to five stimuli were presented for 2500ms each with a 200ms ISI. Each stimulus consisted of three adjacent shapes; two were identical and one was different, i.e. the odd-one-out. The stimulus sequence was followed by a 1500ms delay. Finally, children were asked to recall the position of one of the odd-one-outs presented in the sequence and given 4000ms to respond.

2.2.8. fMRI Analysis

The functional images were analysed using SPM12 (www.fil.ion.ucl.ac.uk/spm). The images were corrected for acquisition order, realigned to the first volume and resliced to correct for motion artefacts. Spatial normalisation was performed by coregistering the mean image created from the realigned images to the structural T1 volume. The images were then spatially normalised into the stereotactic space of the Montreal Neurological Institute (MNI). The spatial transformation was applied to the realigned T2* volumes that were spatially smoothed using a Gaussian kernel of 8mm full-width half maximum. Data were high-pass filtered (128s) to account for low frequency drifts. The Blood-Oxygen-Level Dependent (BOLD) response was modelled by a canonical hemodynamic response function (HRF) and the six head movement parameters were included as covariates. Participants with excessive head movements were excluded from each fMRI analysis in a casewise manner (see Figure 2.4 for details of exclusions). Data acquired for the encoding phase of correct trials were contrasted with the implicit baseline data acquired during phases of the task unrelated to working memory (e.g. instructions and inter-trial intervals). First-level linear contrasts of parameter estimates for each voxel before and after training were taken to the second-level and a random effects analysis was performed. Activation over time was contrasted between each training condition (Cogmed-Control and Control-Cogmed).

The bilateral middle frontal gyrus and superior parietal lobe were selected a priori as Regions of Interest (ROI) from the Automated Anatomical Labelling atlas (AAL; Tzourio-Mazoyer et al., 2002) within the WFU PickAtlas (Maldjian, Laurienti, Kraft, & Burdette, 2003). ROI analyses were conducted at a significance threshold of $p < 0.005$ (uncorrected) and minimum of 10 contiguous voxels, as in previous studies (e.g. Milton, Butler, Benattayallah, & Zeman, 2012). In addition, exploratory whole-brain analyses were conducted at a significance threshold of $p < 0.001$ (uncorrected) and minimum of 20 contiguous voxels to control for multiple comparisons, as in previous studies (e.g. Milton et al., 2012; Milton & Pothos, 2011). Activation coordinates were transformed from normalised MNI space to Talairach space using the ‘icbm2tal’ tool (Lancaster et al., 2007) to locate the site of activations in relation to the atlas of Talairach and Tournoux (1988).

2.2.9. Resting-State Functional Connectivity Analysis

The analysis of functional connectivity was completed within Conn, version 18a (Whitfield-Gabrieli & Nieto-Castanon, 2012). Pre-processing of resting-state images was completed using the default Conn pipeline, which implements the same pre-processing steps in SPM12 as outlined for the task-based fMRI above. Identification of global mean intensity and motion outliers was also performed using an automatic artefact detection tool (http://www.nitrc.org/projects/artifact_detect/). The resulting motion parameters were entered into the model as covariates for subsequent analysis. Using the aCompCor method, physiological and subject motion effects were regressed out, white matter and cerebrospinal fluid components were regressed out, and a linear detrending term was applied. After the removal of signal confounds, the functional data was band-pass filtered between 0.008-0.09Hz.

The ROI analyses of the functional connectivity data were conducted using canonically defined resting-state networks that implicate frontal and parietal regions. This follows a similar approach used by Astle and colleagues (2015). Two fronto-parietal networks of interest were selected within Conn, which incorporates canonically defined resting-state networks using data from the Human Connectome Project (Van Essen et al., 2013). The fronto-parietal network comprised of the bilateral prefrontal cortex and posterior parietal cortex, and the dorsal attention network comprised of the bilateral frontal eye fields and intraparietal sulci. Four ROI to ROI analyses were conducted for each network, including: the left and right ipsilateral connections between the frontal and parietal ROIs, the contralateral frontal ROIs, and the contralateral parietal ROIs. A Bonferroni correction for multiple comparisons was applied to the analysis of each network by dividing alpha by four; thus, setting the significance threshold at $p < 0.0125$. Exploratory whole-brain analyses were conducted at a significance threshold of $p < 0.001$ (uncorrected) and a minimum of 20 contiguous voxels. Activation coordinates were transformed from normalised MNI space to Talairach space using the ‘icbm2tal’ tool (Lancaster et al., 2007) to locate the site of activations in relation to the atlas of Talairach and Tournoux (1988).

2.2.10. Voxel-Based Morphometry

Voxel-based morphometry (VBM) was used to examine whether Cogmed was associated with changes in regional grey matter volume, compared to the control group. The T1 structural images were analysed using the DARTEL package (Ashburner, 2007) in SPM12 (www.fil.ion.ucl.ac.uk/spm). The pre- and post-training images were initially co-registered to produce an average image and a divergence image, taking into account the individual difference in time between the scans. The average images were segmented, and the resulting grey and white matter images were spatially aligned using DARTEL. The template and flow fields from DARTEL were used to spatially normalise the divergence images to MNI space, which were then smoothed using a Gaussian kernel of 10mm full-width half maximum. The data were divided by total intra-cranial volume, to control for individual differences in brain size.

Previous working memory training studies in adults have reported increased (Takeuchi et al., 2013) and decreased grey matter volume in fronto-parietal regions (Takeuchi et al., 2011). However, Cogmed has been associated with no change in grey matter volume in adults (Metzler-Baddeley, Caeyenberghs, Foley, & Jones, 2016b). Therefore, no regions of interest were selected a priori and only exploratory whole-brain analyses were conducted at a significance threshold of $p < 0.001$ (uncorrected) and a minimum of 20 contiguous voxels. Activation coordinates were transformed from normalised MNI space to Talairach space using the ‘icbm2tal’ tool (Lancaster et al., 2007) to locate the site of activations in relation to the atlas of Talairach and Tournoux (1988).

2.2.11. Data Analysis

Per-protocol analyses were conducted on the final sample of children who completed training. T-tests were used to examine baseline differences between the groups in age, working memory, IQ, and accuracy on the fMRI tasks. A chi-square test was used to examine baseline differences in gender between the groups. ANCOVAs were used to examine the effects of working memory training on the composite score of the AWMA and the accuracy of the two fMRI tasks. Baseline scores were entered as a covariate and group was entered as a fixed factor. This approach was chosen because ANCOVA has greater statistical power to detect a treatment effect in randomised designs and it is robust to regression to the mean, compared to repeated measures ANOVA (Van Breukelen, 2006). All analyses of the behavioural data were completed in SPSS version 24.

2.3. Results

2.3.1. Baseline Characteristics

In total, 32 children completed the training and final assessments, 17 from the Cogmed group and 15 from the control group (see Figure 2.4). The final sample included 19 girls and 13 boys with a mean age of 12 years and 2 months (*SD* = 1.22 years). Group characteristics are presented in Table 2.1. At baseline, there were no significant differences between the two conditions in IQ ($p = 0.412$), working memory capacity ($p = 0.649$), age ($p = 0.281$), or gender, $\chi^2(1, N = 32) = 0.43$, $p = 0.513$

Table 2.1. Baseline Characteristics of the Final Sample.

	Control (n=15)	**Cogmed (n=17)**	***t*(30)**	***p***
	Mean (SD)	**Mean (SD)**		
Age (years)	11.9 (1.15)	12.37 (1.27)	1.1	0.281
IQ	116.07 (14.36)	112 (13.28)	0.83	0.412
AWMA	107 (8.34)	108.28 (7.43)	0.46	0.649
Dot Matrix accuracy	0.72 (0.12)	0.73 (0.09)	0.28	0.779
Odd-One-Out accuracy	0.78 (0.14)	0.82 (0.09)	0.97	0.342

Scores on the Dot Matrix and Odd-One-Out indicate proportion of correct responses.

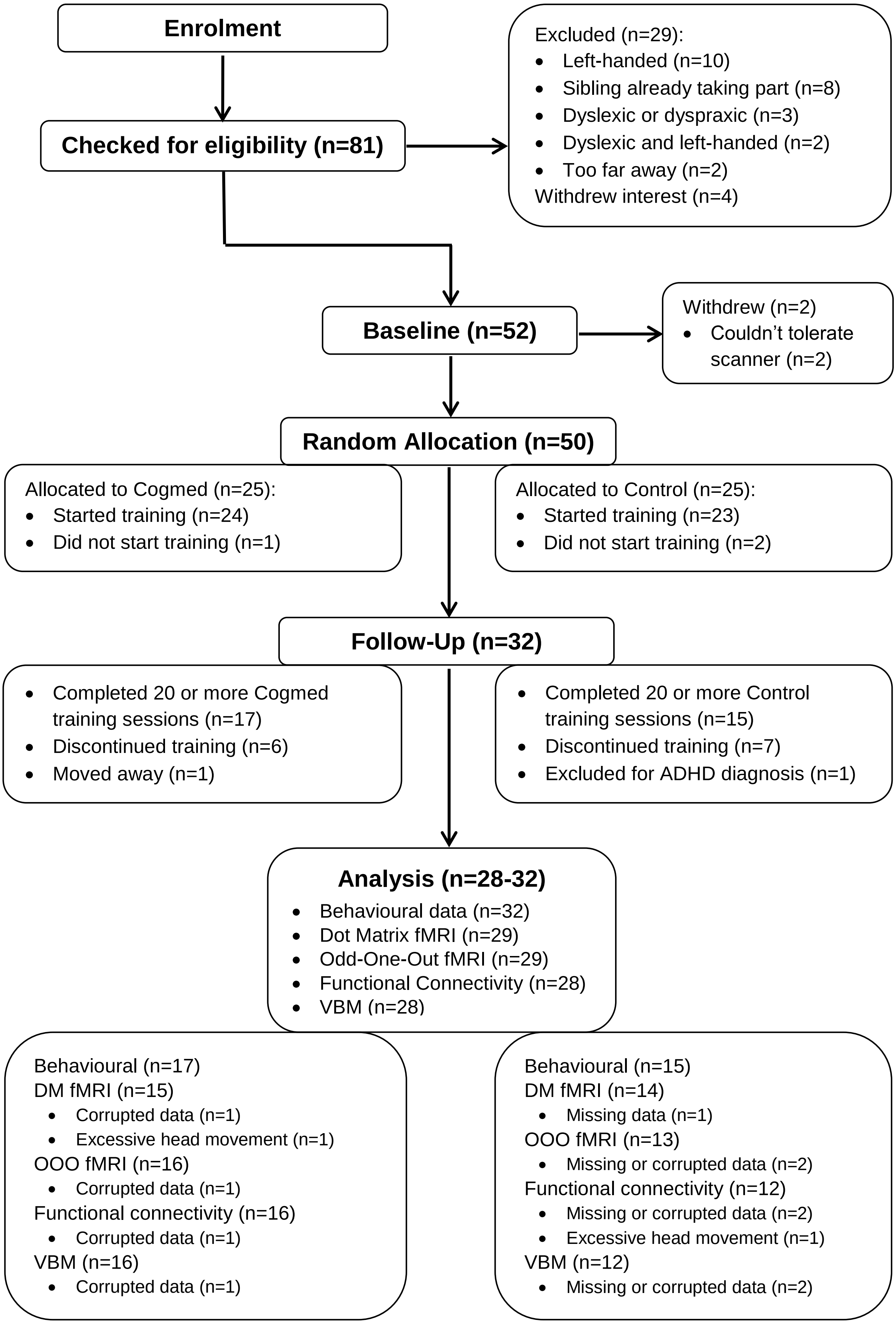

Figure 2.4. CONSORT flow diagram (CONsolidated Standards Of Reporting Trials).

2.3.2. Behavioural Outcomes

To examine near-transfer to the AWMA, composite average scores were computed for each child before and after training. Related samples t-tests showed that scores on the AWMA significantly increased over time for the Cogmed group, Δ +9.06, $t(16) = 5.83$, $p < 0.001$, and for the control group, Δ +3.84, $t(14) = 3.13$, $p = 0.007$. ANCOVAs were used to compare group means on the AWMA and two fMRI tasks at outcome, which were adjusted for baseline scores (covariate). The baseline-adjusted group means at outcome, 95% Confidence Intervals (CIs), and mean differences between the groups (Δ) are presented in Table 2.2. The group means at baseline and outcome are also plotted in Figure 2.5 with 95% CIs. At outcome, scores on the AWMA were significantly greater in the Cogmed group compared to the control group ($p = 0.015$, $\eta_p^2 = 0.188$). This indicated that Cogmed increased working memory performance significantly more than the control group. For the fMRI tasks, the ANCOVAs indicated that there were no significant differences between the groups at outcome in performance on the Dot Matrix ($p = 0.756$) or Odd-One-Out tasks ($p = 0.827$).

Table 2.2. Baseline-Adjusted Group Means at Outcome, 95% CIs, and ANCOVAs

Outcome variables	**Control**	**Cogmed**	**Δ (Control vs. Cogmed)**
	Mean (95% CI)	**Mean (95% CI)**	
Working Memory	111.47 (108.42 to 114.53)	116.79 (113.92 to 119.65)	**5.31*** (1.12 to 9.51)
Dot Matrix accuracy	0.75 (0.69 to 0.81)	0.76 (0.70 to 0.82)	0.01 (-0.01 to 0.01)
Odd-One-Out accuracy	0.82 (0.77 to 0.88)	0.82 (0.76 to 0.87)	0.01 (-0.01 to 0.01)

Scores on the Dot Matrix and Odd-One-Out indicate proportion of correct responses.
*denotes $p < 0.05$

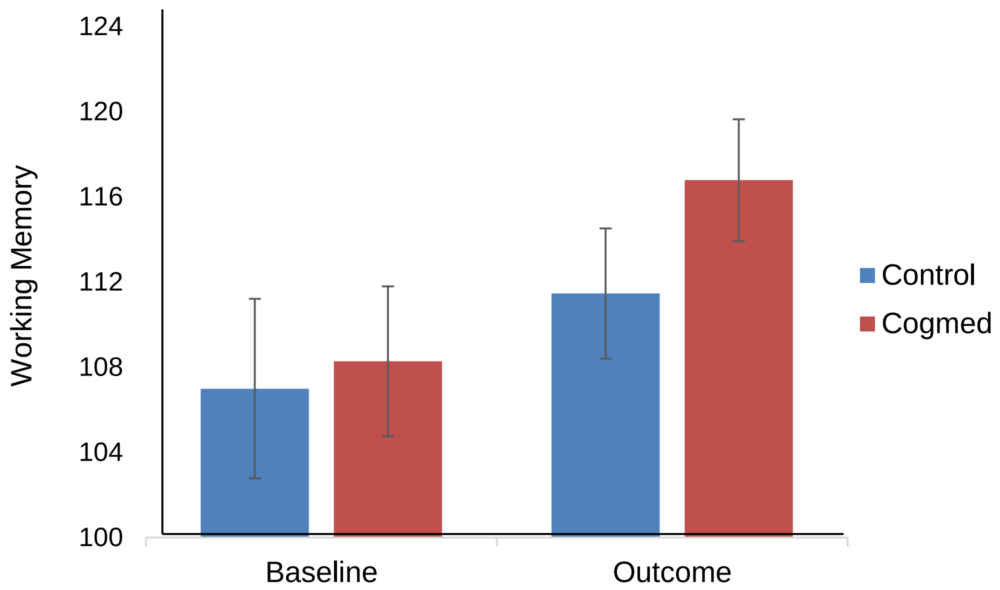

Figure 2.5. Group means for composite scores on the AWMA at baseline and outcome with 95% CIs.

2.3.3. Working Memory fMRI

2.3.3.1. Odd-One-Out Task

Initially, brain activation on the Odd-One-Out was examined to check that the task activated typical working memory regions. Areas of significant activation for both groups at baseline are displayed in Table 2.3. The Odd-One-Out significantly activated the left premotor / middle frontal gyrus (BA6) and bilateral areas of the visual cortex (BA17/18). The ROI analysis further highlighted significant activation of the left middle frontal gyrus (BA6, 30 voxels, peak coordinates: -24, -12, 48). As the extent of expected fronto-parietal activation was quite limited, an exploratory analysis was conducted to investigate subthreshold activation at a significance threshold of $p < 0.005$ and 20 contiguous voxels (see Figure 2.6 & Table 2.4). This analysis revealed additional activation of the bilateral medial frontal gyrus (BA6), right superior frontal gyrus (BA6), bilateral inferior parietal lobe (BA40), and right cerebellum, as well as more extensive activation of the left premotor / middle frontal gyrus (BA6) and bilateral visual cortex (BA17/18/19). Whole-brain activation at baseline was compared between the groups to check that activation was approximately equal. This analysis revealed only one small area of significantly greater activation in the left precuneus (BA7) for the Cogmed group compared to the control group (33 voxels, peak coordinates: -9, -49, 50). Furthermore, the

ROI analysis revealed that there was no significant difference in activation of the middle frontal gyri or superior parietal lobes between the groups at baseline.

Table 2.3. Odd-One-Out Activation at Baseline for both Groups.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Right cuneus / middle occipital lobe (BA17/BA18)	272	4.95	17	-91	9
		3.81	26	-83	4
Left cuneus (BA17)	62	4.18	-18	-92	4
Left premotor cortex / middle frontal gyrus (BA6)	45	3.89	-24	-12	51

Table 2.4. Sub-Threshold Odd-One-Out Activation at Baseline for both Groups.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Right cuneus / middle occipital lobe (BA17/BA19)	434	4.95	17	-91	9
		3.81	26	-83	4
Left cuneus / lingual gyrus (BA17/18)	124	4.18	-18	-92	4
		2.92	-9	-95	-3
		2.77	-24	-84	3
Right medial frontal gyrus (BA6)	48	4.07	8	-3	60
Left premotor cortex / middle frontal gyrus (BA6)	110	3.89	-24	-12	51
Right inferior parietal lobe (BA40)	52	3.51	35	-37	37
Right superior frontal gyrus (BA6)	31	3.35	6	7	48
Left medial frontal gyrus (BA6)	60	3.33	-7	1	53
Left supramarginal gyrus (BA40)	33	3.19	-39	-40	36
Right cerebellum, declive	31	3.19	14	-77	-14

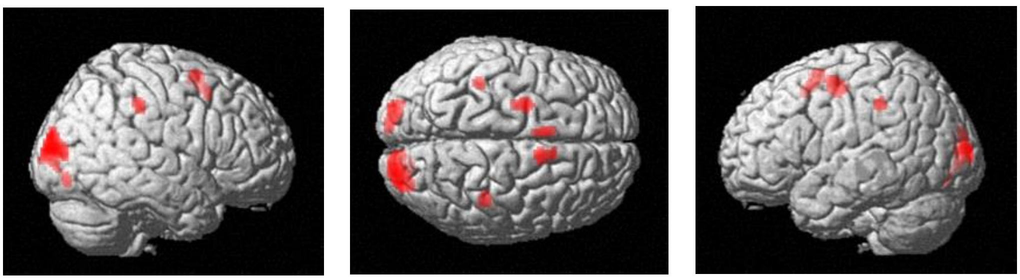

Figure 2.6. Sub-threshold baseline activation on the Odd-One-Out task for both groups. Significance threshold: $p < 0.005$ (uncorrected) and 20 contiguous voxels

Odd-One-Out task activation was compared between the two groups over time. The ROI analysis tested whether there was significant interaction between Group and Time on activation in the bilateral middle frontal gyri and superior parietal lobe. Cogmed showed significantly greater activation over time in three areas of the middle frontal gyrus compared to the control group (see Table 2.5), which were localised to BAs 6, 8, and 9. Within the middle frontal gyri and superior parietal lobe there were no areas of significantly greater activation in the control group relative to the Cogmed group, over time. The exploratory whole brain analysis examined whether Cogmed led to activation change in other regions of the brain compared to the control group. Figure 2.7 and Table 2.6 display the whole brain analysis for the Group x Time interaction. The Cogmed group showed significantly greater activation over time in a number of regions compared to the control group. This included the left superior / medial frontal gyrus (BA6/BA8), left anterior cingulate (BA24), right posterior cingulate (BA23), right parahippocampal gyrus (BA34), and left amygdala.

Table 2.5. ROI Group Comparison of Odd-One-Out Task Activation over Time.

Brain Region	**Cluster size**	**Peak Z**	**Talairach Coordinates**		
			x	**y**	**z**
Cogmed > Control					
Left middle frontal gyrus (BA6/8)	27	3.47	-31	13	43
Right middle frontal gyrus (BA8)	21	3.35	21	20	48
Left middle frontal gyrus (BA9)	23	3.18	-23	39	31
Control > Cogmed					
No significant clusters					

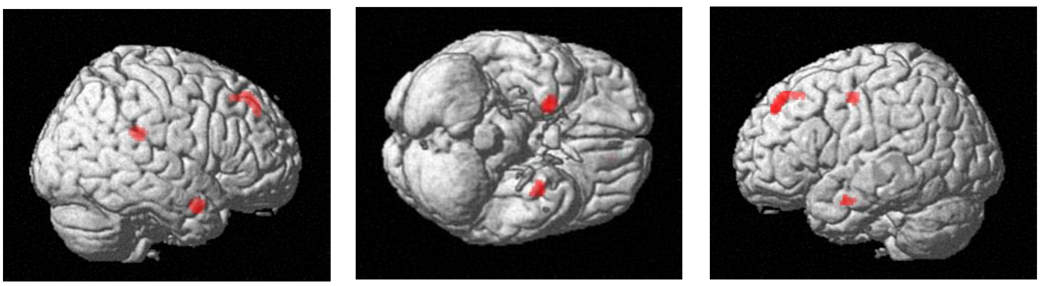

Figure 2.7. Whole brain group comparison of Odd-One-Out activation over time. Regions of increased activation in the Cogmed group relative to control.

Table 2.6. Whole-Brain Group Comparison of Odd-One-Out Task Activation over Time.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Cogmed > Control					
Right posterior cingulate (BA23)	68	4.33	13	-36	23
Right parahippocampal gyrus (BA34)	46	3.92	23	4	-18
Left superior/medial frontal gyrus (BA6/8)	69	3.87	-12	36	43
		3.51	-11	22	49
		3.49	-7	32	49
Left anterior cingulate (BA24)	29	3.75	-18	-13	42
Left amygdala	23	3.48	-32	-5	-17
Control > Cogmed					
No significant clusters					

2.3.3.2. Dot Matrix Task

Brain activation on the Dot Matrix at baseline was examined to check that the task activated typical working memory regions. Figure 2.8 and Table 2.7 display the significant activation for both groups on the Dot Matrix task at baseline. The analysis revealed widespread activation of the fronto-parietal network and bilateral regions of the visual cortex. This included activation in the bilateral middle frontal gyri / premotor cortices (BA6), right medial frontal gyrus (BA6), bilateral precuneus and left superior parietal lobe (BA7), right inferior parietal lobe (BA40), right inferior/middle temporal gyrus (BA37), and bilateral regions of the visual cortex (BA17/BA18). Similarly, the ROI analysis of baseline activation on the Dot Matrix task revealed significant activation of the bilateral middle frontal gyri and bilateral superior parietal lobes (see Table 2.8 and Figure 2.9). Activation at baseline was then compared between the groups to check that activation was approximately equal. This analysis revealed only one small area of significantly greater activation in the right lingual gyrus (BA19) for the Cogmed group compared to the control group (43 voxels, peak coordinates: 38, -70, 6). Furthermore, the ROI analysis revealed that there was no significant difference in activation of the middle frontal gyri or superior parietal lobes between the groups at baseline.

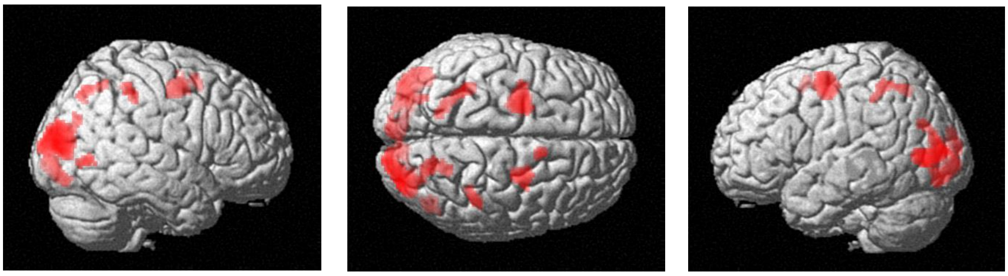

Figure 2.8. Brain activation associated with the Dot Matrix task for both groups at baseline.

Table 2.7. Dot Matrix Task Activation at Baseline for both Groups.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Bilateral middle occipital gyrus / cuneus (BA17/BA18)	1777	6.33	26	-85	7
		6.06	13	-96	6
		4.94	-38	-69	1
Left middle frontal gyrus / premotor cortex (BA6)	366	5.48	-24	-14	49
Right middle frontal gyrus (BA6)	161	4.54	22	-12	49
		3.54	22	-4	48
Right precuneus (BA7)	106	4.49	19	-71	43
		3.99	17	-59	46
Right inferior parietal lobe (BA40)	65	4.29	37	-43	44
		3.23	35	-39	37
		3.21	30	-45	44
Left superior parietal lobe / precuneus (BA7)	118	4.17	-22	-60	45
		3.75	-30	-55	47
		3.57	-17	-65	41
Right medial frontal gyrus (BA6)	35	3.98	9	1	53
Right inferior/middle temporal gyrus (BA37)	55	3.82	40	-67	-1
		3.13	47	-60	-2

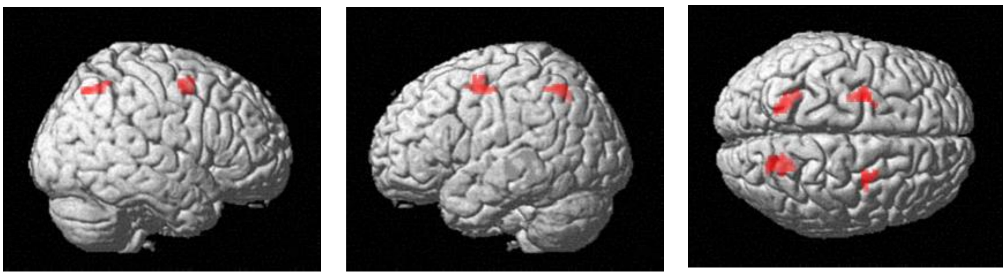

Figure 2.9. ROI activation associated with the Dot Matrix task for both groups at baseline.

Table 2.8. Dot Matrix Task ROI Activation at Baseline for both Groups.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Left middle frontal gyrus (BA6)	67	5.39	-26	-13	48
		3.00	-24	-7	57
		2.77	-20	-2	51
Right superior parietal lobe (BA7)	73	4.49	19	-71	43
		3.99	17	-59	46
Left superior parietal lobe (BA7)	73	4.17	-22	-60	45
		3.57	-17	-65	41
		3.32	-28	-51	44
Right middle frontal gyrus (BA6)	39	3.77	22	-8	49
		3.24	30	-8	51

The Dot Matrix task activation was compared between the two groups over time. The Group x Time interaction for the ROI analysis showed no areas of activation above the significance threshold, indicating that change in activation within the middle frontal gyrus and superior parietal lobe did not significantly differ between the two groups. The exploratory whole brain analysis is displayed in Table 2.9. The whole brain analysis showed that there was significantly greater activation in the left posterior cingulate (BA31) and left putamen for the Cogmed group compared to the control group. Furthermore, activation in the right parahippocampal gyrus (BA34) was significantly reduced in the Cogmed group compared to the control group.

Table 2.9. Whole Brain Group Comparison of Dot Matrix Task Activation over Time.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Cogmed > Control					
Left putamen	22	4.00	-29	-26	1
Left posterior cingulate (BA31)	44	3.94	-13	-51	24
Control > Cogmed					
Right parahippocampal gyrus (BA34)	26	4.01	12	-6	-16

2.3.4. Functional Connectivity

2.3.4.1. The Fronto-Parietal Network

Functional connectivity within the fronto-parietal network, comprising of the bilateral prefrontal and posterior parietal cortices, was initially compared between the groups at baseline to check that they were approximately equal. As can be seen in Table 2.10, functional connectivity between the seeds of the fronto-parietal network did not significantly differ between the two groups at baseline. In the exploratory whole-brain analysis, functional connectivity between the fronto-parietal network and the rest of the brain was also compared between the groups at baseline, and the results can be seen in Figure 2.10 and Table 2.11. In the Cogmed group, there was significantly greater functional connectivity with the right fusiform gyrus (BA37) and left caudate compared to control. In the control group, there was significantly greater functional connectivity with multiple brain regions compared to the Cogmed group. This included the left inferior frontal gyrus (BA45), right primary motor cortex (BA4) / supplementary motor area (BA6), right premotor cortex, right precuneus (BA7), right middle (BA21/BA39) and inferior temporal gyri (BA20), left fusiform gyrus (BA37), right parahippocampal gyrus (BA30), left uncus (BA20), and bilateral cerebellum.

Table 2.10. Group Differences in Functional Connectivity within the Fronto-Parietal Network at Baseline.

Seed Regions	T(26)	p
Left LPFC – Left PPC	-0.68	0.502
Left LPFC – Right LPFC	-1.5	0.146
Right LPFC – Right PPC	-0.32	0.753
Right PPC – Left PPC	0.21	0.833

Note. Comparison of Cogmed-Control, positive values indicate greater functional connectivity in the Cogmed group. LPFC = lateral prefrontal cortex, PPC = posterior parietal cortex. p (uncorrected).

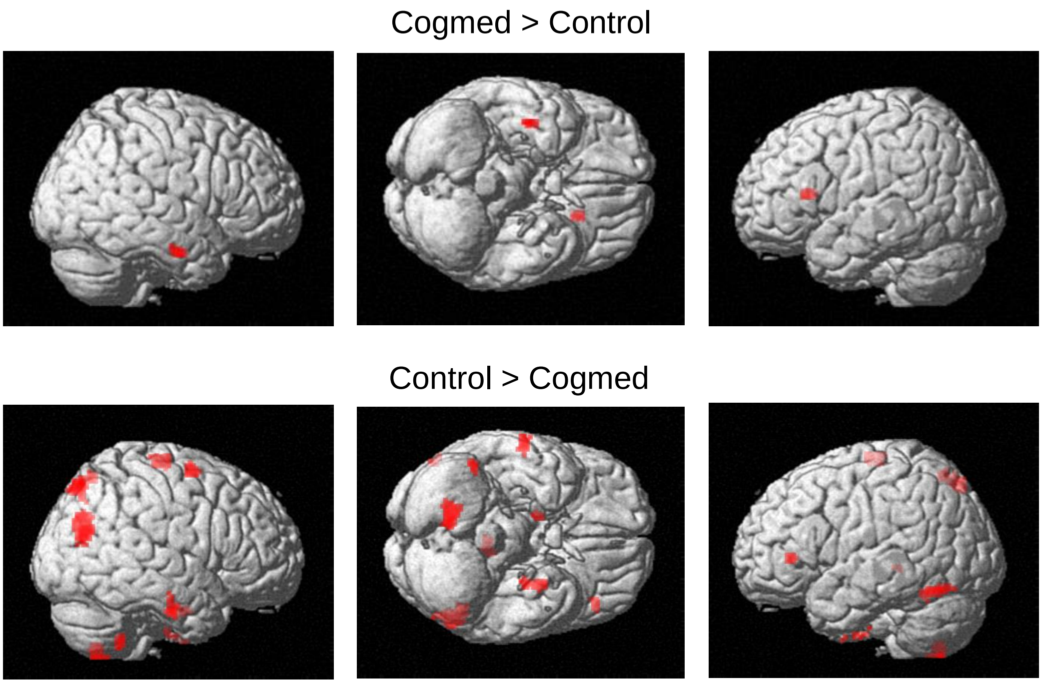

Figure 2.10. Group differences in functional connectivity between the fronto-parietal network and the rest of the brain at baseline.

Table 2.11. Group Differences in Functional Connectivity between the Fronto-Parietal Network and the Rest of the Brain at Baseline.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Cogmed > Control					
Right fusiform gyrus (BA37)	26	4.45	38	-9	-19
Left caudate body	21	3.87	-20	16	18
Control > Cogmed					
Left inferior frontal gyrus (BA45)	28	4.93	-42	30	10
Right precuneus (BA7)	166	4.64	20	-79	48
		3.78	13	-69	52
		3.45	15	-73	44
Right middle temporal gyrus (BA39)	175	4.16	45	-67	20
		3.98	45	-70	13
		3.77	39	-72	25
Right cerebellum, tonsil	125	4.03	16	-54	-56
		4.00	9	-57	-50
Right parahippocampal gyrus (BA34)	23	4.01	12	-7	-23
Right premotor cortex / paracentral lobule (BA4/6)	65	4.00	17	-28	63
		3.53	9	-32	61
Left fusiform gyrus (BA37) / cerebellum	93	3.92	-51	-56	-18
		3.48	-45	-61	-19
		3.31	-47	-48	-19
Right premotor cortex (BA6)	42	3.86	35	-9	60
Right cerebellum, tonsil	23	3.83	46	-42	-46
Right inferior / middle temporal gyrus (BA20/21)	46	3.76	64	-13	-16
		3.69	59	-11	-23
		3.21	51	-12	-23
Left uncus (BA20)	43	3.74	-30	1	-43
		3.71	-26	-11	-39
Left cerebellum, culmen	36	3.58	-8	-37	-3
		3.38	-1	-38	-8

Functional connectivity within the fronto-parietal network was compared between the two groups over time. Changes in functional connectivity between the fronto-parietal seeds are shown for the Cogmed group compared to the control group in Table 2.12. The Cogmed group generally showed increased functional connectivity between nodes of the fronto-parietal network relative to the Cogmed group, however these differences were not statistically significant. In the exploratory whole-brain analysis, changes in functional connectivity between the fronto-parietal network and the rest of the brain were compared between the groups. Figure 2.11 and Table 2.13 show the areas of significantly increased functional connectivity for each group relative to the other. The Cogmed group showed significantly greater increases in functional connectivity with multiple brain regions compared to the control group. This included the right primary motor cortex (BA4) / somatosensory cortex (BA3), bilateral middle temporal gyri (BA21/BA37), left inferior temporal (BA20) / fusiform gyrus (BA37), and left posterior cingulate (BA23). The Cogmed group also showed significantly reduced functional connectivity with the right cerebellum compared to the control group.

Table 2.12. Group Comparison of Functional Connectivity within the Fronto-Parietal Network over Time.

Seed Regions	**T(26)**	**p**
Left LPFC – Left PPC	1.59	0.125
Left LPFC – Right LPFC	1.68	0.105
Right LPFC – Right PPC	0.36	0.721
Right PPC – Left PPC	1.14	0.264

Note. Comparison of Cogmed-Control, positive values indicate greater increase in functional connectivity in the Cogmed group. LPFC = lateral prefrontal cortex, PPC = posterior parietal cortex. p (uncorrected).

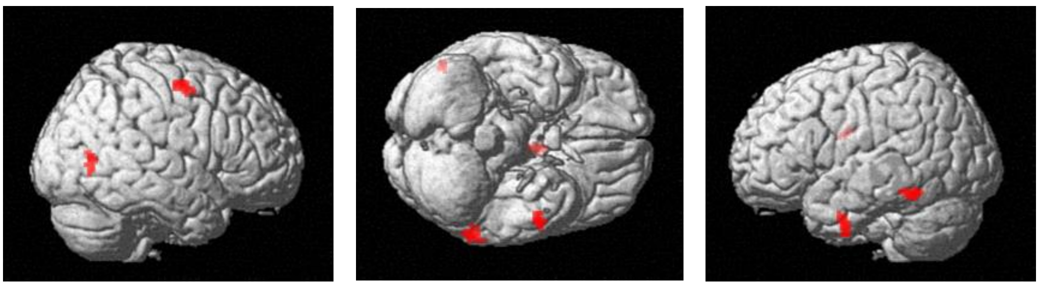

Figure 2.11. Increased functional connectivity between the fronto-parietal network and the rest of the brain in the Cogmed group, compared to control.

Table 2.13. Group Comparison of Functional Connectivity between the Fronto-Parietal Network and the Rest of the Brain over Time.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Cogmed > Control					
Left inferior temporal / fusiform gyrus (BA20/37)	39	4.80	-60	-46	-17
		4.06	-53	-45	-15
Right middle temporal gyrus (BA37)	29	4.37	45	-64	6
		3.74	47	-63	-3
Left posterior cingulate (BA23)	21	4.30	-5	-11	27
		3.50	-5	-3	20
Left middle temporal gyrus (BA21)	35	4.18	-51	0	-29
Right precentral / postcentral gyrus (BA4/3)	40	4.09	45	-10	51
		3.84	45	-18	52
Control > Cogmed					
Right cerebellum, culmen	30	4.07	29	-40	-26
		3.40	38	-40	-28

2.3.4.2. The Dorsal Attention Network

Changes in the dorsal attention network were also predicted because it comprises of the bilateral frontal eye fields and intraparietal sulci, which are implicated in working memory (Rottschy et al., 2012). Functional connectivity within the dorsal attention network at baseline was compared between the two groups to check that the groups were approximately equal. As can be seen in Table 2.14, there were no significant differences in functional connectivity within the dorsal attention network between the groups at baseline when controlling for multiple comparisons (all $p > 0.0125$). However, there were trends for greater connectivity in the control group compared to the Cogmed group between the right frontal eye field and right intraparietal sulcus ($p = 0.051$), and between the right and left intraparietal sulci ($p = 0.028$). The exploratory whole-brain analysis examined group differences in functional connectivity between the dorsal attention network and the rest of the brain at baseline. Figure 2.12 and Table 2.15 show the regions of significantly greater functional connectivity for one group compared to the other. The Cogmed group had significantly higher functional connectivity with the right anterior cingulate (BA24), compared to the control group. The control group had significantly higher functional connectivity with multiple brain regions in the left hemisphere, compared to the Cogmed group. This included regions of the inferior (BA45 & BA47), medial (BA6), and superior frontal cortex (BA6), regions of the inferior (BA20), middle (BA21), and superior temporal cortex (BA38), and the fusiform gyrus (BA37).

Table 2.14. Group Differences in Functional Connectivity within the Dorsal Attention Network at Baseline.

Seed Regions	**T(26)**	**p**
Left FEF – Left IPS	0.44	0.661
Left FEF – Right FEF	-0.45	0.656
Right FEF – Right IPS	-2.05	0.051
Right IPS – Left IPS	-2.34	0.028

Note. Comparison of Cogmed-Control, positive values indicate greater functional connectivity in the Cogmed group. FEF = frontal eye field, IPS = intraparietal sulcus. p (uncorrected).

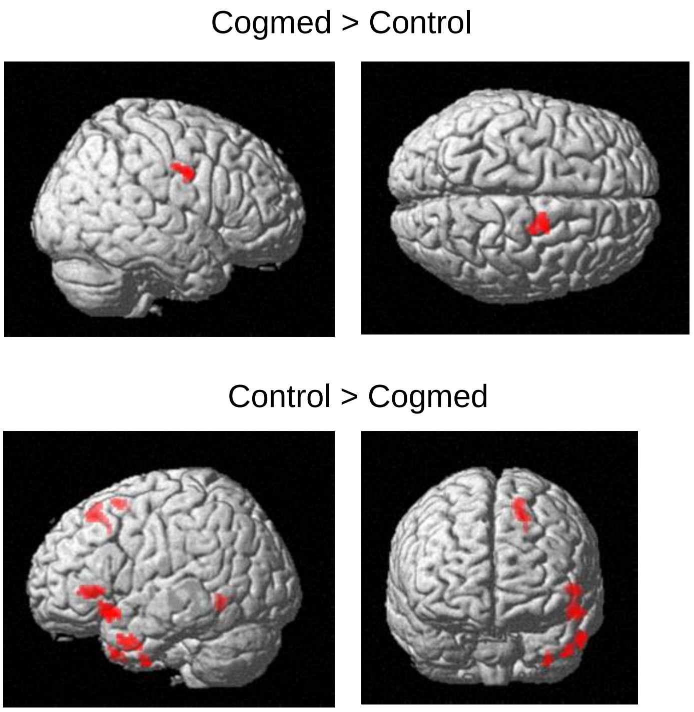

Figure 2.12. Group differences in functional connectivity between the dorsal attention network and the rest of the brain at baseline.

Table 2.15. Group Differences in Functional Connectivity between the Dorsal Attention Network and the Rest of the Brain at Baseline.

Brain Region	Cluster size	Peak Z	Talairach Coordinates		
			x	y	z
Cogmed > Control					
Right anterior cingulate (BA24)	57	4.23	17	-8	33
		3.69	19	-16	37
Control > Cogmed					
Left inferior temporal gyrus (BA20)	22	4.28	-32	-3	-38
Left inferior frontal gyrus (BA47)	66	4.16	-49	14	-6
Left middle / superior temporal gyrus (BA21/38)	33	4.13	-56	3	-23
		3.56	-51	10	-23
Left superior temporal gyrus (BA38)	28	4.07	-45	13	-33
Left medial frontal gyrus (BA6)	25	3.84	-15	3	57
Left superior frontal gyrus (BA6)	52	3.76	-15	22	53
		3.62	-20	17	49
		3.47	-15	16	58
Left fusiform gyrus (BA37)	21	3.62	-40	-51	-8
Left inferior frontal gyrus (BA45)	39	3.57	-47	30	6
		3.46	-47	21	7

Functional connectivity within the dorsal attention network was compared between the two groups over time. Changes in functional connectivity between the network seeds are shown for the Cogmed group compared to the control group in Table 2.16. The Cogmed group showed a significantly greater increase in functional connectivity between the left and right intraparietal sulci compared to the control group (p = 0.005), which survived correction for multiple comparisons. In the exploratory whole-brain analysis, functional connectivity changes between the dorsal attention network and the rest of the brain were compared between the groups over time. Significant changes in functional connectivity for each group relative to the other are shown in Figure 2.13 and Table 2.17. The Cogmed group showed significantly greater increases in functional connectivity with a sub-gyral region of the frontal cortex (BA6), bilateral inferior parietal lobule (BA40), left superior parietal lobule (BA7), and left fusiform gyrus (BA37), compared to the control group. The control group showed no regions of significantly increased functional connectivity, relative to the Cogmed group.

Table 2.16. Group comparison of functional connectivity within the dorsal attention network over time.

Seed Regions	**T(26)**	**p**
Left FEF – Left IPS	0.82	0.419
Left FEF – Right FEF	-0.19	0.853
Right FEF – Right IPS	1.75	0.092
Right IPS – Left IPS	3.11	**0.005***

Note. Comparison of Cogmed-Control, positive values indicate greater increase in functional connectivity in the Cogmed group. FEF = frontal eye field, IPS = intraparietal sulcus. *p < 0.0125

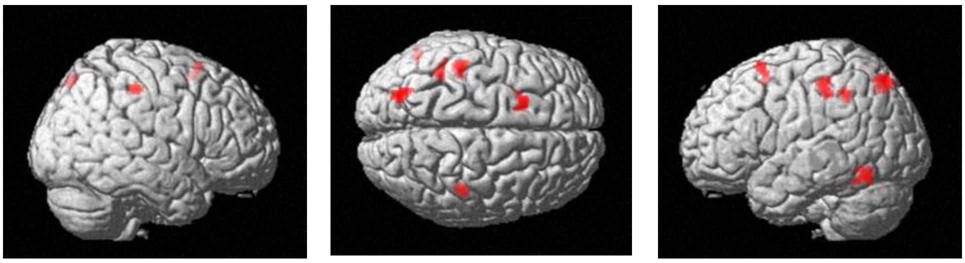

Figure 2.13. Increased functional connectivity between the dorsal attention network and the rest of the brain in the Cogmed group, compared to control.

Table 2.17. Group Comparison of Functional Connectivity between the Dorsal Attention Network and the Rest of the Brain over Time.

Brain Region	**Cluster size**	**Peak Z**	**Talairach Coordinates**		
			x	**y**	**z**
Cogmed > Control					
Left inferior parietal lobule (BA40)	72	4.24	-42	-37	40
		3.14	-42	-38	49
Left inferior parietal lobule (BA40)	36	4.11	-39	-48	37
		3.14	-48	-44	39
Left superior parietal lobule (BA7)	71	4.09	-26	-73	44
Left fusiform gyrus (BA37)	62	4.01	-47	-56	-16
Right inferior parietal lobule (BA40)	30	3.99	39	-34	43
Left inferior frontal sub-gyral (BA6)	48	3.75	-18	4	57
		3.14	-26	3	55
Control > Cogmed					
No significant clusters					

2.3.5. Voxel-Based Morphometry

Regional grey matter volume was compared between the two groups at baseline to check that they were approximately equal. Figure 2.14 and Table 2.18 display the significant group differences in regional grey matter volume at baseline. The Cogmed group had significantly greater grey matter volume in one area of the left cerebellum compared to the control group. The control group had significantly greater grey matter volume in several areas compared to the Cogmed group, which were localised to the left superior / medial frontal gyrus (BA6), left inferior frontal gyrus (BA44), right middle (BA21) and superior temporal gyri (BA38), and the right uncus (BA20).

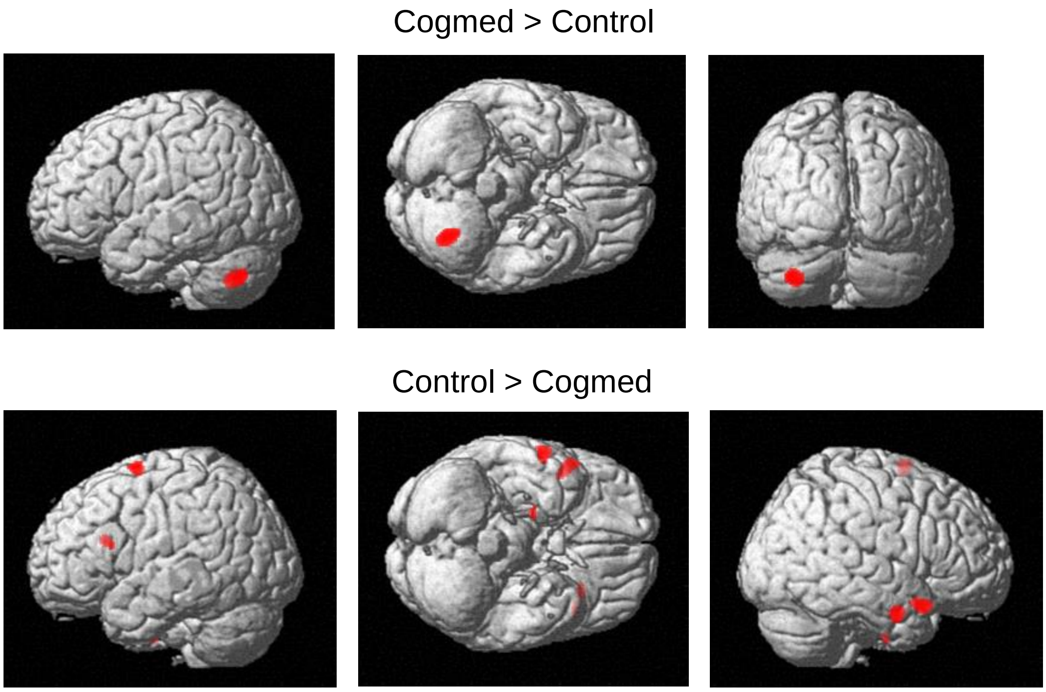

Figure 2.14. Regional differences in grey matter volume between groups at baseline.

Table 2.18. Group Differences in Regional Grey Matter Volume at Baseline.

Brain Region	Cluster size	Peak Z	Talairach Coordinates x	y	z
Cogmed > Control					
Left cerebellum, tonsil	304	3.63	-32	-63	-41
Control > Cogmed					
Left superior / middle frontal gyrus (BA6)	127	4.19	-29	2	71
Left inferior frontal gyrus (BA44)	121	3.63	-29	23	21
		3.32	-42	18	18
Right superior temporal gyrus (BA38)	188	3.49	56	17	-23
		3.43	48	9	-20
Right uncus (BA36)	43	3.44	20	-12	-44
Right middle temporal gyrus (BA21)	134	3.42	63	-3	-29

Grey matter volume was compared between the groups over time, to examine whether Cogmed was associated with changes in grey matter volume relative to the control group. The analysis revealed no significant differences, suggesting that change in grey matter volume over time did not significantly differ for the Cogmed and control groups.

2.4. Discussion

The aim of this study was to investigate near-transfer and the neural correlates of working memory training in typically developing children using a range of neuroimaging techniques. This was the first working memory training study to investigate changes in children's working memory brain activation and grey matter volume, in comparison to an active control group. Furthermore, this was the first working memory training study to investigate task-based fMRI, resting-state fMRI, and VBM in a single sample. Based on a composite score of eight untrained working memory tasks, Cogmed improved children's working memory performance significantly more than the non-adaptive control. The neuroimaging findings indicated that Cogmed increased recruitment of bilateral regions of the middle frontal gyrus during a complex span task. Cogmed was also associated with increased functional connectivity within the dorsal attention network when the brain was at rest. However, Cogmed was not associated with significant change in grey matter volume in comparison to the control group.

2.4.1. Working Memory

It was predicted that Cogmed would increase children's working memory performance in comparison to the non-adaptive control group. As evidenced by the average scores on the eight untrained AWMA tasks, Cogmed improved children's working memory performance significantly more than the non-adaptive control group. Similarly, previous controlled investigations of Cogmed (Astle et al., 2015) and working memory training (Sala & Gobet, 2017b), more generally, have provided converging evidence for near-transfer effects in typically developing children. These results cannot readily be attributed to maturation, test-retest, or expectation effects because the non-adaptive control group also completed a cognitive training programme for a similar length of time and the same assessments. Furthermore, the battery of eight tasks used in this study provides a reliable estimate of general working memory capacity, which encompasses performance on simple and complex span tasks in the verbal and visuospatial domains (Alloway et al., 2006). In accordance with previous findings, this provides strong evidence that Cogmed improves typically developing children's performance on working memory span tasks.

Improved working memory performance may be the result of increased capacity, more effective use of strategies, or both (von Bastian & Oberauer, 2014). Some of the AWMA tasks have similar structure to the Cogmed training tasks, meaning that they are more likely to afford the same strategies (Lustig et al., 2009). In one study of adults, 10 sessions of Cogmed significantly increased performance and the use of grouping strategies on two AWMA tasks, compared to non-adaptive training (Dunning & Holmes, 2014). However, increased performance was also found on another near-transfer task without any significant change in strategy. Therefore, change in strategy may be one mechanism of working memory training, but it may not fully account for near-transfer effects or rule out the possibility that training is increasing working memory capacity. The behavioural data presented here was not suitably powered for an investigation of transfer to individual tasks; however, Chapter 3 presents an exploratory analyses of near-transfer to four individual AWMA tasks in a larger sample of typically developing children.

2.4.2. Brain Activation Associated with Working Memory

The two working memory fMRI tasks activated bilateral regions of the fronto-parietal network that are commonly implicated in working memory (Rottschy et al., 2012), as well as bilateral regions of the visual cortex. This included activation of the bilateral middle frontal gyrus and left superior parietal lobe on the Dot Matrix task, and activation of the left middle frontal gyrus on the Odd-One-Out task. At baseline there was no significant difference in activation of the middle frontal gyri or superior parietal lobes between the groups for either task. However, the Cogmed group had greater activation of the right lingual gyrus (BA19) on the Dot Matrix task and greater activation of the left precuneus (BA7) on the Odd-One-Out, task compared to the control group. These differences may reflect natural variability in the comparison of two small groups. However, it is unlikely that these results confounded the analyses of training effects, as the analyses examined within-subject change over time and identified activations in different regions of the brain.

It was predicted that working memory training would be associated with increased activation in the middle frontal gyri and superior parietal lobes in comparison to the non-adaptive control group. In line with this prediction, the ROI analysis of the Odd-One-Out task revealed that Cogmed increased activation of three regions in the bilateral middle frontal gyrus compared to the control group. Previous studies have also reported increased activation of the middle frontal gyrus following Cogmed in children (Stevens et al., 2016) and adults (Olesen et al., 2004; Westerberg & Klingberg, 2007). However, these studies lacked a control group and therefore could not rule out the potentially confounding effects of maturation, test-retest, and expectation. Therefore, this is the first study to report increased recruitment of the middle frontal gyrus that is specific to Cogmed working memory training, by comparison to an active control group.

Increased activations of the bilateral middle frontal gyri on the Odd-One-Out task were localised to the left BA6/BA8, right BA8, and left BA9. The whole brain analysis revealed a larger cluster of increased activation, near to the ROI, in the left superior-medial frontal gyrus (BA6/BA8). These regions of the middle frontal gyrus have been routinely implicated in working memory in multiple meta-analyses of neuroimaging studies in adults (Owen, McMillan, Laird, & Bullmore, 2005; Rottschy et al., 2012; Wager & Smith, 2003). Increased recruitment of the middle frontal gyrus may reflect greater working memory capacity through training. Indeed, it has been demonstrated that greater prefrontal activity is associated with greater working memory capacity in children (Klingberg et al., 2002a). However, increased activation of the middle frontal gyrus has also been associated with strategic encoding of verbal and visuospatial information in adults (Bor et al., 2004, 2003; Bor & Owen, 2007). In these studies, chunking was associated with significantly greater recall accuracy and significantly greater activation of the lateral prefrontal cortex. As Cogmed has been shown to increase the use of grouping in young adults (Dunning & Holmes, 2014), it is also possible that the increased use of grouping or other strategies in children facilitated performance on the near-transfer tasks and increased recruitment of the middle frontal gyrus. The neural correlates of memory strategies have yet to be investigated in children, but Chapter 4 will examine whether grouping is associated with activation of the middle frontal gyrus in children.

In contrast to the findings on the Odd-One-Out task, the ROI analysis for the Dot Matrix task revealed that Cogmed was not significantly associated with activation in the middle frontal gyri compared to the control group over time. Both tasks require visuospatial storage, but only the Odd-One-Out requires task switching and maintaining information in the face of competing processing. It is possible then, that increased recruitment of the middle frontal gyrus in the Odd-One-Out task reflects greater executive control, rather than increased working memory capacity more generally. Alternatively, it is possible that Cogmed was associated with a change in strategy specifically for the Odd-One-Out task. For example, the spatial positions of the Odd-One-Out can be verbally recoded into ‘left’, ‘middle’, and ‘right’, which would facilitate sub-vocal rehearsal, whereas there are 16 possible spatial locations on the Dot Matrix task, which cannot be easily verbally recoded.

The ROI analyses also revealed that Cogmed was not associated with significant change in superior parietal activation on either working memory task. Previous uncontrolled studies have suggested that working memory training increased superior parietal activation in children (Jolles et al., 2012) and adults (Olesen et al., 2004). However, these findings may be explained by test-retest or expectation effects in the absence of a control group. Furthermore, both studies reported improvements on the fMRI task and so the activations were confounded by performance. Errors may have cognitive and emotional consequences, and so a change in errors could result in changes in brain activation (Poldrack, 2000). The results of the present study are not confounded by test-retest, expectation, maturation, or performance, because neural correlates were compared to a non-adaptive control group and performance on the fMRI tasks did not change. This suggests that working memory training is not associated with activation in the superior parietal lobe in children and corroborates the lack of superior parietal activation in the only other fMRI study of Cogmed in children (Stevens et al., 2016).

The exploratory whole-brain analyses revealed that Cogmed was associated with increased activation in the left anterior cingulate, bilateral posterior cingulate, right parahippocampal gyrus, and left putamen, compared to the control group. The results of these analyses should be treated with caution, however some tentative explanations are proposed. Cogmed has previously been associated with activation in the anterior cingulate and right posterior cingulate in adolescents with and without ADHD (Stevens et al., 2016), however this study lacked a control group. The results of the present study extend these findings, suggesting that the anterior and posterior cingulate are associated with processes specific to working memory training, by comparison to a non-adaptive control group. The anterior cingulate is commonly implicated in online monitoring of performance and error detection (e.g. Carter et al., 1998), and is regularly activated in working memory studies in adults (Owen et al., 2005; Wager & Smith, 2003). A meta-analysis of working memory studies in adults also showed that activation of the anterior cingulate is greater for working memory tasks that require selective attention to certain features of a stimulus (Wager & Smith, 2003). Similarly, the Odd-One-Out task presents three shapes simultaneously and requires selective encoding of the target location for later recall. Thus, increased recruitment of the anterior cingulate in the Odd-One-Out task may be associated with improved selective attention through training on working memory tasks that require selective encoding of stimuli. This may reflect increased attentional capacity or it could reflect a change in strategy; for instance, a more effective strategic allocation of attention to target stimuli.

Cogmed was associated with increased activation of the left putamen on the Dot Matrix task compared to the control group. Activation in the putamen has previously been associated with working memory training in adults in a recent meta-analysis (Li et al., 2015). In one study, updating training increased activity in the striatum (caudate and putamen), which was related to behavioural improvements on a near-transfer task (Dahlin et al., 2008). The striatum is broadly implicated in motor control (Groenewegen, 2003) and the left striatum has been associated with working memory in a meta-analysis of studies in adults (Rottschy et al., 2012). Computational models have suggested the role of the striatum in working memory may serve a gating function that allows stored representations to be rapidly updated (O'Reilly & Frank, 2006). Therefore, one possible explanation for increased recruitment of the putamen may be the additional recruitment of updating mechanisms, which would be necessary to perform tasks with serial presentation of stimuli.

Cogmed was also associated with increased activation of the right parahippocampal gyrus (BA34) on the Odd-One-Out task, compared to the control group. The parahippocampal gyrus is commonly implicated in visuospatial processing and memory, as evidenced by activation in fMRI studies and impairment in patients with damage to this area (see Aminoff, Kveraga, & Bar, 2013, for a review). One study also showed that activation of the parahippocampal gyrus was associated with whether participants reported using a visuospatial strategy compared to a verbal strategy on an n-back task that afforded both strategies (Glabus et al., 2003). Specifically, the numbers one to four were presented in four corresponding positions and participants only needed to encode the numbers or positions to perform the task. Similarly, the Odd-One-Out task affords visuospatial and verbal rehearsal strategies. As Cogmed predominantly involves training on visuospatial tasks, these children may have more readily applied a visuospatial strategy after training, compared to the control group. Therefore, increased activation of the parahippocampal gyrus in the Cogmed group could reflect greater visuospatial processing on the Odd-One-Out task after training. Future work could investigate whether children are more likely to employ visuospatial memory strategies after Cogmed by examining strategy-use and performance on working memory tasks that afford both a visuospatial and verbal strategy.

2.4.3. Resting-State Functional Connectivity

The neural correlates of working memory training were also investigated at the network level by examining functional connectivity within the dorsal attention and fronto-parietal networks at rest. It was predicted that Cogmed would increase functional connectivity within these networks compared to the control group. In the dorsal attention network, functional connectivity between the bilateral intraparietal sulci significantly increased in the Cogmed group relative to the control group. Increased functional connectivity between the dorsal attention network and the posterior parietal cortex has also been reported in the only other controlled investigation of working memory training and resting-state functional connectivity in children (Astle et al., 2015). Specifically, increase in working memory performance was significantly correlated with increased functional connectivity within the dorsal attention network, to a region of the left superior parietal lobule. This further suggests that increased working memory performance, as a result of Cogmed, was associated with increased functional connectivity in the dorsal attention network. In contrast to the task-based fMRI, these findings cannot be easily explained in terms of strategy-use because functional connectivity was measured when the brain was at rest.

The results of the exploratory whole brain analysis corroborated the finding in the ROI analysis. Cogmed was associated with significantly increased functional connectivity between the dorsal attention network and bilateral regions of the posterior parietal cortex; specifically, the left superior parietal lobe, as in Astle et al. (2015), and the bilateral inferior parietal lobe. The posterior parietal cortex is commonly implicated in selective attention (see Behrmann, Geng, & Shomstein, 2004, for a review) and sustained visuospatial attention (Malhotra, Coulthard, & Husain, 2009), and local functional connectivity in this region has been associated with working memory performance (Chen et al., 2016). Therefore, working memory training may increase capacity through attentional mechanisms, whereby the repeated co-activation of fronto-parietal regions during training enhances connectivity and attentional control (Astle et al., 2015).

Within the fronto-parietal network, comprising of the bilateral prefrontal cortex and posterior parietal cortex, Cogmed was not associated with increased functional connectivity relative to the control group. Although this network encompasses similar regions of the brain as the dorsal attention network, the ROIs are much larger. Therefore, this analysis may not have been sensitive to smaller regional changes in functional connectivity. The whole brain analysis suggested that Cogmed increased functional connectivity between the fronto-parietal network and left inferior temporal / fusiform gyrus, relative to the control group. The inferior temporal cortex is broadly associated with visual object recognition as evidenced by single neuron recordings in primates (Gross, 2008) and fMRI studies in humans (Grill-Spector & Weiner, 2014), and has been associated with maintenance of visual information in working memory (Ranganath, 2006). Although these results were exploratory and close to the significance threshold, Cogmed has previously been associated with significantly increased functional connectivity between the fronto-parietal network and left inferior temporal cortex in typically developing children (Astle et al., 2015). The authors suggested that this may reflect greater top-down regulation of lower level sensory and cognitive processes that affords better performance on working memory tasks.

The results of the whole-brain functional connectivity analyses should be treated with some caution as they were exploratory and there were a number of significant differences between the groups at baseline. This may be because the two groups were relatively small and it is possible that there was greater natural variation in brain activity because cognitive processes were not constrained by a task. Although the analysis of training effects examined within-subject change over time, baseline differences in functional connectivity in the same regions of the brain could indicate regression to the mean. Of note, functional connectivity between the fronto-parietal network and an area of the fusiform gyrus, close to the inferior temporal cortex, was significantly greater in the control group at baseline. Therefore, the increase in functional connectivity observed between the fronto-parietal network and inferior temporal cortex may be explained by regression to the mean rather than working memory training. There were no significant group differences in functional connectivity at baseline within the dorsal attention network or between the dorsal attention network and posterior parietal cortex. Therefore, there is no statistical evidence that these findings were the result of regression to the mean.

2.4.4. Grey Matter Volume

Change in grey matter volume was analysed using voxel-based morphometry. As there is a paucity of studies investigating the structural neural correlates of cognitive training, exploratory analyses were conducted and no predictions were made regarding ROIs. In the Cogmed group there was no significant change in grey matter volume compared to the control group. The lack of significant evidence for change in grey matter volume corroborates the findings of the only other investigation of the effects of Cogmed on grey matter structure (Metzler-Baddeley et al., 2016b). This study in adults found no significant effects of Cogmed on cortical thickness or subcortical volume, compared to non-adaptive training. In another study, adaptive mental arithmetic training was found to improve working memory performance and decrease grey matter volume in bilateral fronto-parietal regions, compared to non-adaptive training (Takeuchi et al., 2011). These findings suggest that adaptive cognitive training may sometimes be associated with reduced grey matter volume. However, whilst mental arithmetic training may tax working memory, it likely also trains numerical skills that are not related to working memory. Therefore, current evidence for the effects of working memory training on grey matter volume in children and adults is very limited.

2.4.5. Strengths, Limitations, and Future Directions

As the majority of previous studies were uncontrolled or only used a passive control group, the non-adaptive control group was a major strength of the present study. However, non-adaptive training is not as challenging as adaptive training, which may affect children's motivation and expectations and lead to improved performance on the AWMA (Shipstead et al., 2012). Only one behavioural study in children has attempted to control for these possible confounds by comparing working memory training to adaptive general knowledge training (Jaeggi, Buschkuehl, Jonides, & Shah, 2011). However, these two training tasks were not well matched for demands on concentration and attention. Chapter 3 will describe an investigation of working memory training in children in comparison to adaptive visual search training, which is better matched for attentional demands. A further criticism of the control group is that the training may not have been as engaging as Cogmed because it only involved training on one task, the graphics were basic and lacked a theme, and there was no reward of a game at the end of each training session. This may have influenced children's enjoyment and the perceived effectiveness of the training, which could have limited children's performance on the working memory tasks. Further differences include the presence of a pre-learning stage, time-limited responses, the task taxed updating working memory rather than serial recall on simple and complex span tasks, the material was purely verbal and not visuospatial, and trial timings differed; however, it is unclear how these may affect children's performance on working memory tasks, brain activation, or brain structure.

The sample had above average IQ and slightly above average working memory capacity at baseline, which may limit the generalisability of the findings. Furthermore, a significant number of children were unable to complete the training. Although these figures are comparable to previous Cogmed studies in typically developing children (Chacko et al., 2014), children who completed training may have differed in certain characteristics compared to those who withdrew. Intrinsic motivation, pre-existing ability, and the need for cognition have been identified as characteristics that may mediate training adherence and transfer (Jaeggi, Buschkuehl, Shah, & Jonides, 2014). Finally, there was no improvement on the working memory tasks used during scanning. Although it is difficult to an interpret the absence of an effect, there were a number of differences between the training tasks and fMRI tasks that may explain the lack of transfer. For instance, the scanning environment may have limited optimal performance and the use of strategies, the fMRI tasks measured recognition compared to serial recall in training, the difficulty and pace of the tasks were unpredictable, and some children performed near ceiling. Furthermore, the BOLD signal may have been more sensitive to the effects of training than performance on the fMRI tasks. Average performance on the AWMA provided a more reliable estimate of near-transfer effects because it included eight working memory tasks and indicated that working memory significantly improved in the Cogmed group compared to the control group.

2.4.6. Conclusion

This was the most comprehensive investigation of the neural correlates of working memory training to date. No previous study in children has examined changes in task-related brain activation or grey matter volume, by comparison to an active control group. Adaptive training significantly increased performance on a standardised battery of eight working memory tasks and increased recruitment of the bilateral middle frontal gyrus on a complex span task requiring executive control. These findings may reflect increased capacity, a change in strategy, or a combination of both. However, strategy-use cannot easily explain changes in resting-state functional connectivity. Working memory training was associated with significantly increased functional connectivity within the dorsal attention network, between bilateral regions of the posterior parietal cortex, consistent with previous evidence. It is suggested that increased connectivity within the posterior parietal cortex may reflect enhanced attentional control, through the repeated and demanding co-activation of these regions during training. There were no significant changes in grey matter volume, however working memory training may be associated with other structural changes in the brain. Working memory training may effect white matter, which supports long-range connections within networks. Future studies could use techniques such as Diffusion Tensor Imaging (DTI) to measure the integrity of white matter tracts and examine whether training effects structural connectivity.

Chapter 3: MetaCogmed – Facilitating Far-Transfer to Academic Achievement with Concurrent Working Memory and Metacognitive Training

3.1. Introduction

Chapter 2 demonstrated that working memory training improves typically developing children's performance on working memory tasks relative to an active control group, and corroborated findings in a recent meta-analysis (Sala & Gobet, 2017b). Working memory training was also associated with increased functional connectivity between the bilateral intraparietal sulci, which may reflect increased attentional capacity. If training is increasing capacity to some extent, then behavioural effects would be expected to generalise to other cognitive processes that are supported by the same neural systems (Lövdén et al., 2010). However, there is very limited evidence for far-transfer to cognitive capacities associated with working memory (see Section 1.2.). This may be because children do not change their approach to other cognitive tasks and they may require guidance to apply these cognitive gains more broadly. Metacognitive strategy training teaches children how to plan, monitor, and evaluate across a range of settings, and is associated with generalisable academic benefits (e.g. Adey & Shayer, 1993). This chapter presents a randomised controlled trial investigating the academic outcomes of concurrent working memory and metacognitive strategy training in typically developing children. The trial endorses recent recommendations by utilising an adaptive control group to better account for expectations and motivation (Shipstead et al., 2012).

3.1.1. Far-Transfer and Metacognitive Training

As working memory is an important predictor of children's academic achievement (Alloway & Alloway, 2010; Gathercole, Pickering, Knight, et al., 2004), it is feasible that working memory training will have academic benefits. Certain components of Maths and English are more dependent on working memory than others. For example, working memory is essential for mental arithmetic (Hitch, 1978), which requires remembering numbers, performing operations, and updating the contents of memory after each operation. A meta-analysis of 110 studies investigating the relationship between working memory and maths abilities demonstrated that working memory is most strongly correlated with arithmetic and word problem-solving (Peng et al., 2015). These correlations were significantly larger than for other components of maths, such as geometry. This suggests that working memory training may be most likely to transfer to measures of maths ability that include word problems and arithmetic. Concerning English, working memory capacity has been found to predict children's reading comprehension but not basic word reading (Leather & Henry, 1994). In addition, a longitudinal study found that the correlation between children's working memory capacity and reading comprehension significantly increased over time (Seigneuric & Ehrlich, 2005). At seven and eight years old, reading comprehension was significantly predicted by children's word reading ability and vocabulary, but not working memory. At nine years old, working memory capacity independently predicted reading comprehension when controlling for word reading ability and vocabulary. This suggests that working memory is particularly important for reading comprehension in older children, when basic word reading skills become more automatic. Therefore, working memory training in older children may be most likely to transfer to reading comprehension, rather than basic word reading skills.

Although working memory capacity predicts maths and reading ability, there is very limited evidence for far-transfer effects of working memory training (see Section 1.2; Redick et al., 2015). A meta-analysis of working memory training studies in typically developing children found significant far-transfer to maths in the short-term, but only when including studies with passive control groups (Sala & Gobet, 2017b). There was no evidence of far-transfer to maths, reading, or science, when only considering studies with active control groups. However, some working memory training programmes may be more effective than others. Cogmed has been associated with larger near-transfer effects than n-back training and Jungle Memory (Melby-Lervåg & Hulme, 2013), and so it may be associated with larger far-transfer effects. Only two studies have investigated Cogmed in typically developing children. One study reported improvements on a reading and spelling test 24 months after training, compared to education as usual (Söderqvist & Bergman-Nutley, 2015). However, children in the Cogmed group may have had greater expectations and motivation to perform well on the transfer tasks, as they took part in a novel intervention. When compared to non-adaptive training, which better controls for these confounds, a larger randomised controlled trial found no evidence of near-transfer and no evidence of far-transfer to maths or reading comprehension immediately or three months after training (Hitchcock & Westwell, 2017). This suggests that working memory training alone does not improve typically developing children's academic outcomes.

One explanation for these findings is that working memory training promotes the development of task-specific strategies that only transfer to structured working memory tasks that are similar to the training tasks (Dunning & Holmes, 2014). This theory is partly supported by the finding that after 10 sessions of Cogmed, young adults showed significant improvements on the AWMA and reported significantly more grouping strategies, relative to a non-adaptive control group (Dunning & Holmes, 2014). Grouping is effective for memorising a sequence of items (e.g. Farrell, 2008), but it may be difficult for children to spontaneously use this in more diverse tasks at school. Indeed, memory strategies significantly predict performance on working memory tasks, but do not significantly explain the relationship between reading comprehension and span tasks (Bailey et al., 2008; Dunlosky & Kane, 2007). This provides support for the strategy affordance hypothesis (Bailey et al., 2008), which states that working memory strategies will only benefit performance on cognitive tasks that afford the same strategies. This would predict no far-transfer from the strategies learnt during working memory training.

Working memory training may be partially strategic, but it is also possible that there are improvements in capacity, given the evidence for changes in functional connectivity when the brain is at rest (see Chapter 2). Theoretically, increased working memory capacity should support reading comprehension, arithmetic, and problem-solving, as mentioned earlier. The strategy-as-effect hypothesis proposes that high working memory capacity affords the production and implementation of effortful and effective strategies on cognitively demanding tasks (Dunlosky & Kane, 2007). Indeed, higher working memory capacity is associated with greater use of normatively effective strategies on memory tasks (Bailey et al., 2008, 2011; Dunlosky & Kane, 2007) and maths problems (Imbo & Vandierendonck, 2007). However, this does not necessarily mean that increased working memory capacity through training will automatically promote the production and implementation of effective strategies on different tasks (e.g. Partanen et al., 2015), particularly as children's ability to generate and utilise strategies is still developing (Bjorklund, Dukes, & Brown, 2008). Children may require specific instruction and guidance on how to apply their newly acquired additional capacity in other situations. Children could be taught strategies to complete particular tasks more effectively or efficiently, however these strategies will typically be task-specific and will not generalise to other situations (Bailey et al., 2008; Lustig et al., 2009). Wider benefits may be achieved by teaching children how to approach, engage, and evaluate in a variety of cognitively demanding situations. These skills may enable the generation and retrieval of appropriate cognitive strategies for the current task and, therefore, facilitate generalised improvements at school and daily life.

Salomon and Perkins (1989) defined two routes for transfer of learning to occur, which may explain the limited evidence for far-transfer from working memory training. The 'low-road' to transfer can be achieved by extensive and varied practice but this typically only facilitates performance on similar tasks, which afford the same strategies or routines. The 'high-road' to transfer requires mindful abstraction of something learnt in one context and its application to a new context. The high-road implicates metacognition (as defined in Section 1.4.1.); it requires awareness of what was previously learnt and the cognitive demands of the new task, and the deployment of appropriate cognitive strategies. Planning, monitoring, and evaluating are metacognitive skills that have been proposed to be important in problem-solving (Sternberg, 1988) and have been a common target for metacognitive interventions (Fisher, 1998b).

Educational interventions targeting metacognition are associated with the development of broad thinking skills (see Salomon & Perkins, 1989, for a review) and they are highly recommended as one of the most impactful interventions (Higgins et al., 2016). Interventions are typically delivered by teachers in a group setting to promote group discussion (e.g. Adey & Shayer, 1993). Teachers may directly instruct children how to use certain planning and evaluating strategies on problem tasks (Ashman & Conway, 1993), whereas others recommend that children generate their own strategies to solve problems through guided metacognitive questioning and reflective discussion (Brown & Walter, 2005). As discussed in Section 1.4.1., metacognitive interventions have been shown to improve children's academic performance (Dignath & Büttner,

2008) and generalise to other untrained domains (Adey & Shayer, 1993). Therefore, if working memory training increases children's capacity, then metacognitive strategy training may facilitate far-transfer to academic outcomes, as outlined above. However, it should be noted that metacognitive interventions have typically been compared to education as usual, which may not appropriately control for expectation effects.

Very few studies have incorporated metacognitive strategy training with working memory training and have achieved mixed results (see Section 1.4.2.). These interventions have encouraged children to formulate goals on the training tasks, identify strategies, and monitor their comprehension either through group dialogue with a special educational needs coordinator (Partanen et al., 2015) or through teacher instruction and independent work on written materials (Carretti et al., 2014). Another study delivered psychoeducation about executive functions, strategies (e.g. repeat instructions), and common pitfalls (e.g. distraction) to children with ADHD through an audiobook. Subsequently, children practised using these strategies on school-related tasks, such as arithmetic, which were provided in a workbook format. The children also trained on three paper and pencil working memory tasks. The children were assessed on measures of executive function and academic performance in comparison to a group that received Cogmed. However, inferences regarding the effectiveness of the combined working memory and metacognitive training programme were limited due to a number of differences between the conditions, including: different working memory training exercises, psychoeducation, the presence of an audiobook, practise on school-based tasks, and teacher involvement.

Only one study has investigated combined working memory and metacognitive strategy training in typically developing children. The intervention was found to improve children's working memory and reading comprehension compared to simple reading comprehension practice (Carretti et al., 2014). This suggests that concurrent working memory and metacognitive training may improve academic outcomes. However, it was unclear whether the improvement in reading comprehension was an effect of working memory training, metacognitive strategy training, instruction in specific reading strategies, or a combination of the three. There is extensive evidence for the efficacy of instruction in reading comprehension strategies (Higgins et al., 2016), but these improvements would not be expected to generalise further. On the other hand, metacognitive strategies may facilitate performance on a wide range of tasks. Therefore, it is important to determine which aspects of multi-component interventions are effective in order to aid the design of effective and efficient interventions in future.

3.1.2. Adaptive Control Groups

A significant limitation of the current working memory training literature is that the majority of actively controlled studies have used a non-adaptive variant of the training programme. This means that the difficulty of the training tasks remains at a very low level and the participants see no improvement on the training tasks over time. In contrast, adaptive training continually challenges children at the height of their current ability. Children improve on the training tasks over time, and they receive regular feedback, support, and encouragement for these improvements. Therefore, the adaptive training group may have greater expectations and motivation to perform well on the outcome measures, compared to the non-adaptive control group (Shipstead et al., 2012). Non-adaptive control groups have also been criticised for showing effects of training, changes in brain activation, decreased parental involvement and coach support, more positive parental perceptions, and less training time (Cogmed, personal communication, April 2015). Improvements from non-adaptive training have been reported for children with low working memory capacity (Dunning et al., 2013), ADHD (van Dongen-Boomsma, Vollebregt, Buitelaar, & Slaats-Willemse, 2014), and intellectual disability (Soderqvist, Nutley, Ottersen, Grill, & Klingberg, 2012). Furthermore, a study of older adults showed that adaptive and non-adaptive training reduced brain activation in a number of similar areas, including fronto-parietal regions (Brehmer et al., 2011). These findings suggest that non-adaptive training may provide a low dose of working memory training, which could potentially mask transfer effects. Therefore, non-adaptive training may contribute to false-positives by not appropriately controlling for expectation or motivation, or contribute to false-negatives by training working memory.

Many reviews have recommended using an adaptive control group, that effectively trains a capacity that is unrelated to working memory (Boot, Simons, Stothart, & Stutts, 2013; Green, Strobach, & Schubert, 2014; Noack, Lovden, & Schmiedek, 2014; Shipstead et al., 2012; Simons et al., 2016). Individuals in an adaptive control group will be challenged, will see improvements during training, and should, therefore, have similar expectations about their performance on the assessments. Only a few published investigations have used adaptive control groups and these have predominantly been designed for adults. These include: adaptive visual search training (Redick et al., 2013), adaptive knowledge training (Jaeggi et al., 2011), and Tetris (Kundu, Sutterer, Emrich, & Postle, 2013).

In adaptive visual search training, participants must search for a target letter in a briefly presented visual array and report the orientation of the target with a keypress (Redick et al., 2013). At the end of each block the difficulty is adapted by increasing or decreasing the size of the visual array. If accuracy is below 75% the array decreases, if accuracy is between 75% and 87.5% the array stays the same, and if accuracy is greater than 87.5% the array increases. In comparison to adaptive visual search training, a study of single n-back training found evidence of near-transfer to an untrained spatial 3-back task but no far-transfer to inhibition, sustained attention, or measures of fluid intelligence (Covey, 2016). Similarly, a study of dual n-back training found no evidence of near-transfer to a simple span or running span task and no evidence of far-transfer to fluid intelligence, crystallised intelligence, multitasking, or perceptual speed, when compared to adaptive visual search training (Redick et al., 2013). In the running span task participants are required to recall the last n trials from a sequence, which requires updating the contents of working memory (Broadway & Engle, 2010). Therefore, it is interesting to note that n-back training has been shown to improve performance on other n-back tasks but not to other updating tasks, when compared to an adaptive control group.

Adaptive visual search training has also been used as a control in a study investigating simple span training and complex span training (Harrison et al., 2013), which include similar tasks to Cogmed. Complex span training was found to improve performance on two untrained complex span tasks, two running span tasks, and a free recall task. Simple span training was found to improve performance on two running span tasks and a free recall task. However, there was no evidence of far-transfer to measures of fluid intelligence for either training programme, in comparison to adaptive visual search training. Working memory training in comparison to adaptive visual search training has provided consistent evidence of near-transfer when the measures are structurally similar to the training tasks, some evidence of moderate transfer to other working memory and long-term memory tasks, and a consistent lack of evidence for any far-transfer.

In adaptive knowledge training, participants are asked general knowledge and trivia questions in a multiple choice format (Anguera et al., 2012; Jaeggi et al., 2011). The task adapts by asking new questions in each training session and repeating incorrectly answered questions in the next session. In comparison to adaptive knowledge training, a study of single n-back training in adults found evidence of near-transfer to an untrained 3-back task, 4-back task, and complex span task (Anguera et al., 2012), but no far-transfer to mental rotation or sensorimotor processing speed. Another study reported that both single n-back training and dual n-back training improved adults' visuospatial reasoning relative to knowledge training, however these effects were not maintained three months later (Jaeggi et al., 2014). The authors suggested that the absence of any effects at the three month follow-up may be explained by the high attrition rate (31%), leading to a loss of power. The only study to use an adaptive control group with children compared n-back training to adaptive knowledge training (Jaeggi et al., 2011). Relative to the control, n-back training did not improve fluid intelligence at the immediate outcome or at the three month follow-up. In summary, working memory training in adults has shown evidence of near-transfer, when measured, and some evidence of far-transfer to visuospatial reasoning in the short-term, compared to adaptive knowledge training. However, there is no evidence of near- or far-transfer in children, relative to adaptive knowledge training.

Visual search training adapts after each block of trials, meaning that the difficulty changes on a similar time scale to Cogmed and other working memory training programmes. On the other hand, knowledge training only adapts after each session and it is questionable whether the training becomes progressively more difficult. Furthermore, both Cogmed and the visual search place demands on visuospatial attention and sustained attention, whereas knowledge training does not. Knowledge training requires answering quiz-like questions, which may be perceived as easier because it does not require the same degree of concentration. Tetris is a reasonable control for the visuospatial and attentional demands of Cogmed, however it may not have the same face validity as the visual search task because it is widely recognised as a recreational computer game. Therefore, visual search training may provide the most suitable control for the adaptive difficulty, visuospatial demands, attentional demands, and expectations of Cogmed.

3.1.3. The Present Study

The purpose of this study was to examine two questions. First, what are the immediate and three month outcomes of working memory training in typically developing children when compared to an adaptive control group that appropriately controls for expectations? No previous study in children has examined near-transfer or far-transfer to academic outcomes in comparison to an adaptive control group. Furthermore, few controlled studies have examined longer term outcomes of working memory training in typically developing children (see Sala & Gobet, 2017b), and so it is unclear whether near-transfer effects are maintained. Second, does combined working memory and metacognitive strategy training facilitate far-transfer to academic achievement? Only one previous study has investigated this question in typically developing children and found promising improvements in reading comprehension (Carretti et al., 2014). However, it was unclear which components of training were effective and whether these benefits would be likely to generalise further.

These two research questions will be examined in a double-blind randomised controlled trial. A novel metacognitive strategy workbook was developed and combined with the standard Cogmed protocol to form the ‘MetaCogmed’ programme. For comparison, an adaptive visual search training programme was developed for children using the same parameters as previous studies (Harrison et al., 2013; Redick et al., 2013). To make this more engaging for children, the task includes a narrative, a colour scheme, and high scores. As both training programmes are challenging and provide feedback on improvement, children should be blind to which programme is most effective. MetaCogmed will be compared to Cogmed alone and adaptive visual search training, so that the efficacy of working memory training and metacognitive training can be individually evaluated. To control for non-specific effects of the metacognitive workbook, the Cogmed and adaptive control groups will receive a placebo workbook with similar materials but without any metacognitive content. Blinded assessments will be conducted at three time points: before training, immediately after training, and three months after the immediate outcome assessment.

To assess transfer, measures of working memory and academic achievement were selected for their potential sensitivity to the effects of working memory training. Significant near-transfer to the Automated Working Memory Assessment (AWMA; Alloway, 2007) was reported in Chapter 2, and a previous Cogmed study reported significant near-transfer to a composite score of four AWMA tasks (Astle et al., 2015). Therefore, near-transfer will be assessed on a composite score of four AWMA tasks, which include simple and complex span tasks in the verbal and visuospatial domains. The Reading Comprehension and Mathematical Reasoning subtests of the Wechsler Individual Achievement Test-II (WIAT-II; Wechsler, 2004) were selected as appropriate measures to examine far-transfer to academic achievement, as in previous studies (Rode et al., 2014; Holmes et al., 2009). Furthermore, reading comprehension is more strongly associated with working memory in older children than basic reading skills (Seigneuric & Ehrilich, 2005), and Mathematical Reasoning primarily includes word problems, which are more strongly correlated with children's working memory than other maths skills (Peng et al., 2015). In addition, a recent review suggested that Cogmed has more commonly shown improvements in passage comprehension and mathematical reasoning than other measures of maths and reading (Bergman-Nutley & Soderqvist, 2017).

To maximise the ecological validity of the study, the training will be conducted at school as a group and supervised by at least one researcher. This setup would presumably be the most feasible for schools to implement if the intervention was found to be effective, as a class of children could be supervised by one member of staff. The training sessions will be held after school as recent evidence from a large randomised controlled trial has shown that replacing lessons with working memory training can be detrimental to long-term academic achievement in children with poor working memory (Roberts et al., 2016). Children may have missed important material in class, which may have affected their future attainment. Working memory training did not appear to compensate for the lessons missed, suggesting that it cannot be recommended for children with poor working memory within the school curriculum. However, it is possible that it may be beneficial for typically developing children when offered in addition to school as usual, either after-school or at home.

3.1.4. Hypotheses

4. Working memory training has been shown to improve typically developing children's working memory capacity, which is maintained three to six months later (Sala & Gobet, 2017). It is predicted that Cogmed and MetaCogmed will improve performance on the AWMA significantly more than the control group, and that this will be maintained three months later.

5. There is evidence to suggest that metacognitive strategy training promotes far-transfer (Adey & Shayer, 1993), and improves academic outcomes when combined with working memory training (Carretti et al., 2014). It is predicted that MetaCogmed will improve reading comprehension and mathematical reasoning significantly more than the control group and Cogmed alone, and that this will be maintained three months later.

3.1.5. Exploratory Questions

There is substantial evidence that working memory training improves performance on tasks that are similar to the training, however studies have reported an absence of near-transfer to tasks that have different structure (Ang et al., 2015; Hitchcock & Westwell, 2017). The Dot Matrix and Backwards Digit Recall tasks from the AWMA closely resemble Cogmed training tasks, whereas the Forwards Digit Recall and Spatial Span tasks are less similar. Therefore, it is predicted that MetaCogmed and Cogmed will perform significantly better on the tasks that are similar to training compared to the control group, and that this will be maintained three months later. Furthermore, metacognitive training may facilitate the production and application of strategies to near-transfer tasks that are less similar to the training. Therefore, it is predicted that near-transfer may be greater on these tasks for MetaCogmed compared to Cogmed, and that this will be maintained three months later.

3.2. Method

3.2.1. Participants

Ninety-five typically developing children aged between 9 and 14 years (*M* = 12.51, *SD* = 1.18) were recruited from four public schools in Devon, England. The sample included 45 girls (47.4%) and 50 boys (52.6%), who were primarily white British. Seven children were recruited from one primary school and 88 children from three secondary schools. Children were excluded if they had a diagnosis of a developmental disorder, acquired brain injury, or uncorrected visual, hearing, or motor impairment that might hinder their engagement with the training. All participating children provided written assent and their parent/guardian provided written consent. The study was approved by the University of Exeter Ethics Committee (Ref: 2016/1288).

3.2.2. Design & Procedure

After consenting to participate, children completed baseline assessments of working memory, IQ, reading comprehension and mathematical reasoning immediately before beginning training (*M* = 7.71 days before, *SD* = 5.26). Within each school, children were randomly allocated to one of three training conditions: Cogmed, MetaCogmed, and Control (see Figure 3.2. for CONSORT diagram). Randomisation was completed by a research team member who did not complete outcome assessments at that school and was repeated until group sizes differed by one or less. The MetaCogmed and Cogmed groups completed the Cogmed RoboMemo programme (see Section 2.2.4.) and the Control group received adaptive visual search training. In addition, the MetaCogmed group received a metacognitive workbook and the Cogmed and Control groups received a placebo workbook. The training was conducted as an afterschool club, where children trained together in one of the school's computer rooms for approximately one hour following the end of the normal school day. The afterschool club ran every day for six weeks, and children were instructed to complete at least 20 training sessions in that time, in accordance with the Cogmed protocol. The sessions were always supervised by one to three members of the research team who were certified Cogmed coaches. Parents and guardians were contacted weekly with updates on their child's progress and any issues were discussed. Children were rewarded with a £1 Amazon voucher or fun item of stationery every time they completed four training sessions, and a £15 Amazon voucher when they finished the training programme. Children were reassessed after completing the training programme (*M* = 3.87 days later, *SD* = 3.63) and again at least three months later (*M* = 14.42 weeks later, *SD* = 1.06). The assessments were administered by members of the research team who were blind to group assignment.

3.2.2.1. Adaptive visual search training

'Codebreak' (see Figure 3.1) is an adaptive visual search training programme that was developed in OpenSesame 3.1 (Mathôt, Schreij, & Theeuwes, 2012). The programme was based on a similar paradigm that has been used previously in the literature (Redick et al., 2013). A narrative, a black and green colour scheme, and high scores were added to make this more engaging for children. In the first session children were introduced to the narrative; it was explained that MI6 needed their help to successfully break a code that was protecting important information. The children were instructed how to complete the task and had to complete a practice block that required perfect accuracy on eight easy trials in order to progress to the training. The training involved adaptive practice on a visual search task where each session consisted of 24 blocks of 24 trials, lasting approximately 40 minutes. In the visual search task, children searched for the target letter 'F' amongst an array of distracter letters which consisted of 'E's or 't's. The letters could either face to the right, as normal, or to the left, as mirror images. A fixation dot was presented for 500ms, followed by an array presented for 500ms, which was then replaced with a mask for 2500ms. Children had to report the orientation of the target by pressing the right arrow when the 'F' was facing to the right, or left arrow when it was facing to the left. Feedback was given on each trial in the form of a tone presented for 200ms; a high tone indicated a correct response and a low tone indicated an incorrect response. If no response was made during the array or mask presentation the trial was considered incorrect.

As in Cogmed, the visual search training had an adaptive difficulty and feedback on performance. The initial search array was set at 2x2, but was adapted at the end of each block. If accuracy was greater than 87.5% the difficulty was increased by adding a row or column to the array, if accuracy was between 75 and 87.5% the difficulty remained the same, and if accuracy was less than 75% the difficulty was reduced by removing a row or column from the array. A difficulty level of one indicated a 2x1 array, a difficulty level of two indicated a 2x2 array, a difficulty level of three indicated a 3x2 array, and so on. Children received feedback about their performance at the end of each block, the highest difficulty level they had achieved that session, and the highest difficulty level they had achieved overall across all sessions.

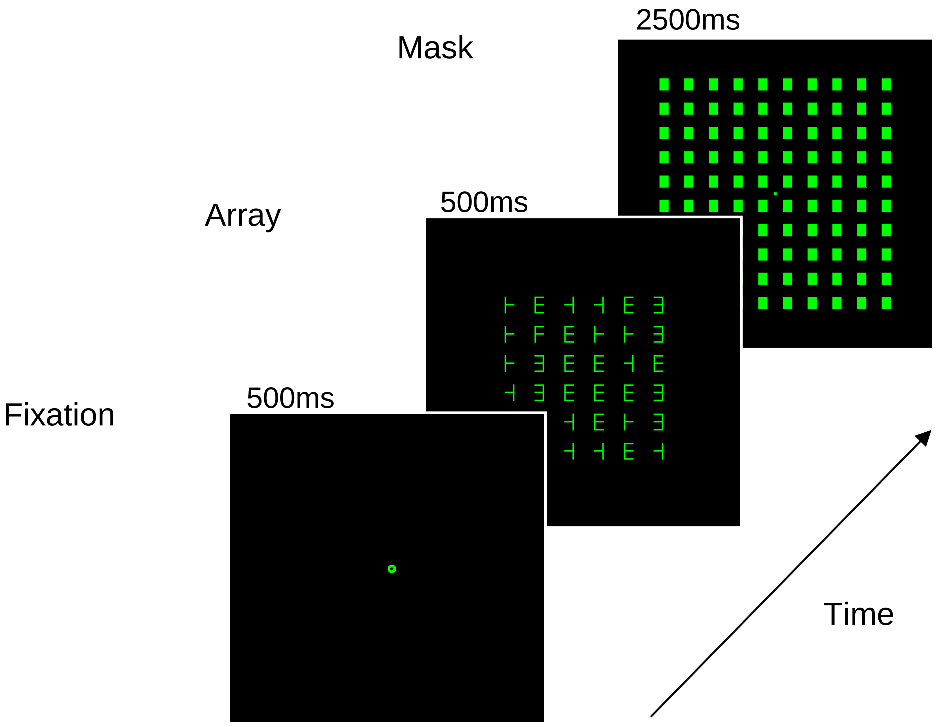

Figure 3.1. Overview of the visual search training task. Each trial began with a fixation dot presented for 500ms, followed by an array presented for 500ms, and mask presented for 2500ms. Children were required to report the orientation of the target letter ‘F’ amongst an array of distracter letters by pressing the right or left keys. Responses had to be made during the array or mask presentation.

3.2.2.2. Metacognitive workbook

Children assigned to the MetaCogmed group received the metacognitive workbook (see Appendix 2) to complete alongside their computerised training, whereas the Cogmed and Codebreak groups received a placebo workbook (see

Appendix 3). The metacognitive and placebo workbooks were divided into 25 sections that took 10-15 minutes to complete. Children were required to complete one section each day after completing one session of their respective computerised training. The workbooks consisted of written information, illustrations, and exercises. Both workbooks included goal setting, five reading comprehension exercises, and five word-based maths problems (see Appendix 1). To ensure that the language and difficulty of the exercises were age-appropriate, two versions of the workbooks were developed. One was designed for primary school children aged 9-11 years and the other for secondary school children aged 11-14 years. The workbooks were checked by the coaches during the sessions to ensure that they had been completed appropriately and with sufficient detail.

The purpose of metacognitive workbook was to instruct children how to use three metacognitive strategies: planning, monitoring, and evaluating. These metacognitive strategies are common in educational interventions (see Fisher, 1998b, for a review) and the importance of these strategies to reading, maths, and memory was emphasised. The metacognitive workbook began with three reflection exercises, which encouraged children to think about their thinking as they completed a Cogmed training task, a reading comprehension exercise, and a maths problem. Children were then introduced to planning, monitoring, evaluating, and specific metacognitive strategies that serve to self-motivate and refocus. These motivation and concentration strategies were adopted from paediatric neurorehabilitation programmes that combine training of cognitive skills and instruction in metacognitive strategies (Butler & Copeland, 2002; Sohlberg et al., 2014). Children were instructed to use these strategies when completing the Cogmed training tasks, the reading comprehension exercises, and the maths problems. Questions prompted children to plan before starting the task, reminded them to monitor their thoughts during the task, and required them to evaluate their thinking after the task (see Appendix 2). The questions particularly focused on: the goal of the task, which strategies might aid performance, the steps to complete the task, and strategies to improve motivation and focus. As children progressed through the workbook, the questions were replaced with prompts to encourage children to remember how to plan, monitor, and evaluate. Children were not instructed to use any task-specific mnemonic, reading, mathematical, or problem-solving strategies, but were instead encouraged to generate and implement their own strategies. The children wrote down how to use, when to use, and why to use these strategies in their ‘Personal Strategy Guide’ (see Schraw, 1998), which was available at any time.

The placebo workbook included the same reading and maths exercises as the metacognitive workbook but without the metacognitive content. Instead, the placebo workbook contained: word searches that were related to the passages, number searches linked to the maths problems (see Appendix 2), and questions pertaining to the acceptability of the training (see Appendix 4). The placebo workbook was designed to have face validity and to hold children’s attention for a similar amount of time as the metacognitive workbook.

3.2.3. Measures

IQ was measured at baseline using the two sub-tests version of the (FSIQ-2) of the Wechsler Abbreviated Scale of Intelligence-II (WASI-II; Wechsler, 2011), as in Chapter 2. Working memory, reading, and maths were measured at baseline, immediate outcome, and three month follow-up.

Working memory was assessed using four tasks from the Automated Working Memory Assessment (AWMA; Alloway, 2007). This included a measure of verbal storage (Digit Recall), verbal working memory (Backwards Digit Recall), visuospatial storage (Dot Matrix), and visuospatial working memory (Spatial Span). The psychometric properties of the AWMA are reported in Section 2.2.2.

Academic achievement was assessed using the Reading Comprehension and Mathematical Reasoning subtests from the Wechsler Individual Achievement Test-II (WIAT-II; Wechsler, 2005). Reading Comprehension includes questions that examine comprehension of written passages and sentences. All responses were scored by the principal investigator to reduce subjective variability. The Reading Comprehension subtest has excellent internal consistency for ages 9-14 (r = 0.94-0.96), excellent test-retest reliability (r = 0.93), and has reasonable convergent validity with other measures of reading achievement (*r* = 0.45-0.70). Mathematical Reasoning predominantly includes single and multi-step word problems relating to whole numbers, fractions or decimals, interpreting graphs, identifying patterns, rotating shapes, and probability. The Mathematical Reasoning subtest has excellent internal consistency for ages 9-14 (*r* = 0.92-0.95), excellent test-retest reliability (*r* = 0.94), and good convergent validity with other measures of Maths achievement (*r* = 0.59-0.67).

3.2.4. Data Analysis

Near- and far-transfer were examined using intention-to-treat (ITT) analyses, treating missing data as missing at least at random assumption. First, ANCOVA models analysed the difference between the groups at immediate and three month outcomes, whilst adjusting for baseline scores. Contrasts then examined whether there were significant differences between MetaCogmed and Control, Cogmed and Control, and MetaCogmed and Cogmed. Second, maximum likelihood based multilevel-mixed models analysed the change in outcome variables from one time point to another, and whether this change differed across the groups. These analyses were completed in Stata (version 15.1) and SPSS (version 24). The ANCOVAs were considered the primary test of transfer effects at the immediate outcome as they are generally recommended in randomised controlled trial analysis of two time points and have greater statistical power (Van Breukelen, 2006; Vickers & Altman, 2001). The mixed models were considered the primary test of transfer effects at the three month outcome as they model change over all three time points.

3.3. Results

3.3.1. Baseline Characteristics

Baseline data were collected for all participants at the point of randomisation (N=95). The number of data points (N), means, standard deviations (SD), and group differences (Δ) with 95% confidence intervals (CI) are presented for all variables in Table 3.1. Between-group differences were analysed using t-tests for all continuous variables and chi-square tests for gender. There were no significant differences across the three groups (all *p* > .05), suggesting that the randomisation was effective. The only exception was for IQ, which was higher for the MetaCogmed group compared to the control group at borderline significance (*p* = 0.044*)*. However, controlling for this factor did not significantly contribute to the regression models and, therefore, it was not added to the model results presented in the following sections.

Table 3.1. Baseline characteristics and tests of differences across groups.

Variables	**Control**	**MetaCogmed**	**Cogmed**	**Δ MetaCog vs. Control (95% CI)**	**Δ Cogmed vs. Control (95% CI)**	**Δ MetaCog vs. Cogmed (95% CI)**
Randomised (N = 95, 100%)	31 (33%)	32 (34%)	32 (34%)	—	—	—
Gender: Control vs. MetaCogmed (N)	31	32	32	—	—	–
Male: N	16	18	16	—	—	–
Female: N	15	14	16	—	—	–
Other variables: (N)	31	32	32	—	—	—
Age: mean (± SD)	13 (±1)	12 (±1)	13 (±1)	-0.14 (-1 to 0)	0.12 (0 to 1)	-0.26 (-1 to 0)
IQ: mean (± SD)	104 (±11)	110 (±11)	108 (±12)	5.84 (0 to 11)*	3.75 (-2 to 10)	2.09 (-4 to 8)
Training days: mean (± SD)	18 (±6)	18 (±5)	16 (±7)	-0.35 (-3 to 2)	-2.11 (-5 to 1)	1.77 (-1 to 5)
Primary outcome variables: (N)	31	32	32	—	—	
Maths: mean (± SD)	102 (±9)	104 (±11)	104 (±12)	2.55 (-3 to 8)	2.58 (-3 to 8)	-0.03 (-6 to 6)
Reading: mean (± SD)	102 (±9)	107 (±11)	104 (±12)	4.95 (0 to 10)	2.17 (-3 to 8)	2.78 (-3 to 8)
Working Memory: mean (± SD)	103 (±10)	105 (±9)	105 (±9)	1.43 (-3 to 6)	1.66 (-3 to 6)	-0.23 (-5 to 4)
Secondary outcome variables: (N)	31	32	32	—	—	—
Digit recall (± SD)	101 (±12)	103 (±15)	101 (±13)	1.83 (-5 to 8)	0.07 (-6 to 6)	1.76 (-5 to 9)
Back digit (± SD)	101 (±14)	102 (±15)	108 (±14)	0.67 (-7 to 8)	6.40 (-1 to 14)	-5.73 (-13 to 2)
Dot matrix (± SD)	103 (±12)	104 (±14)	104 (±11)	0.72 (-6 to 7)	0.39 (-5 to 6)	0.33 (-6 to 7)
Spatial span (± SD)	109 (±17)	111 (±12)	108 (±15)	2.49 (-5 to 10)	-0.23 (-8 to 8)	2.72 (-4 to 9)

Note. All outcome variables are standardised, X ~ N (100, 15^2), higher scores indicate higher performance. *denotes p<0.05

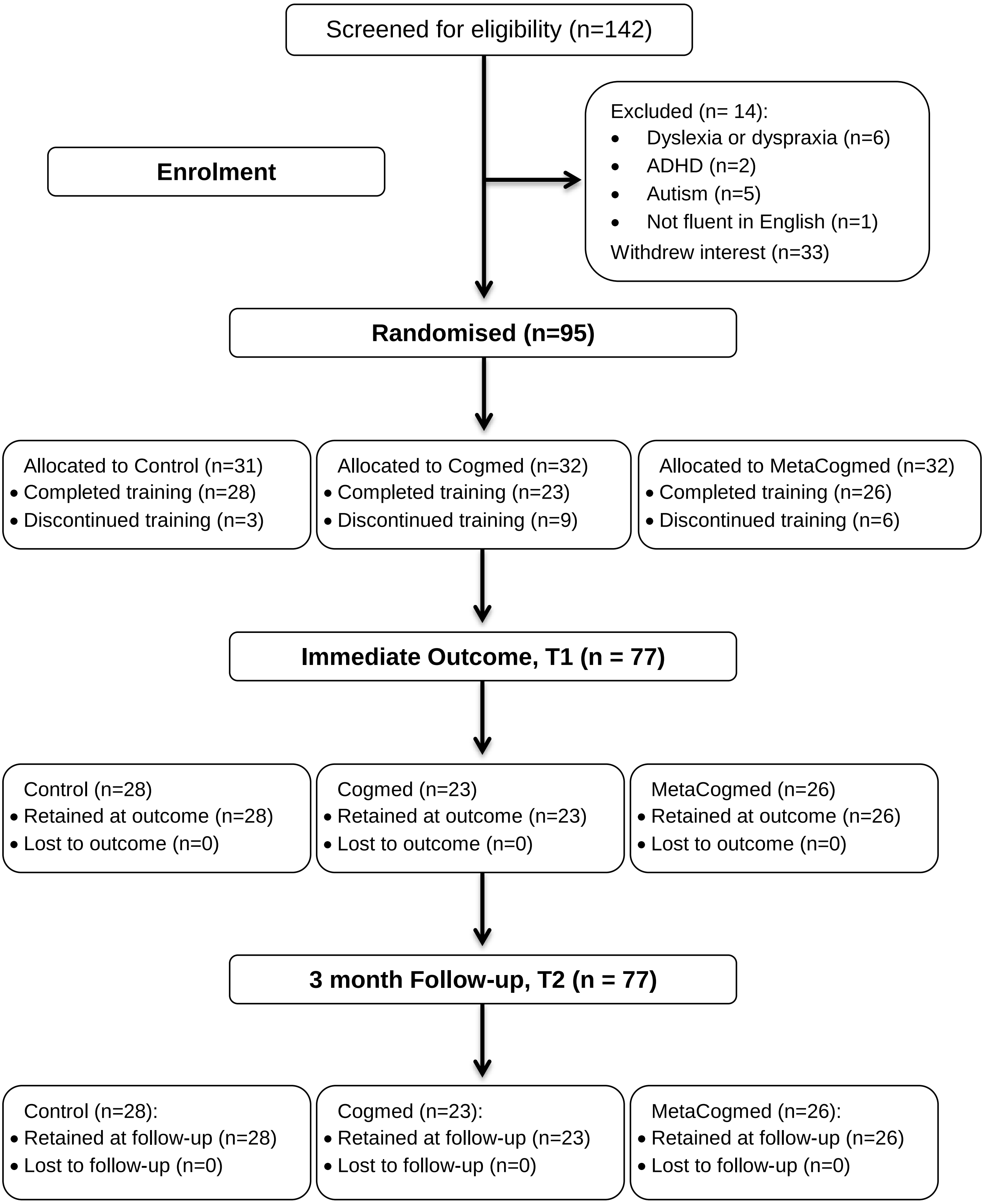

Figure 3.2. CONSORT flow diagram. Note, all available data were used in analysis.

3.3.2. Training Adherence

A total of 77 children finished the training programme: 28 children in the Control group, 26 in the MetaCogmed group, and 23 in the Cogmed group (see Figure 3.2). These children completed between 18 and 24 training sessions (*M* = 20.03, *SD* = 0.76) over an average of five weeks (*M* = 4.99, *SD* = 0.68). Data were collected for all 77 children at immediate outcome and three month follow-up. Eighteen children withdrew from training and no further data were collected at the immediate or three month outcome. This included three children from the Control group, six from the MetaCogmed group, and nine from the Cogmed group. Between the groups there was no significant difference in the number of children that withdrew, $\chi^2(2, N = 95) = 3.49$, $p = 0.175$, or the number of training sessions completed, $F(2, 92) = 1.09$, $p = 0.341$.

3.3.3. Primary Outcome ANCOVA Models

ANCOVAs compared group means at the immediate and three month outcome for each variable. Means were adjusted for baseline scores as the covariate. Adjusted group means, 95% CIs, and mean differences (Δ) are presented in Table 3.2. The adjusted means and 95% CIs are also plotted in Figure 3.3. Scores on the AWMA were significantly greater for the MetaCogmed group compared to the Control group at the immediate ($\eta_p^2 = .313$, $p < 0.001$) and three month outcomes ($\eta_p^2 = .199$, $p < 0.001$). Similarly, scores on the AWMA were significantly greater for the Cogmed group compared to the Control group at the immediate ($\eta_p^2 = .254$, $p < 0.001$) and three month outcomes ($\eta_p^2 = .062$, $p = 0.031$). This indicates that working memory scores in both groups that completed Cogmed training significantly improved relative to the Control group, and this was maintained three months later. No difference in working memory performance was predicted between the Cogmed and MetaCogmed groups at immediate or three month outcome, and these differences did not reach conventional levels of significance. However, at the three month outcome, the MetaCogmed group had higher scores on the AWMA than the Cogmed group with borderline significance (Δ +3.73, 95% *CI*: -0.22 to 7.68, $\eta_p^2 = .046$, $p = 0.06$). This indicates that working memory improvements in the MetaCogmed group were greater than the Cogmed group at three month outcome.

Scores on Mathematical Reasoning were numerically higher for the MetaCogmed and Cogmed groups compared to the Control group at immediate outcome. This difference was significant for the Cogmed group (*p* = 0.019) and at borderline significance for the MetaCogmed group (Δ +3.35, 95% *CI*: -0.13 to 6.83, *p* = 0.059). At the three month outcome, Maths scores were not significantly higher for the MetaCogmed group (*p* = 0.196) or Cogmed group (*p* = 0.24) compared to the Control group. Maths scores did not significantly differ between the MetaCogmed and Cogmed groups at the immediate outcome (*p* = 0.595) or three month outcomes (*p* = 0.939). As Cogmed had a significant effect on Maths scores at the immediate outcome, a combined analysis was conducted to test the difference between both Cogmed groups and the Control group with increased power. The groups that completed Cogmed training had significantly higher Maths scores relative to Control group at the immediate outcome (Δ +3.84, 95% *CI*: 0.77 to 6.9, *p* = 0.015) but not at the three month outcome (Δ +2.58, 95% *CI*: -0.93 to 6.09, *p* = 0.147). This indicates that Cogmed improved Mathematical Reasoning in the short-term.

Table 3.2. ANCOVAs of primary near- and far-transfer outcomes

Outcome variables	Time[1]	N	Control	MetaCogmed	Cogmed	Δ (Control vs. MetaCogmed)	Δ (Control vs. Cogmed)	Δ (MetaCogmed vs. Cogmed)
			Mean (95% CI)	Mean (95% CI)	Mean (95% CI)			
Working memory	2	77	106.30 (104 to 109)	117.17 (114 to 120)	116.00 (113 to 119)	10.86*** (7 to 15)	9.69*** (6 to 14)	1.17 (-3 to 5)
	3	77	107.64 (105 to 110)	115.64 (113 to 118)	111.91 (109 to 115)	8.00*** (4 to 12)	4.27* (0 to 8)	3.73 (0 to 8)
Maths	2	77	102.96 (101 to 105)	106.32 (104 to 109)	107.29 (105 to 110)	3.35 (0 to 7)	4.33* (1 to 8)	-0.98 (-5 to 3)
	3	77	104.94 (102 to 108)	107.60 (105 to 111)	107.43 (104 to 111)	2.66 (-1 to 7)	2.49 (-2 to 7)	0.17 (-4 to 4)
Reading	2	77	107.39 (105 to 110)	108.92 (106 to 112)	106.66 (104 to 109)	1.53 (-2 to 5)	-0.74 (-4 to 3)	2.26 (-2 to 6)
	3	77	109.63 (107 to 112)	110.88 (108 to 113)	107.89 (105 to 111)	1.25 (-2 to 5)	-1.74 (-5 to 2)	2.99 (-1 to 7)

[1]Time:2 = Immediate, Time: 3 = 3-month; *denotes p<0.05, **p<0.01, ***p<0.001

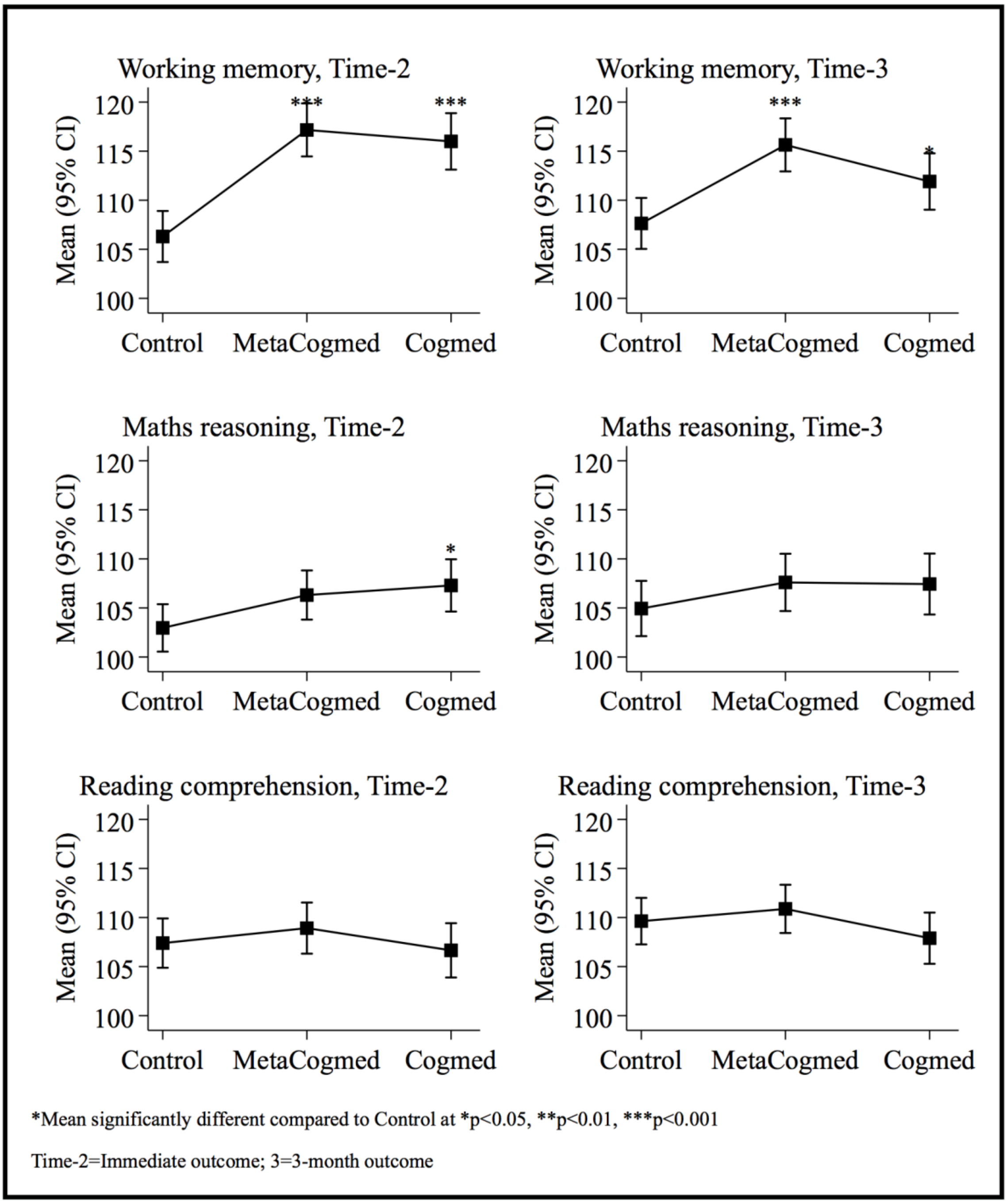

Figure 3.3. Baseline-adjusted group means at immediate and three month outcomes

There were no significant differences in Reading Comprehension across the groups over time. There was no significant difference in Reading Comprehension between the MetaCogmed group and Control group at the immediate (p = 0.404) or three month outcomes (p = 0.47). There was no significant difference in Reading Comprehension between the Cogmed group and Control group at the immediate (p = 0.696) or three month outcomes (p =

0.329). Finally, there was no significant difference in Reading Comprehension between the MetaCogmed group and Cogmed group at the immediate (p = 0.238) or three month outcomes (p = 0.101). This indicates that neither MetaCogmed nor Cogmed improved Reading Comprehension.

3.3.4. Primary Outcome Mixed Models

Random intercept models were developed for each of the outcome variables to segregate the variance due to repeated measures. 'Time x Group' interactions tested the hypotheses that change from one time to another is different for the Cogmed or MetaCogmed compared to the Control group. The log likelihood ratio (LR) test revealed that all models are highly significant compared to a single level model (Working Memory: $\chi^2(4, N = 77) = 83.34$, $p < 0.001$; Maths: $\chi^2(4, N = 77) = 131.12$, $p < 0.001$; Reading: $\chi^2(4, N = 77) = 91.03$, $p < 0.001$), indicating a substantial amount of variance at an individual/upper level attributable to repeated measurements. The resulting coefficients and 95% confidence intervals from the random intercept models are presented in Table 3.3. The estimated means for each group are plotted in Figure 3.4.

Table 3.3. Results from linear random intercept regressions

Variables	**AWMA: Coefficient (CI)**	**Maths: Coefficient (CI)**	**Reading: Coefficient (CI)**
Time: (ref: Baseline-Time1)	—	—	—
[1]Time-2	2.21 (-0.22 to 4.64)	0.34 (-2.33 to 3.01)	4.01** (1.33 to 6.66)
Time-3	3.55** (1.12 to 5.98)	2.27 (-0.4 to 4.94)	6.43*** (3.76 to 9.09)
Randomized (ref: Control)	—	—	—
MetaCogmed	1.43 (-3.58 to 6.44)	2.55 (-2.67 to 7.76)	4.95* (0.15 to 9.74)
Cogmed	1.66 (-3.35 to 6.67)	2.58 (-2.64 to 7.79)	2.17 (-2.63 to 6.96)
Interaction (ref: Baseline x Control)	—	—	—
Time-2 x MetaCogmed	10.66*** (7.17 to 14.15)	2.71 (-1.12 to 6.55)	0.07 (-3.76 to 3.91)
Time-2 x Cogmed	9.22*** (5.62 to 12.81)	3.68 (-0.27 to 7.63)	-1.4 (-5.34 to 2.55)
Time-3 x MetaCogmed	7.82*** (4.33 to 11.31)	2.09 (-1.74 to 5.93)	-0.55 (-4.38 to 3.28)
Time-3 x Cogmed	3.76* (0.17 to 7.36)	1.92 (-2.03 to 5.87)	-2.65 (-6.59 to 1.29)
Interaction (ref: Baseline x Cogmed)			
Time-2 x MetaCogmed	1.45 (-2.21 to 5.10)	-0.97 (-4.97 to 3.04)	1.47 (-2.53 to 5.47)
Time-3 x MetaCogmed	4.06* (0.40 to 7.71)	0.17 (-3.84 to 4.18)	2.10 (-1.90 to 6.10)

[1]Time:2=Immediate, 3=3month; *denotes p<0.05, **p<0.01, ***p<0.001

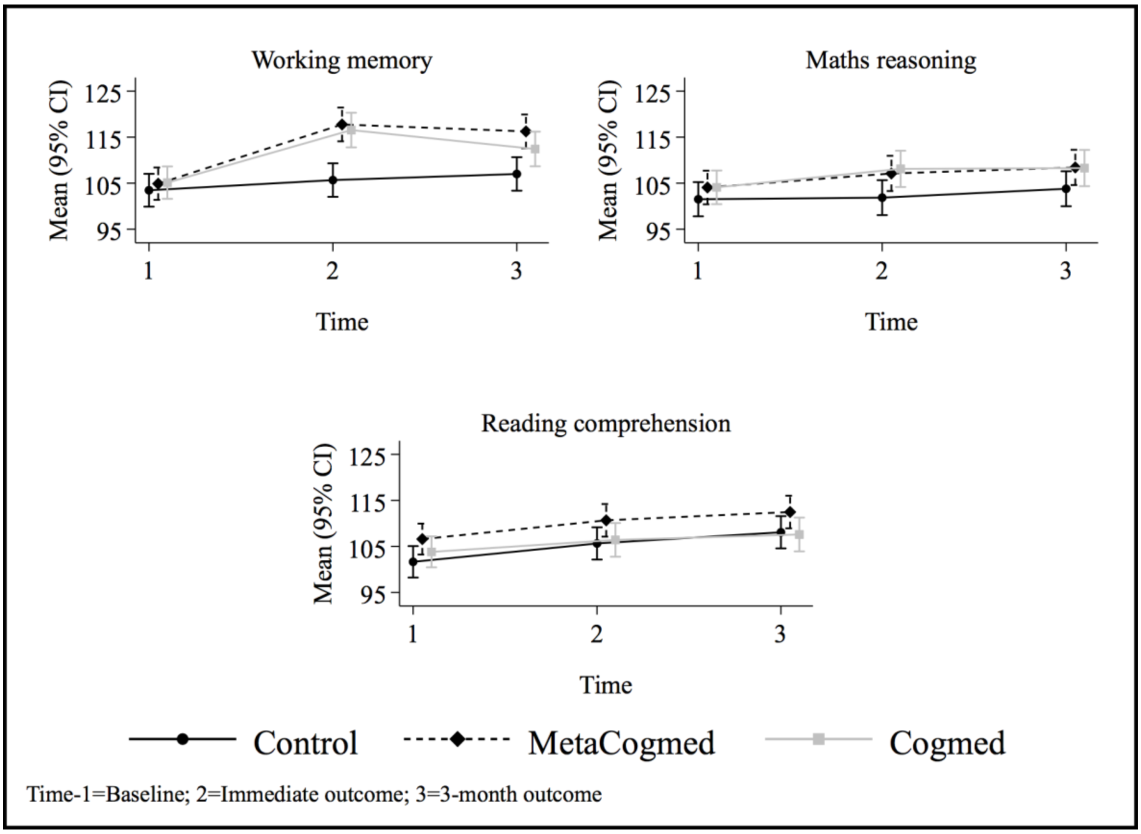

Figure 3.4. Plots of estimated means and 95% confidence intervals.

The results of the Time x Group interactions from the random intercept models are presented for each variable in Table 3.3. Scores on the AWMA significantly increased in the MetaCogmed group compared to the Control group at the immediate ($p < 0.001$) and three month outcomes ($p < 0.001$). Similarly, scores on the AWMA significantly increased in the Cogmed group compared to the Control group at the immediate ($p < 0.001$) and three month outcomes ($p = 0.04$). Improvements on the AWMA were significantly greater in the MetaCogmed group compared to the Cogmed group at the three month outcome ($p = 0.03$), but not at the immediate outcome ($p = 0.438$). Although the Cogmed group showed a greater decline in AWMA scores than the MetaCogmed group from the immediate to three month outcome, this was not significant (Δ +2.61, *CI*: -1.09 to 6.31, $p = 0.17$). The findings reaffirm the results of the ANCOVA models, indicating that MetaCogmed and Cogmed improved working memory at the immediate and three month outcomes, but that the improvement at three months was greater for MetaCogmed.

Scores on Mathematical Reasoning showed a numerical increase over time for the Cogmed and MetaCogmed groups relative to the Control group, but these differences were not statistically significant (see Table 3.3). In the MetaCogmed group Maths scores did not significantly improve at the immediate (p = 0.166) or three month outcomes compared to the Control group (p = 0.285). Relative to the Control group, the improvement in Maths scores for the Cogmed group was at borderline significance (p = 0.068), but not significant at the three month outcome (p = 0.34). The improvements in Maths scores for the MetaCogmed and Cogmed groups did not significantly differ at the immediate (p = 0.637) or three month outcomes (p = 0.935). The results indicate that Cogmed may have improved Mathematical Reasoning at the immediate outcome but not at the three month outcome.

Scores on the Reading Comprehension significantly increased for all groups at the immediate (p = 0.003) and three month outcomes ($p < 0.001$), but there were no significant differences between the groups over time (see Table 3.3 and Figure 3.4). Reading scores did not significantly improve in the MetaCogmed group compared to the Control group at the immediate (p = 0.97) and three month outcomes (p = 0.779). Similarly, reading scores did not significantly improve in the Cogmed group compared to the Control group at the immediate (p = 0.488) and three month outcomes (p = 0.188). Finally, the improvements in reading scores did not significantly differ between the MetaCogmed and Cogmed groups at the immediate (p = 0.472) and three month outcomes (p = 0.303). The results indicate that neither MetaCogmed nor Cogmed improved Reading Comprehension at the immediate or three month outcome.

3.3.5. Secondary Near-Transfer Outcomes

Exploratory analyses were conducted to examine the extent of near-transfer to the individual working memory tasks using ANCOVAs and mixed models. The adjusted group means, 95% CIs, and mean differences (Δ) from the ANCOVAs are presented in Table 3.4. The adjusted means are also plotted in Figure 3.5. At the immediate outcome, the MetaCogmed group had significantly higher scores on the Dot Matrix (p = 0.009), Backwards Digit Recall

($p < 0.001$), Digit Recall ($p = 0.001$), and Spatial Span tasks ($p = 0.006$) compared to the Control group. At the three month outcome, the MetaCogmed group had significantly higher scores on the Backwards Digit Recall ($p < 0.001$) and Digit Recall tasks ($p = 0.003$) compared to the Control group, and the comparison for the Spatial Span task was at borderline significance ($p = 0.055$). At the immediate outcome, the Cogmed group had significantly higher scores on the Dot Matrix ($p = 0.001$), Digit Recall ($p < 0.001$) and Backwards Digit Recall tasks ($p = 0.001$) compared to the Control group. At the three month outcome, the Cogmed group had significantly higher scores on the Digit Recall task ($p = 0.04$) compared to the Control group, and the comparison for the Backwards Digit Recall task was at borderline significance ($p = 0.063$). This indicates that MetaCogmed improved performance on all four near-transfer tasks and these improvements were maintained for three of these tasks three months later. Cogmed improved performance on three near-transfer tasks and this was maintained for two tasks three months later.

In comparison of the MetaCogmed and Cogmed groups, the MetaCogmed group performed significantly higher on the Spatial Span task at immediate outcome ($p = 0.027$) and the Backwards Digit Recall task at three month follow-up ($p = 0.01$). This indicates that the MetaCogmed group showed greater improvements on the Spatial Span task in the short-term and Backwards Digit Recall task after three months.

Table 3.4. ANCOVAs of secondary near-transfer outcomes

Outcome variables	Time[1]	N	Control	MetaCogmed	Cogmed	Δ (Control vs. MetaCogmed)	Δ (Control vs. Cogmed)	Δ (MetaCogmed vs. Cogmed)
			Mean (95% CI)	Mean (95% CI)	Mean (95% CI)			
Dotmatrix	2	77	108.27 (103 to 114)	118.97 (113 to 125)	122.11 (116 to 128)	10.71** (3 to 19)	13.85** (6 to 22)	-3.14 (-12 to 5)
	3	77	114.54 (108 to 121)	117.15 (111 to 124)	114.25 (107 to 121)	2.61 (-6 to 11)	-0.29 (-9 to 9)	2.90 (-6 to 12)
Back digit	2	77	102.22 (98 to 106)	116.91 (113 to 121)	112.51 (108 to 117)	14.69*** (9 to 21)	10.29** (4 to 16)	4.40 (-2 to 11)
	3	77	102.53 (98 to 107)	117.72 (113 to 122)	108.82 (104 to 114)	15.19*** (9 to 22)	6.29 (0 to 13)	8.90** (2 to 16)
Spatial span	2	77	113.27 (109 to 118)	121.89 (118 to 126)	114.59 (110 to 119)	8.62 (3 to 15)**	1.32 (-5 to 8)	7.30* (1 to 14)
	3	77	111.37 (107 to 116)	117.97 (113 to 123)	116.72 (112 to 122)	6.60 (0 to 13)	5.34 (-2 to 12)	1.26 (-6 to 8)
Digit recall	2	77	101.98 (98 to 106)	111.41 (107 to 115)	113.55 (109 to 118)	9.43*** (4 to 15)	11.57*** (6 to 17)	-2.14 (-8 to 4)
	3	77	102.17 (99 to 106)	109.92 (106 to 113)	107.52 (104 to 111)	7.75** (3 to 13)	5.35* (0 to 10)	2.40 (-3 to 8)

[1]Time:2=Immediate, 3=3month; *denotes p<0.05, **p<0.01, ***p<0.001

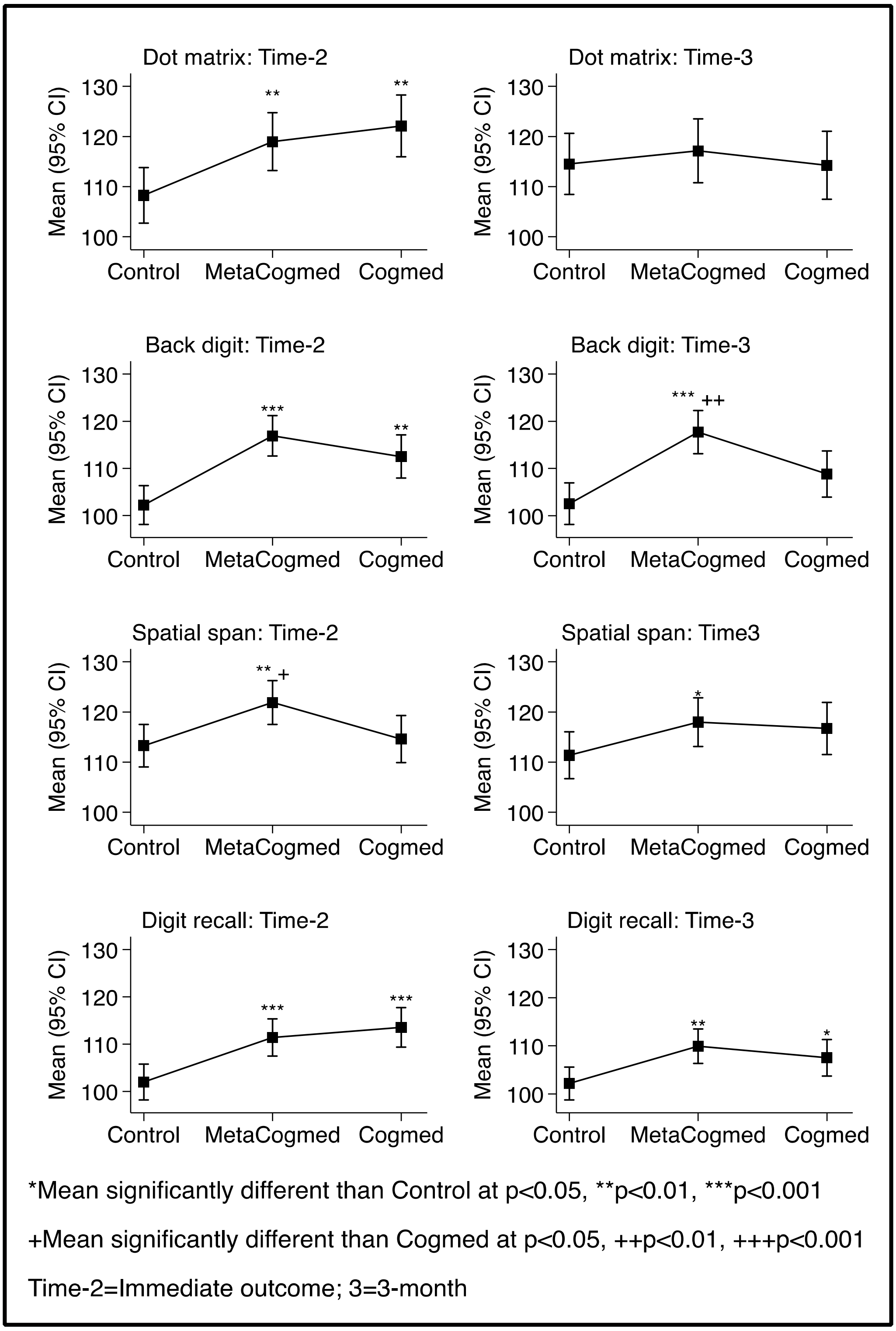

Figure 3.5. Baseline adjusted group means for secondary near-transfer outcomes

The coefficients and CIs from the Mixed Models are presented in Table 3.5 and the estimated means are plotted in Figure 3.6. The Time x Group interactions tested the hypotheses that change from one time to another is different between the groups. Similar to the ANCOVAs the mixed models showed that the MetaCogmed group significantly improved on the Dot Matrix ($p = 0.01$), Digit Recall ($p < 0.001$), Spatial Span ($p = 0.028$), and Backwards Digit Recall tasks ($p < 0.001$) at the immediate outcome, compared to the Control group. The Cogmed group significantly improved on the Dot Matrix ($p = 0.002$), Digit Recall ($p < 0.001$), and Backwards Digit Recall tasks ($p = 0.009$) at the immediate outcome, compared to the Control group. The MetaCogmed group significantly improved on the Digit Recall ($p = 0.002$) and Backwards Digit Recall tasks ($p < 0.001$) at the three month outcome, compared to the Control group. Finally, the Cogmed group significantly improved performance on the Digit Recall task ($p = 0.045$) at the three month outcome, compared to the Control group. This indicates that MetaCogmed improved performance on all four near-transfer tasks at the immediate outcome, which was maintained at the three month outcome for two tasks. Cogmed alone improved performance on all three near-transfer tasks at the immediate outcome, which was maintained at the three month outcome for one task. In comparison of the MetaCogmed and Cogmed groups, the MetaCogmed group showed significantly greater improvement on the Backwards Digit Recall task at the three month outcome ($p = 0.001$).

Table 3.5. Mixed model results for secondary near-transfer outcomes

Variables	Dot Matrix: coefficient (CI)	Back Digit: coefficient (CI)	Spatial Span: coefficient (CI)	Digit Recall: coefficient (CI)
Time: (ref: Baseline-Time1)	—	—	—	—
[1]Time-2	4.52 (-1 to 10)	0.02 (-4 to 4)	4.47 (0 to 9)	0.56 (-3 to 4)
Time-3	10.8*** (5 to 16)	0.58 (-4 to 5)	2.78 (-2 to 8)	0.76 (-3 to 4)
Randomized (ref: Control)	—	—	—	—
MetaCogmed	0.72 (-7 to 8)	0.67 (-6 to 8)	2.49 (-5 to 10)	1.83 (-5 to 9)
Cogmed-group	0.39 (-7 to 8)	6.4 (-1 to 14)	-0.23 (-7 to 7)	0.07 (-7 to 7)
Interaction (ref: Baseline x Control)	—	—	—	—
Time-2 x MetaCogmed	10.7** (3 to 19)	14.47*** (8 to 21)	7.65* (1 to 14)	9.4*** (5 to 14)
Time-2 x Cogmed	13.18** (5 to 22)	8.54** (2 to 15)	1.74 (-5 to 9)	11.36*** (6 to 16)
Time-3 x MetaCogmed	2.66 (-5 to 11)	14.97*** (9 to 21)	5.54 (-1 to 12)	7.69** (3 to 13)
Time-3 x Cogmed	-1.03 (-9 to 7)	3.69 (-3 to 10)	5.2 (-2 to 12)	5.15* (0 to 10)
Interaction (ref: Baseline x Cogmed)				
Time-2 x MetaCogmed	-2.48 (-11 to 6)	5.92 (-1 to 12)	5.91 (-1 to 13)	-1.97 (-7 to 3)
Time-3 x MetaCogmed	3.69* (-5 to 12)	11.28*** (5 to 18)	0.33 (-7 to 7)	2.53 (-3 to 8)

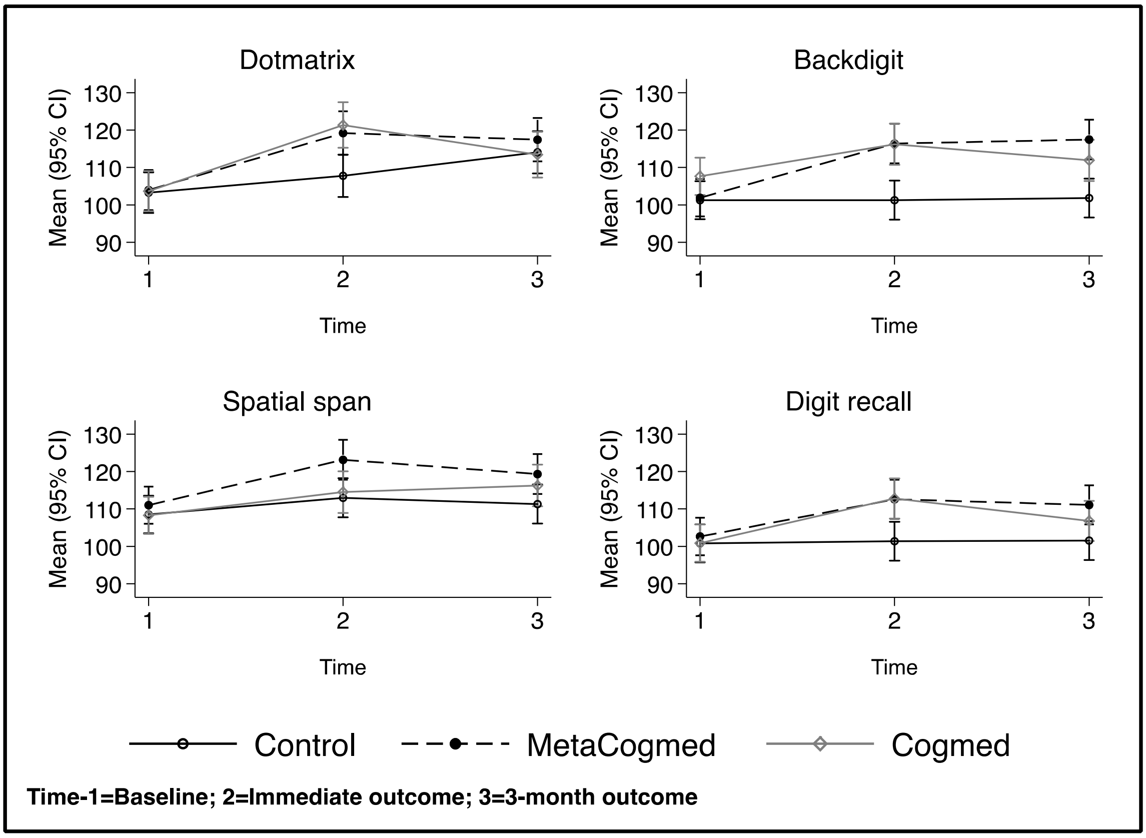

Figure 3.6. Estimated means from mixed models for secondary near-transfer outcomes

3.4. Discussion

The present study examined the effectiveness of MetaCogmed, a novel combination of Cogmed and metacognitive strategy training, which was designed to facilitate far-transfer to academic achievement. The effects of MetaCogmed and Cogmed were investigated immediately and three months after training, in comparison to an adaptive control group. Overall, the results suggested that both MetaCogmed and Cogmed improved working memory performance at the immediate and three month outcomes, and there was some evidence for immediate improvements in Mathematical Reasoning. There was no evidence that MetaCogmed or Cogmed improved Reading Comprehension relative to the adaptive control group. Lastly, there was no evidence that MetaCogmed facilitated far-transfer to academic achievement, when compared to Cogmed. However, there was some evidence that MetaCogmed facilitated near-transfer at the immediate and three month outcome.

It was predicted that both MetaCogmed and Cogmed would improve working memory performance more than an adaptive control, and that this effect would be maintained three months later. In strong support of this hypothesis, the results from the ANCOVAs and Mixed Models provided consistent evidence that MetaCogmed and Cogmed improved scores on the AWMA immediately and three months after training, compared to the control group. This is the first study in children to investigate near-transfer in comparison to an adaptive control. The results are broadly consistent with adult working memory training studies that have reported near-transfer when compared to adaptive visual search training (Harrison et al., 2013; Covey et al., 2016) and adaptive general knowledge training (Anguera et al., 2012). The findings are also consistent with other Cogmed (see Chapter 2; Astle et al., 2015) and working memory training studies (Sala & Gobet, 2017) in typically developing children that reported near-transfer compared to non-adaptive control groups. The evidence suggests that Cogmed improved children’s working memory performance immediately and three months after training. Importantly, these findings cannot easily be attributed to expectation and motivation effects because the control group were continually challenged during training and they received feedback on their improvement.

It was predicted that MetaCogmed would facilitate far-transfer to Mathematical Reasoning and Reading Comprehension, by teaching children metacognitive strategies that can be used across contexts. The ANCOVA revealed that Mathematical Reasoning was higher for the MetaCogmed group compared to the adaptive control group at immediate outcome, however this was only at borderline significance and there was no difference at the three month follow-up. This result tentatively suggests that MetaCogmed may have improved Mathematical Reasoning immediately after training. However, the mixed models indicated that Mathematical Reasoning in the MetaCogmed group did not improve significantly more than the adaptive control group at the immediate or three month outcomes. Both the ANCOVA and mixed models indicated that MetaCogmed did not significantly improve Reading Comprehension compared to the adaptive control group at the immediate or three month outcomes. Finally, MetaCogmed did not improve Mathematical Reasoning or Reading Comprehension significantly more than Cogmed at the immediate or three month outcome. Therefore, there was no evidence that metacognitive training facilitated far-transfer of working memory training to Mathematical Reasoning or Reading Comprehension.

A previous investigation of combined working memory and metacognitive training found significant improvement in children’s reading comprehension when compared to simple practice on reading comprehension exercises alone (Caretti et al., 2014). However, the training group also received instruction in reading strategies and there is extensive evidence for the efficacy of reading comprehension strategies in educational interventions (Higgins et al., 2016; National Reading Panel, 2000). Furthermore, the training group also received instruction in how to integrate information between texts and with pictures. Therefore, it is unclear whether working memory and metacognitive training contributed to the improvement in reading comprehension. This is important because whilst specific training in reading skills and strategies may benefit reading comprehension, the benefits are unlikely to transfer to other domains (Bailey et al., 2008; Lustig et al., 2009). The real potential of working memory and metacognitive training is to enhance core cognitive capacity and develop metacognitive awareness that will aid children’s approach, engagement, and learning in a variety of situations.

Unexpectedly, the ANCOVA provided statistical evidence that Cogmed improved Mathematical Reasoning immediately after training, compared to the adaptive control group. This was also significant when comparing the two groups that received Cogmed (MetaCogmed and Cogmed alone) to the adaptive control group. The mixed models showed similar effects, however they did not reach conventional levels of significance. The ANCOVAs were the primary analysis of immediate transfer effects because they have greater statistical power than the mixed models (Vickers & Altman, 2001). Therefore, this result suggests that Cogmed may improve typically developing children's mathematical reasoning ability in the short-term. Short-term improvements in maths ability have also been reported in a meta-analysis of 17 working memory training studies in typically developing children (Sala & Gobet, 2017); however, this was not significant when only considering studies with active control groups. This may indicate that the effects reported in studies with passive control groups are confounded by expectation and motivation effects, although it could indicate a lack of power to detect an effect in the 11 studies with active control groups. In fact, some studies reported far-transfer to maths when compared to education as usual but no far-transfer when compared to maths training (Kuhn & Holling, 2014; Passolunghi & Costa, 2016). However, this is not a suitable control to estimate the effects of working memory training on academic outcomes because maths training also improved children's maths ability.

Mathematical reasoning was selected as an appropriate measure of far-transfer because it primarily includes word problems and arithmetic, which are more strongly associated with working memory capacity (Peng et al., 2015). The idea that working memory training may be more likely improve certain aspects has been investigated in one study (Kuhn & Holling, 2014). Working memory training did not significantly improve arithmetic or geometry compared to education as usual, but there was a marginally significant improvement in word problem solving. Using the same measure of mathematical reasoning as the current study, there is some previous evidence of far-transfer. Cogmed was associated with improved mathematical reasoning in children with poor working memory six months after training (Holmes et al., 2009). However, it should be noted that a replication found no improvements in mathematical reasoning immediately or 12 months after Cogmed in a larger randomised controlled trial, compared to non-adaptive training (Dunning et al., 2013). While this suggests that working memory training did not improve maths ability, there were significant training effects in the non-adaptive control group, which may explain the absence of a significant difference. Specifically, non-adaptive training was associated with significant improvements in working memory compared to education as usual, and so it is also possible that there was some far-transfer to maths.

A recent randomised controlled trial of Cogmed in typically developing children reported no evidence of far-transfer to a mixed assessment of maths ability compared to non-adaptive training (Hitchcock & Westwell, 2017). However, maths scores were found to improve in the non-adaptive control group at the immediate outcome. This may have been due to a small training effect, as discussed above, or regression to the mean because children in this group had significantly lower scores at baseline compared to the other groups. The present study does not have the same limitations because maths scores were equivalent at baseline and the control group received no working memory training. Furthermore, because children completed training after school they did not miss any school lessons, which may have been the cause of a decline in maths ability in a previous randomised controlled trial (Roberts et al., 2016). The mixed evidence for far-transfer to maths may suggest that working memory training has a small effect on certain components of maths, but that this may be obscured by control groups that also train working memory or maths skills. This finding will need to be replicated in future research utilising adaptive control groups. Future studies should also consider the type of training programme, training duration, level of supervision, and location of training, which significantly moderate the effects of working memory training (Schwaighofer et al., 2015).

There was no statistical evidence that Cogmed or MetaCogmed benefited children’s Reading Comprehension. One previous study found that Cogmed improved children’s performance on a reading and spelling test 24 months after training, compared to education as usual (Söderqvist & Bergman-Nutley, 2015). This may suggest that Cogmed improved spelling or certain components of reading that were not measured in the present study. However, this could also be an effect of increased expectations or motivation in the training group. The absence of an improvement in reading comprehension is consistent with the only other randomised controlled trial of Cogmed in typically developing children (Hitchcock & Westwell, 2017). The present study extends upon these findings by demonstrating an absence of far-transfer to reading comprehension even where there is significant near-transfer. Similar null effects on reading skills have been reported in a meta-analysis of 17 working memory training studies with typically developing children (Sala & Gobet, 2017). Actively controlled studies have also reported null effects on reading skills in children with ADHD (Chacko et al., 2014) and poor working memory (Holmes et al., 2009; Dunning et al., 2013; Roberts et al., 2016). Overall, the most reliable available evidence suggests that working memory training does not benefit children's reading abilities. In the present study it was clear that all groups showed similar improvements on Reading Comprehension over time, which could be suggestive of test-retest effects. Anecdotally, the children often reported that they remembered the passages from the previous assessment. On the second and third readings, it is likely that memory of the passages aided children's comprehension. This is in contrast to the AWMA and Mathematical Reasoning where the adaptive control group showed no improvement over time.

The primary analyses revealed unexpected evidence for superior near-transfer effects in the MetaCogmed group compared to the Cogmed group. The mixed models indicated that overall performance on the AWMA increased significantly more in the MetaCogmed group compared to the Cogmed group at the three month follow-up. The ANCOVA revealed a comparable effect, although this was at borderline significance. This tentatively suggests that metacognitive training may have facilitated greater near-transfer longer term. It is possible that metacognitive training enabled children to better apply the cognitive gains of training in everyday life and that these were maintained through more frequent use. However, there was also evidence for significantly greater near-transfer to the Spatial Span task in the MetaCogmed group compared to the Cogmed group at the immediate outcome, suggesting that the effects of metacognitive training may have been more immediate. It may be possible that children were more metacognitively aware of how they were performing the working memory training and assessment tasks, which could have facilitated the identification, retrieval, and application of memory strategies. Alternatively, metacognitive strategies may have facilitated performance at the immediate and three month outcomes, whereas cognitive gains faded over time.

Secondary analyses were conducted to investigate the extent of near-transfer from the Cogmed training tasks to the individual AWMA tasks. The findings from the ANCOVAs and Mixed Models were largely consistent. The MetaCogmed group showed significant near-transfer to all four working memory tasks, which was maintained for two or three tasks, three months after training. The Cogmed group showed significant near-transfer for three working memory tasks, which was only maintained for the Digit Recall task three months after training. Both groups improved on the Backwards Digit Recall and Dot Matrix tasks that are very similar to the Input module and Visual Data Link training tasks, respectively. Near-transfer was expected to be greatest for these AWMA tasks, as they afford the same strategies as the training tasks. Both groups improved on the Digit Recall task, which was maintained three months later. No Cogmed task trains forwards digit recall, but the Input Module task requires backwards digit recall where similar rehearsal or grouping strategies may be used to encode the stimuli. Finally, there was least near-transfer to the Spatial Span task, which is arguably the least similar to any individual training task. However, Cogmed does include training tasks that require visuospatial short-term memory and mental rotation, including the Rotating Data Link and Rotating Dots tasks. Therefore, it is possible that the strategies used on these tasks were transferable to the Spatial Span. However, it is also possible that increased working memory capacity explains these specific near-transfer effects, and that power may have been limited to detect effects on each individual AWMA task.

3.4.1. Strengths, Limitations, and Future Directions

This was the first investigation of working memory training in children to examine near-transfer and far-transfer to academic achievement, in comparison to an adaptive control group. This is a major strength because the control group were challenged during training and they received feedback as they improved on the training tasks. Therefore, this should provide a better control for expectations and motivation, which may confound training effects. There is also less chance that adaptive visual search training will effect working memory performance, whereas non-adaptive working memory training has been associated with small improvements (Dunning et al., 2013), that may obscure the effects of adaptive working memory training.

The adaptive visual search training included a narrative, colour scheme, feedback, and high scores to match features of Cogmed. There were no significant difference in the number of training sessions completed or number of withdrawals across the groups, suggesting that training adherence was similar. However, there were still differences between the training programmes that may affect children's engagement or enjoyment. For instance, Cogmed includes a variety of training tasks on rotation, whereas the visual search training only includes one task. Cogmed provides spoken instructions and feedback, whereas it is written in the visual search training. Furthermore, performance on Cogmed is rewarded with tokens for the Robo Racing game at the end of each session, whereas the visual search has no additional game at the end. These features may make Cogmed more engaging, which could improve outcomes. Therefore, it is recommended that future research build upon the adaptive control by incorporating additional training tasks, such as word search and Tetris, verbal feedback, and tokens that can be spent on playing a fun game at the end of training.

The metacognitive workbook was a novel intervention that drew from existing metacognitive interventions in education (see Fisher, 1998a, for a review) and paediatric neurorehabilitation (e.g. Butler & Copeland, 2002; Sohlberg et al., 2014). Children were primarily taught how to plan, monitor, and evaluate, and to reflect on their thinking, which are fundamental components of metacognitive interventions in education (Dignath & Büttner, 2008). MetaCogmed was designed to fit into hourly whole-classroom sessions that would be feasible for a school to implement after school, during lunch, or in place of a non-statutory lesson. The workbook afforded a standard delivery of metacognitive strategy instruction for a whole classroom that could be conducted by one or two teachers. Furthermore, the workbooks could be regularly checked for comprehension and progress, and extra support was provided to children who had difficulties engaging with the material.

The metacognitive workbook also differed to established metacognitive interventions, which may explain the absence on far-transfer. Metacognitive training was limited to approximately 15 minutes per session and split across working memory, mathematical reasoning, and reading comprehension. This may not have been enough time for children to foster metacognitive awareness and the activities may have been too narrow to encourage generalisation. Other interventions have prescribed much more extensive training; for example, Thinking Science includes 30 one-hour sessions (Adey & Shayer, 1993). Thinking Science is also more interactive, involving group work and discussion with the teacher. Similarly, metacognitive interventions in neurorehabilitation have prescribed one-to-one to support with a clinician (e.g. Butler & Copeland, 2002). Children may have found the workbooks less engaging and they had fewer opportunities to learn from each other, as the workbooks were completed independently. Coaches were able to offer some individual support by scaffolding children's metacognitive reflection and checking children's answers for depth of understanding. However, the MetaCogmed group received little guidance as a class, because they were mixed with the two other training groups. The metacognitive training may have been more engaging if the whole class were receiving the intervention as this would afford teacher instruction, group work, and the independent workbooks.

The 3x1 design in the current study afforded investigation of whether Cogmed was superior to an adaptive control group and whether MetaCogmed was superior to an adaptive control group or Cogmed alone. These were the two primary questions of the trial because they could inform us whether existing working memory training programmes for children are effective and whether they can be improved. However, interpretation of the specific effects of the metacognitive workbook is limited because it was paired with Cogmed but not with the adaptive control group. A full-factorial design, including a group that received adaptive visual search training and the metacognitive workbook, would have afforded examination of whether the metacognitive workbook alone improved children's working memory, mathematical reasoning, and reading comprehension. It was not feasible to recruit an adequate number of children for a 2x2 design in the current study, but this may be an important question for future studies in order to determine whether metacognitive strategy training can be delivered as an effective educational intervention in a workbook format, which may be used alone or in combination with other intervention components.

A further limitation was that there was no examination of children's metacognitive awareness and regulation. Therefore, it was not possible to determine whether MetaCogmed fostered metacognitive awareness or strategies. Children were asked to complete the Metacognitive Awareness Inventory (MAI; Schraw & Dennison, 1994); however, the data were lost for one of the participating schools (n = 19) at baseline and immediate outcome. This meant that the analysis would have limited power and would not accurately reflect the whole sample. Furthermore, as the MAI is self-report, the children's responses would have been subject to bias. They may be more likely to recognise key words from their workbook and more likely to respond positively, simply because they have been instructed to be more aware of their thinking and to self-regulate using metacognitive strategies. It is recommended that future research investigates task-based measures of metacognition, such as post-task appraisal of difficulty (Krasny-Pacini et al., 2015), or parent-report measures, such as the Behaviour Rating Inventory of Executive Function (Gioia & Isquith, 2011), which may be less susceptible to bias.

3.4.2. Conclusion

Working memory training is an effective intervention to boost working memory performance in typically developing children. It also shows some promise at improving children's academic outcomes in maths in the short-term. Future studies will need to confirm whether working memory training can improve children's mathematical reasoning ability when it is provided in addition to school and compared against an adaptive control group. Future studies should also examine the generalisability of these academic improvements and how they can be maintained longer term. Metacognitive training may have facilitated near-transfer effects, which were better maintained three months after training. However, more time and greater instructional support may be required to foster metacognitive awareness and the effective use of strategies on maths and reading exercises at school.

Chapter 4: Investigating the neural correlates of working memory strategies in children.

4.1. Introduction

Chapters 2 and 3 aimed to increase children's working memory capacity through intensive practice-based training. However, working memory training typically ignores the role of strategy-use in performance on working memory tasks (Jaeggi et al., 2008; Klingberg et al., 2005; although see St Clair-Thompson et al., 2010; Witt, 2011). This is important considering that working memory capacity is significantly associated with strategy-use (Bailey et al., 2008, 2011; Dunlosky & Kane, 2007) and that working memory training has been shown to increase the use of grouping strategies (Dunning & Holmes, 2014). Therefore, performance improvements may be achieved in less time and at less expense by teaching children to use effective memory strategies. This chapter investigates whether children can recall more information when using a grouping strategy, whether grouping can be transferred to a novel task, and what neural processes are associated with this strategy. The study has implications for understanding the mechanisms of working memory training, current theories regarding the relationship between strategy-use and working memory capacity, and accounts of temporal grouping in models of short-term memory.

4.1.1. Training Capacity and Strategy

Transfer effects of working memory training may be mediated by capacity, strategy, or both (von Bastian & Oberauer, 2014). Chapter 2 presented evidence that working memory training increased resting-state functional connectivity within the dorsal attention network and Chapter 3 presented some evidence for far-transfer to mathematical reasoning. These findings cannot easily be explained by the acquisition of memory strategies, as they would not be expected to generalise to structurally different tasks (Bailey et al., 2008; Lustig et al., 2009) or affect brain activity at rest. However, there is otherwise a lack of evidence for far-transfer effects when considering studies with active control groups in typically developing children (Hitchcock & Westwell, 2017; Sala & Gobet, 2017b), children with low working memory capacity (Ang et al., 2015; Dunning et al., 2013; Roberts et al., 2016), and children with ADHD (Chacko et al., 2014; Cortese et al., 2015). Furthermore, near-transfer effects are less consistent on working memory tasks that are structurally dissimilar to training (see Simons et al., 2016, for a review). When the tasks are structurally similar, near-transfer effects are typically larger and more consistent (e.g. Chapter 2 & 3; Simons et al., 2016), which may result from increased use of grouping or other strategies (Dunning & Holmes, 2014). In summary, working memory training may be increasing capacity and the use of memory strategies.

The effects of strategy on working memory performance can be more precisely estimated by examining the effects of strategy instruction on short-term and working memory tasks (see Section 1.5. for a review). Chapter 3 provided some evidence that metacognitive strategy training facilitated near-transfer effects of working memory training. Studies have also shown that children can recall more information when they have been instructed to use rehearsal (Asarnow & Meichenbaum, 1979), imagery (Pressley & Levin, 1977), or a semantic sorting strategy (Schleepen & Jonkman, 2012), provided that children have sufficiently developed cognitive capacity to use that strategy (Guttmann et al., 1977). However, studies have yet to investigate whether children can transfer these strategies to untrained tasks and whether instructing children to use grouping improves recall. Grouping may be partly responsible for near-transfer effects of working memory training because it has been shown to be increasingly used after training (Dunning & Holmes, 2014). Therefore, instructing children to group may also improve recall and it could be achieved in much less time than typical working memory training programmes. Furthermore, this approach would isolate the effects of strategy from the effects of task practice, providing valuable insights into the possible mechanisms of near-transfer.

4.1.2. Grouping and Rehearsal in Models of Short-term Memory

Grouping has been investigated experimentally by manipulating the timing of stimulus presentation so that there is a longer pause in between groups of items in a sequence (see Section 1.5.2.). These temporally grouped lists are typically easier to recall than ungrouped lists (Hitch et al., 1996; Ryan, 1969a, 1969b; Towse et al., 1999). Early accounts of the temporal grouping effect suggested that it was a product of rehearsal (Ryan, 1969b), which is accountable within the function of the phonological loop (Baddeley & Hitch, 1974; Repovš & Baddeley, 2006). Accordingly, studies have shown that instructing individuals to group items together during rehearsal improves recall (Farrell, 2008; Farrell et al., 2011; Wickelgren, 1964). However, these findings are not consistent (e.g. Ryan, 1969a), and have been confounded by practice and expectation effects in within-subjects experiments without a control group or counterbalancing (Farrell, 2008; Farrell et al., 2011). Furthermore, previous studies compared grouping to single item repetition, rather than sequential rehearsal (Wickelgren, 1964). Therefore, it is not currently clear whether grouping instructions improve recall over sequential rehearsal, which is the most commonly reported strategy on short-term and working memory tasks in adults (Morrison et al., 2016).

Alternative accounts suggests that the temporal grouping effect is a product of the timing of stimulus presentation (Frick, 1989; Hitch et al., 1996). This is supported by evidence that the temporal grouping effect persists under articulatory suppression, where sub-vocal rehearsal should be unavailable (Frick, 1989; Hitch et al., 1996). One account within a connectionist model of verbal short-term memory (see Section 1.5.1.) suggests that grouped sequences are associated with a first set of timing signals that codes for the order of a stimulus within the whole sequence and an additional set of timing signals that codes for the order of a stimulus within its group (Hitch et al., 1996). Furthermore, it was suggested that strategic grouping of ungrouped lists may also invoke an additional set of timing signals that facilitates recall. However, strategic grouping may involve additional processes as it requires effortful division of the stimulus set.

4.1.3. The Development of Rehearsal and Grouping

Early accounts of rehearsal suggested that young children are less strategic because either they do not benefit from verbalising items to be remembered, i.e. a mediational deficiency, or they do not produce the verbal mediators at the appropriate time, i.e. production deficiency. Early experiments demonstrated that young children aged five to six years do not verbalise the objects to be remembered in a serial recall task, although they could name the objects when asked (Flavell, Beach, & Chinsky, 1966). Older children showed more instances of verbalisation with age, reported more instances of rehearsal, and showed corresponding increases in recall performance. Coding of verbalisations in 10 to 11 year old children was reasonably consistent with children's self-reports of rehearsal, however the experimenter did not observe verbalisations in some children that convincingly reported using rehearsal. Self-reports may be a more reliable measure of strategy-use because verbalisations may have been missed by the experimenter or the children may have been subvocally rehearsing. It was suggested that young children who did not produce verbalisations or report rehearsal had a production deficiency, i.e. that they did not produce the verbal mediators at the appropriate time. Yet it may be possible that these children would not benefit from using a rehearsal strategy, i.e. that they had a mediational deficiency.

Experiments with children aged six to seven years old showed that children who generally rehearsed the names of objects, 'rehearsers', in a serial recall task recalled more items than those that generally did not rehearse, 'non-rehearsers' (Keeney, Cannizzo, & Flavell, 1967; Kennedy & Miller, 1976). When non-rehearsers were trained to name the objects during presentation and rehearse them during the delay, their recall performance improved and was indistinguishable from rehearsers. This suggests that the children were production deficient, because they failed to produce the verbal mediators spontaneously but they did benefit from using them when instructed to do so. Furthermore, when non-rehearsers were given the option to continue using the strategy or not, they tended to abandon the strategy and recalled less items from memory. This may be because children did not recognise the value of rehearsal and so they did not invest the mental effort to use this strategy. Interestingly, in a further condition, when non-rehearsers were given explicit feedback about the benefit of rehearsal after training they continued to use rehearsal when given the option (Kennedy & Miller, 1976). On the other hand, children who did not receive explicit feedback abandoned the strategy and their performance reduced.

A production deficiency may occur because children have immature metamemory, such that they are unaware of certain variables and strategies that effect memory and their ability to remember information (Flavell, Wellman, Kail, & Hagen, 1977). Furthermore, they may be unable to monitor their mental operations and performance on a task, limiting their ability to discover new and effective strategies. Five and six year old children have been shown to greatly overestimate predictions of their memory performance (Flavell, Friedrichs, & Hoyt, 1970) and, therefore, if the belief is that they will perform very well then the perceived the value of using a particular strategy may be minimal. Yet if the value of a strategy is explained, children may persist with using a strategy after training (Kennedy & Miller, 1976).

Children may also be discouraged from producing a strategy because it requires mental effort. One study investigated this hypothesis by requiring children to perform a secondary finger tapping task whilst rehearsing words in a free recall task (Guttentag, 1984). Primary school children in Years two to six were instructed to cumulatively rehearse the words during presentation in sets of three or more whilst tapping their finger as rapidly as possible. Children in Years two and three experienced more interference of using the rehearsal strategy, as evidenced by a reduced number of finger taps. Furthermore, when children were instructed to use a single-item rehearsal strategy there were no age differences in the amount of interference on the finger tapping task. This suggests that cumulative rehearsal was more effortful for younger children who are typically production deficient in this strategy compared to older children, whereas all children can efficiently use a single-item rehearsal strategy. Finally, it was shown that older children rehearsed in larger set sizes and remembered more words. Rehearsal set size negatively correlated with interference on the finger tapping task suggesting that mental effort associated with cumulative rehearsal decreased as set size increased. The transition from single-item to multi-item rehearsal may occur as a result of increases in processing capacity or the effort associated with basic rehearsal processes.

In addition to mediational and production deficiencies, Miller (P. H. Miller, 1990) suggested a further phase of strategy development where children spontaneously use a strategy but with little or no benefit to performance, i.e. a utilisation deficiency. This may occur when the mental effort of using a strategy counteracts the advantage it offers, perhaps by limiting the resources available for basic memory processes. Studies have shown that nine and twelve year old children, after training or spontaneous discovery, are able to cluster semantically related words together during rehearsal on a free recall task (Bjorklund, Coyle, & Gaultney, 1992; Bjorklund & Harnishfeger, 1987). However, the clustering strategy was only associated with improved performance in the twelve year old children and not the nine year old children. This may be because children believed using a strategy was better than not using one, but they may have lacked the insight to realise that this may have required considerable effort which limited their ability to remember the information.

Whilst development of a single strategy may progress from a mediational deficiency, to a production deficiency, to a utilisation deficiency, and to effective use, it is important to consider that children use multiple strategies on the same task. Siegler's (1996) overlapping waves theory suggests that children think about multiple strategies to complete a task, that these strategies compete with each other, and that development involves the acquisition of more advanced strategies and gradual changes in how frequently these strategies are used on certain tasks. It is suggested that a strategy of interest is initially acquired, it is then applied to novel problems and strengthened over time, choices between alternative strategies are then refined, and the strategy becomes increasingly effective with use. Strategies vary in terms of what age they are discovered, how long it takes to become to be proficient in that strategy, how frequently it is used, and at what age it becomes less frequently used or abandoned. This results in a dynamic and flexible use of strategies across children's development.

Investigations of the word-length and temporal grouping effects in children suggest that rehearsal and grouping develop at a similar time. Children as young as four show worse recall for lists of spoken words that have more syllables, demonstrating the word-length effect (Hitch et al., 1989). It is not until eight years of age that children show evidence of the word-length effect for pictures that are associated with longer words (Hitch et al., 1989). This suggests that sub-vocal rehearsal is present at an early age, but that other modalities are not strategically recoded into a phonological form until later in development. However, this interpretation should be treated with caution because more recent work has demonstrated that the magnitude of the word-length effect is proportional to recall performance (Jarrold, Danielsson, & Wang, 2015; Wang, Logie, & Jarrold, 2016). Since adults' (Wang et al., 2016) and children's (Jarrold et al., 2015) serial recall is worse for visually presented lists than aurally presented lists the magnitude of the word-length effect is necessarily smaller. Furthermore, the word-length effect would generally be smaller in young children because their overall recall performance is poorer (Jarrold & Citroën, 2013). Therefore, there may have been limited power to detect the word-length effect for four year old children, particularly under visual presentation conditions.

Regarding the development of grouping, eight year old children show a recall advantage for letters or numbers that have been visually or aurally presented in temporally grouped lists, whereas younger children do not (Towse et al., 1999). This suggests that temporal grouping requires some minimal cognitive capacity that develops in middle childhood. However, as discussed above, it should be considered whether the size of the temporal grouping effect is proportional to recall performance as the effect may be smaller in young children due to their limited performance. Furthermore, it has yet to be investigated at what age children develop the ability to strategically use grouping for ungrouped lists.

As discussed in Section 1.5.2., investigations of children's self-reported use of memory strategies indicates more protracted development. Eight year old children have been shown to typically repeat single items, whereas 10 year old children typically rehearse multiple items in sequence (Lehmann & Hasselhorn, 2007; Ornstein et al., 1975). Very few of these 10 year olds reported grouping or chunking strategies, but 13 year olds were able to spontaneously rehearse semantically related words together and this was associated with improved recall (Ornstein et al., 1975). Similarly it has been shown that eight and nine year old children typically do not spontaneously sort pictures into semantically related categories for subsequent recall whereas 10-12 year old children do (Schleepen & Jonkman, 2012). However, after explicit instructions the younger children showed better sorting, more instances of grouped rehearsal, and better recall. These findings indicate that children can spontaneously use chunking strategies between the ages of 10 and 13, but they can be taught to use chunking at a younger age. The ability to group may develop at a similar time to chunking as they both require division of a stimulus sequence into groups. Grouping is an effective strategy for remembering lists (Bailey et al., 2008, 2011; Dunlosky & Kane, 2007) and does not depend on semantic associations between the items. However, studies have yet to investigate whether self-reported grouping or grouping instruction improves children's recall in short-term memory tasks.

4.1.4. The Neural Correlates of Grouping and Rehearsal

Chapter 2 suggested that working memory training was associated with increased recruitment of the middle frontal gyrus when children were performing a working memory task. However, it was unclear whether this indicated increased neural capacity or a change in strategy. Activation of the middle frontal gyrus is associated with children's working memory capacity (Klingberg et al., 2002a), as well as grouping (Henson et al., 2000; Kalm et al., 2012) and chunking strategies in adults (Bor et al., 2004, 2003; Bor & Owen, 2007). However, there is no previous published work that has investigated the neural correlates of grouping in children. Children may use different strategies or be less adept at using grouping or chunking strategies. Even when using the same strategies, neural correlates may differ because of neurodevelopmental differences in the working memory network (e.g. Geier et al., 2009; Scherf et al., 2006).

Only two published studies have investigated the neural correlates of grouping in adults (Henson et al., 2000; Kalm et al., 2012). Both studies found decreased recruitment of the left middle frontal gyrus and left premotor cortex for encoding of temporally grouped sequences compared to encoding of ungrouped sequences. This finding may reflect that grouped rehearsal was less effortful than sequential rehearsal. Indeed, increased activation of the left middle frontal gyrus has been reported for encoding of a sequence of letters compared to a single letter (Henson et al., 2000), and when rehearsing a random sequence of letters from memory compared to rehearsing "A-B-C-D-E" (Logie et al., 2003). However, these findings may also be related to the timing of stimulus presentation, as mentioned earlier. It has been suggested that decreased activation of the left premotor cortex reflects modulation of the timing signal that codes for the within-group positions of the stimuli (Henson et al., 2000). However, it is not possible to determine whether these findings are the result of the timing of stimulus presentation or grouped rehearsal. It is also not clear how this relates to grouping as a strategy to remember lists that are not grouped. Strategic grouping can be investigated by instructing participants to use a grouping strategy on ungrouped lists, which therefore controls for the timing of stimulus presentation across conditions.

4.1.5. The Current Study

The aim of the current study is to examine the behavioural effects and neural correlates of grouped rehearsal in children. Stimuli will be ungrouped and identical across conditions, so that the effects of grouped rehearsal are not confounded by perceptual differences. Children will be randomly assigned to either a grouping or control condition according to the instructions that they will receive. On a digit recall task, half of the children will be instructed to sub-vocally rehearse digits in groups, and the other half will be instructed to "keep the numbers in mind". This will control for practice and expectation effects that may have confounded previous findings (Farrell, 2008; Farrell et al., 2011). The digit recall task will be completed during fMRI acquisition to measure the neural correlates of grouping. Transfer will then be assessed on a letter recall task outside the scanner without guidance and conducted by a second researcher who is blind to group assignment. These tasks make basic demands on short-term memory and should enable children to implement the grouping strategy. To examine the adoption of the grouping strategy, children will also be asked to report what strategy they were using after each task. Children aged 11-14 years will be recruited for the study because they are capable of sequential rehearsal (Lehmann & Hasselhorn, 2007; Ornstein et al., 1975), begin to adopt chunking strategies spontaneously (Ornstein et al., 1975), and are capable of learning chunking after brief instruction (Schleepen & Jonkman, 2012).

4.1.6. Hypotheses

1. It is predicted that children will report more grouping and have more accurate recall on the digit recall task when they have been instructed to use grouping compared to the control condition.

2. Children will transfer the grouping strategy to the letter recall task and perform better than children in the control condition.

3. It has previously been demonstrated that short-term memory for temporally grouped sequences of letters is associated with decreased activation in the left middle frontal gyrus (Henson et al., 2000; Kalm et al., 2012) and increased activation in the left inferior parietal lobe in adults (Kalm et al., 2012). Similarly, sequences that can be chunked according to mathematical rules or long-term memory have been associated with increased activation of the bilateral inferior parietal lobes (Bor et al., 2004; Bor & Owen, 2007). Therefore, it is predicted that grouping will be associated with decreased recruitment of the middle frontal gyrus and increased activation of the inferior parietal lobe.

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4.2. Method

4.2.1. Participants

Fifty typically developing children between the age of 11 and 14 years were recruited from one selective secondary school in Devon. Only right handed children without the presence of a developmental disorder or brain injury were recruited for the study. The data from six children were excluded from analysis: four for excessive head movements and two for scanner faults. The final sample included 44 children, including 22 boys and 22 girls. The average age was 12.58 years (*SD* = 0.81) and the large majority were white British (95%). All participating children provided written assent and their parent/guardian provided written consent. The study was approved by the University of Exeter Ethics Committee (Ref: eCLESPsy00010888).

4.2.2. Procedure

Children were first required to complete the word recall task from the AWMA (Alloway, 2007) to assess their baseline working memory capacity. This task provides an index of working memory capacity that is standardised according to age using normative data, with a mean of 100 and standard deviation of 15. The psychometric properties of the AWMA were formerly discussed in Section 2.2.2. Children were then randomly assigned to the experimental or control group. The experimental group were given explicit instructions on how to use grouping on a digit recall task. Specifically, they were instructed to rehearse the numbers aloud in twos or threes, leaving pauses between each group. They were then given practice and feedback on four self-paced trials, from span four to seven, followed by six timed trials, from span five to seven. Finally, the children were instructed to use grouping silently in their heads for six more timed trials, from span five to seven. Immediately before scanning, children were told to continue grouping silently in their heads, to only speak when they see ‘Respond’ on the screen, to speak loudly and clearly, and to keep their heads still throughout. The control group received identical task instructions, practice, and feedback, but were instructed to “hold the numbers in mind” instead of being instructed to group.

Following the instructions, fMRI was acquired as children performed a digit recall task. The task required children to remember six or seven digits that were simultaneously presented on a screen for a short duration and to verbally recall them after a brief delay. Six and seven digit strings were selected because piloting indicated that children aged 11-14 years performed very poorly on eight digit strings. It is possible, therefore, that if the task was too hard children may give up trying to remember the sequences, which may obscure the neural correlates of grouping. Three practice trials were presented at the start of scanning and repeated until the experimenter could clearly hear the child and accurately record their responses over the noise of the scanner. A simple odd/even task was used as a baseline task and alternated with digit recall in blocks of six trials (Stark & Squire, 2001). The scanning procedure was completed over three runs, which each included three blocks of memory trials and two blocks of baseline trials, with each block containing six trials. Each block of memory trials presented three at span six and three at span seven in a pre-randomised order that was the same for all children. In total, there were 54 memory trials, comprising of 27 trials at span six and 27 trials at span seven, and 36 odd/even trials. On completion of the scanning procedure, children were asked two questions regarding what strategy they had used to complete the digit recall task and how they would use this strategy on an example:

“We want to know how you were remembering the numbers during the task. This may be the same as the strategy that we showed you earlier or it may be something different that you thought of. What were you doing to help you remember the numbers most of the time?”

“How would you remember 914723?” [Experimenter points to the digits]

Responses to the strategy questions were recorded verbatim and then coded according to whether they had reported grouping or another strategy. All coding was completed by the principal investigator (J.J.). A child was considered to have grouped if a sufficient explanation or demonstration of the strategy had been provided on at least one of the questions. An explanation of grouping had to refer to the grouping or division of a stimulus, typical examples included: “Doing the grouping thing”, “The grouping method”, “remembering them in blocks”, and “Put them in groups of two”. Grouping was typically demonstrated as “9, 1, 4 … 7, 2, 3”, leaving a distinct pause between the third and fourth digits. Three children reported using three groups “9, 1 … 4, 7 … 2, 3”, leaving distinct pauses between the second and third and fourth and fifth digits. The most common alternative strategy was sequential rehearsal, examples included: “repeated them over and over again in my head”, “Saying them in my head”, “mouthing them”. Rehearsal was typically demonstrated as “9, 1, 4, 7, 2, 3”, without any distinct pauses that would otherwise suggest grouping. Inter-rater reliability was established on 10 children’s responses to the two strategy questions for each task. Five children were randomly selected from each condition. A member of the supervisory team (A.A.), who was blind to the conditions and classifications of child-reported strategies, independently coded the responses. Across the two independent classifications there was 100% agreement.

Transfer of the grouping strategy was assessed using a letter recall task outside of the scanner. This task required children to remember letters that were simultaneously presented on a screen for a short duration and to verbally recall them after a brief delay. There were six trials at each span length from two letters up to 10 letters. The task would proceed to the next span length after four correct responses or terminate after three incorrect responses at that span length. Children were asked to report what strategy they had been using on the task and to demonstrate this on an example (as shown above for the digit recall task). Finally, all children were debriefed on the aims of the study and given a £5 gift voucher and images of their brain, as an appreciation for taking part.

Children were initially randomly assigned to the experimental and control groups in equal numbers. However, a number of the children assigned to the control group were in fact spontaneously grouping on the tasks. Therefore, group allocation was adjusted so that more children were randomly assigned to the control group to allow sufficient power to analyse differences between children that were and were not grouping. The final sample included 18 children allocated to the grouping condition and 26 children allocated to the control condition.

4.2.3. Measures

4.2.3.1. Digit Recall fMRI Task

The digit recall task was performed inside the MRI scanner and required children to remember visually presented strings of six or seven digits over short durations. Digit strings were randomly generated from numbers one to nine, without replacement. To control for memory strategies based on mathematical rules, the strings did not contain three or more consecutive digits that were in ascending or descending order counting in ones, twos, or threes. In addition, no two strings had the same first or last three digits. The digit recall task was alternated with the odd or even baseline task, which required children to verbally identify single digits as odd or even (Stark & Squire, 2001). Digits were randomly selected from 1-9 and presented with three underscores either side to control for visual features of the digit recall task, e.g. '_ _ _ 3 _ _ _'.

Before each block, task instructions were presented for 3000ms. A block of memory trials was preceded by the instruction to 'remember the numbers and say them back' and a block of odd or even trials was preceded by the instruction to 'respond odd or even'. Each trial began with a variable jitter, which presented a fixation dot for 1000-4500ms. Digit recall trials then presented instructions to remember six or seven digits for 2000ms, which allowed children to identify what their group sizes should be. After a 500ms delay children were shown the corresponding six or seven digit string. Six digit strings were simultaneously presented for 4800ms and seven digit strings were simultaneously presented for 5600ms in black font on a white screen. This was followed by a 500ms mask and 8000ms response window. Children were instructed to verbally recall the digits in the order they were presented, as in previous studies (Bor et al., 2004; Bor & Owen, 2007; Kalm et al., 2012). Responses were only scored correct if the whole string was recalled in the correct order, within the 8000ms response window. If the experimenter was uncertain about the verbal response, they would make a note and check the audio recording at the end of the experiment; a total of four changes were made.

Odd or even trials began with a variable jitter, which presented a fixation dot for 1000-4500ms. A single digit was then presented for 2000ms in black font on a white screen. This was followed by a 500ms mask and 2500ms response window. Children were instructed to verbally classify the digit as ‘odd’ or ‘even’. This task was used to control for features of the digit recall task that were not specific to short-term memory, such as reading and the preparation of verbal responses.

4.2.3.2. Letter Span Transfer Task

The letter span task was performed outside of the scanner and required children to remember visually presented letter strings over short durations. This task was used to assess whether children would transfer the strategy they had learned from a different researcher on a different task and apply it to a new task with similar structure but different stimuli, without instruction. The letter strings were randomly generated from the consonants C-F-H-K-L-N-Q-R-S-Y-Z without replacement, as in Towse et al. (1999). No four letters were presented consecutively more than once and no three letter strings were repeated in longer strings. To control for chunking, common abbreviations and consecutive letters of the alphabet were removed that might reduce memory load; for example KFC, NHS, and NFL, and instances of QRS. As in the digit recall task, strings were presented on a white screen in black font for 800ms per letter. For example, a six letter string was presented for 4800ms. This was followed by a 500ms mask, and 8000ms was allowed for children to verbally recall the digits in the order they were presented. Responses were only recorded as correct if the whole string was recalled in the correct order, within the 8000ms response window. The assessment was conducted by an experimenter who was blind to the child’s group assignment.

The task followed a span procedure that was modelled on the AWMA (Alloway, 2007). The task began with three practice trials from span one to three. The task then proceeded to six trials at each span length, beginning at span two and ending at span 10. If four trials were answered correctly on a certain span length, the remaining trials were skipped and considered correct. If three incorrect answers were given at one span length, then the task was terminated. Span scores were computed by adding 0.25 for each correct trial at the current span length to the previous span length. For instance, if the child had progressed to span six and correctly answered three out of six trials, they would receive 0.75 marks for the three correct trials at span six and 5 marks for completing span five, giving them a total score of 5.75. Immediately following the task, children were asked to report what strategy they had used to remember the letters and to demonstrate this on a six letter example (as detailed above).

4.2.4. Data Analysis

All 18 children in the grouping condition reported using grouping on the digit recall task, and 14 out of 18 reported using grouping on the letter span task. Unexpectedly however, 15 out of 26 children in the control condition spontaneously reported grouping on the digit recall task, and 12 out of 26 reported grouping on the letter span task. Condition was not a reliable measure of what strategy children were using on the task and the analysis of condition may have been underpowered to detect the effects of grouping. Therefore, self-reported grouping was selected as the primary independent variable of interest instead of condition. The high rates of spontaneous grouping in the control group may be explained by the fact that this was a high ability group, as evidenced by their high scores on the standardised assessment of working memory (see Section 4.3.1.).

The analysis of behavioural data was completed in SPSS version 24. Independent samples t-tests were used to examine the effect of self-reported grouping on recall accuracy for the digit recall and letter span tasks.

4.2.6. MRI Acquisition

Images were acquired at the Exeter MR Research Centre using a 1.5T Phillips Gyroscan magnet, equipped with a Sense coil. A T2*-weighted echo planar sequence was used (TR=3000ms, TE= 45ms, flip angle 90º, 35 transverse slices, 2.5 x 2.5 x 3.5mm). Participants completed one scanning session, which included three runs of five blocks. In each run there were three blocks of six digit recall trials and two blocks of six odd/even trials that were alternated. One hundred and fifty five scans were acquired for each run. A standard volumetric anatomical MR image was collected after functional scanning using a 3D T1-weighted pulse sequence (TR = 25ms, TE = 4.2ms, flip angle = 30˚, 0.9 x 0.9 x 0.9mm).

4.2.7. fMRI Analysis

The functional images were analysed using SPM12 (www.fil.ion.ucl.ac.uk/spm). The images were corrected for acquisition order, realigned to the first volume and resliced to correct for motion artefacts. Spatial normalisation was performed by coregistering the mean image created from the realigned images to the structural T1 volume. The images were then spatially normalised into the stereotactic space of the Montreal Neurological Institute (MNI). The spatial transformation was applied to the realigned T2* volumes that were spatially smoothed using a Gaussian kernel of 8mm full-width half maximum. Data were high-pass filtered (128s) to account for low frequency drifts. The BOLD response was modelled by a canonical hemodynamic response function (HRF) and the six head movement parameters were included as covariates. First-level linear contrasts of parameter estimates for each voxel were taken to the second-level and a random effects analysis was performed.

Data acquired for each participant during the encoding phase of correct trials was contrasted with baseline data acquired during the odd/even task. The resulting activations were contrasted at the second level, comparing those who reported grouping on the task to those who did not report grouping (‘grouping’ – ‘not grouping’ and ‘not grouping’ – ‘grouping’). Region of Interest (ROI) analyses were carried out in the bilateral middle frontal gyrus and inferior parietal lobe. ROIs were selected a priori from the Automated Anatomical Labelling atlas (AAL; Tzourio-Mazoyer et al., 2002) within the WFU PickAtlas (Maldjian et al., 2003). ROI analyses were conducted at a significance threshold of $p < 0.005$ (uncorrected) and minimum of 10 contiguous voxels, as in previous studies (Milton et al., 2012). Coordinates were transformed from normalised MNI space to Talairach space using the ‘icbm2tal’ tool (Lancaster et al., 2007) to locate the site of activations in relation to the atlas of Talairach and Tournoux (1988). Exploratory whole brain analyses were conducted at a significance threshold of $p < 0.001$ (uncorrected) and minimum of 20 contiguous voxels to control for multiple comparisons, as in previous work (Milton et al., 2012; Milton & Pothos, 2011).

4.3. Results

4.3.1. Sample Characteristics

Standardised scores on the word recall task (*M* = 116.39, *SD* = 13.42) were significantly higher than the normative average, $t(43) = 8.10$, $p < 0.001$. This indicated that the sample had significantly greater baseline short-term memory capacity than children of the same age. Age was not significantly correlated with accuracy on the digit recall, $r(42) = -0.04$, $p = 0.776$, or letter span tasks, $r(42) = -0.06$, $p = 0.690$. Similarly, performance did not significantly differ between boys and girls on the digit recall, $t(42) = 1.43$, $p = 0.159$, or letter span tasks, $t(42) = 0.16$, $p = 0.876$. On the digit recall task, accuracy for six digit trials (*M* = 0.94, *SD* = 0.03) was significantly greater than recall accuracy for seven digit trials (*M* = 0.81, *SD* = 0.13), $t(43) = 8.01$, $p < 0.001$.

4.3.2. Self-reported Strategy

The proportions of self-reported strategies on the digit recall and letter span tasks are displayed in Table 4.1. In total, 33 children reported grouping on the digit recall task and 11 reported rehearsing the digits, without grouping them. On the letter span task 26 children reported grouping, 16 reported rehearsal, and two reported using rhythm or relating letters to objects in the room. Age, gender, and baseline working memory capacity were compared between children that did and did not report grouping on the digit recall (see Table 4.2) and letter span tasks (see Table 4.3). There were no significant differences in age on the digit recall, $t(42) = 0.07$, $p = 0.944$, or letter span tasks, $t(42) = 1.29$, $p = 0.206$. There were no significant differences in gender on the digit recall, $\chi^2(1, N = 44) = 1.09$, $p = 0.296$, or letter span tasks, $\chi^2(1, N = 44) = 1.50$, $p = 0.220$. Finally, there were no significant differences in baseline working memory capacity on the digit recall, $t(42) = 1.42$, $p = 0.162$, or letter span tasks, $t(42) = 0.33$, $p = 0.741$.

Table 4.1. Proportion of Self-reported Strategies on the Digit Recall and Letter Span Tasks as a Function of Condition.

Condition	**N**	**Digit Recall Strategy**			**Letter Span Strategy**		
		Grouping	**Rehearsal**	**Other**	**Grouping**	**Rehearsal**	**Other**
Total	44	0.75	0.25	0	0.59	0.36	0.05
Grouping	18	1.00	0	0	0.78	0.11	0.11
Control	26	0.58	0.42	0	0.46	0.54	0

4.3.3. Grouping Instruction

Chi square tests were used to examine whether grouping instruction increased children's use of this strategy compared to the control instructions (see Table 4.1). Instruction was significantly associated with self-reported grouping on the digit recall task, $\chi^2(1, N = 44) = 10.15$, $p = 0.001$, and self-reported grouping on the letter span task, $\chi^2(1, N = 44) = 4.40$, $p = 0.036$. T-tests examined whether instruction was associated with short-term memory. There was no significant effect of instruction on digit recall accuracy, $t(42) = 0.71$, $p = 0.706$, $\eta^2 = 0.003$, or letter span, $t(42) = 1.87$, $p = 0.069$, $\eta^2 = 0.077$. The marginal difference in letter span scores indicated that those who received grouping instruction ($M = 6.11$, $SD = .54$) performed worse than the control group ($M = 6.62$, $SD = 1.05$).

4.3.4. Behavioural Effects of Grouping

To test the hypothesis that grouping was associated with higher recall accuracy, independent samples t-tests were conducted to compare performance of children that did and did not report grouping on the two short-term memory tasks (see Tables 4.2 & 4.3). On the digit recall task, there was no significant difference in performance between the children who reported grouping and those who reported rehearsal, $t(42) = 0.09$, $p = 0.928$. Similarly, there was no significant difference in letter span performance between children that did and did not report grouping, $t(42) = 0.46$, $p = 0.65$. All of the children who were instructed to group reported using this strategy, however some children may have only said this to appease the experimenter. Therefore, t-tests were repeated for only the control group who received no explicit instructions in strategy-use. Again, there was no significant difference in digit recall performance, $t(24) = 0.31$, $p = 0.761$, or letter span, $t(24) = 0.6$, $p = 0.556$, between children that did and did not report grouping.

Table 4.2. Group Differences between Children that did and did not Report Grouping on the Digit Recall fMRI Task.

	Grouping (n=33)	**Rehearsal (n=11)**	***t*(42)**	***p***
Age	12.58 (.83)	12.56 (.78)	0.07	.944
Word Recall	114.75 (13.53)	121.33 (12.40)	1.42	.162
DR Total Accuracy	0.88 (0.09)	0.88 (0.07)	0.09	.928
DR Span 6 Accuracy	0.94 (0.06)	0.94 (0.06)	0.10	.921
DR Span 7 Accuracy	0.82 (0.14)	0.83 (0.11)	0.18	.862
Odd/Even Accuracy	1.00 (.33)	1.00 (.30)	0.27	.790

Note. DR = Digit recall. Accuracy scores reported in proportion correct.

Table 4.3. Group Differences between Children that did and did not Report Grouping on the Letter Span Task.

	Grouping (n=26)	**Not grouping (n=18)**	***t*(42)**	***p***
Age	12.71 (.83)	12.39 (.75)	1.29	0.206
Word recall	115.82 (14.13)	115.83 (14.13)	0.33	0.741
Letter span	6.46 (1.03)	6.33 (.71)	0.46	0.650

4.3.5. Neural Correlates of Grouping

Brain activity was compared between the stimulus presentation phases of the digit recall and odd/even trials to examine areas of significant activation related to short-term memory for the whole sample. This analysis revealed a large cluster of significant activation that included the bilateral anterior cingulate (BA24/BA32), bilateral caudate head, and right putamen. Significant activation was also found in the bilateral superior temporal gyri (BA22) and Heschl's gyri (BA42; aka transverse temporal gyri), left primary motor (BA4) and somatosensory cortices (BA3), bilateral visual cortex (BA19), and bilateral areas of the cerebellum (see Figure 4.1 and Table 4.4).

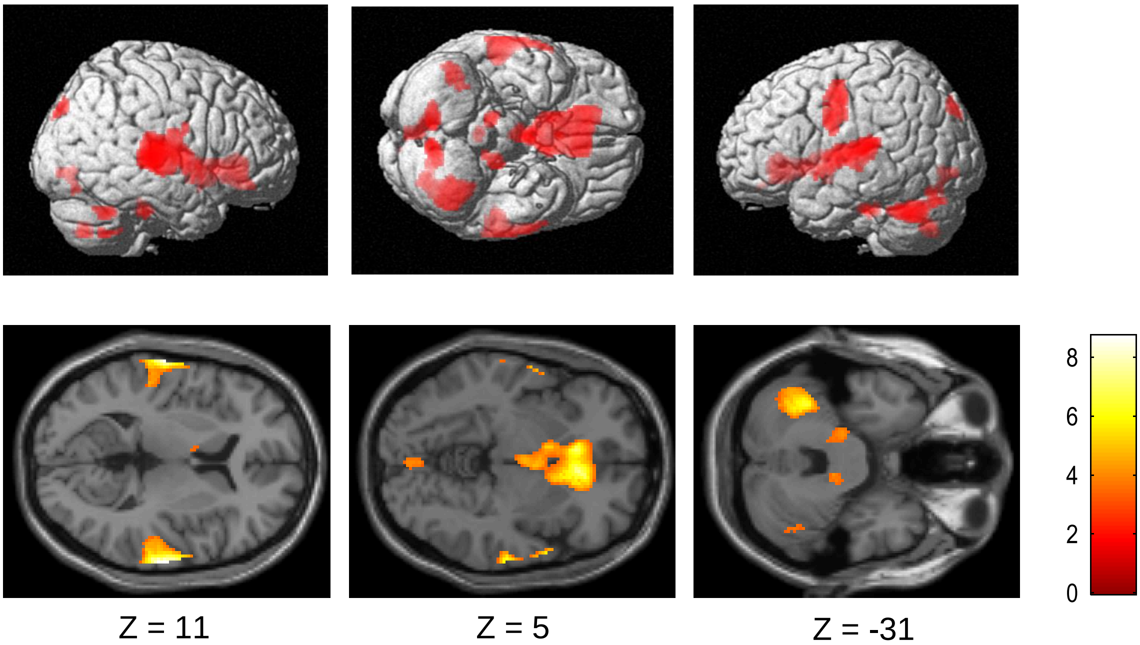

Figure 4.1. Significant activation associated with digit recall compared to odd/even for the whole sample. Z coordinates for slices are in Talairach space.

Brain activation specific to digit recall was compared between the children who reported using grouping and rehearsal. The ROI analysis revealed that grouping was associated with significantly decreased activation in two clusters of the left middle frontal gyrus compared to rehearsal (see Figure 4.2 and Table 4.5). Similarly, the sub-analyses of span six and span seven trials both revealed decreased activation in the same two regions of the middle frontal gyrus. The whole brain analysis revealed that grouping was associated with significantly increased activation in the left premotor cortex (BA6) and right lingual / parahippocampal gyrus (BA19), as well as decreased activation in the left inferior frontal gyrus (BA46), compared to rehearsal (see Figure 4.3 and Table 4.6). The cluster of decreased activation in the left inferior frontal gyrus (peak coordinate: -43, 38, 4) was very close to, but slightly inferior of, the activation in the left middle frontal gyrus identified from the ROI analysis (peak coordinate: -42, 39, 7).

Table 4.4. Regions of Significant Activation for the Digit Recall Task Compared to the Odd/Even Task.

Brain Region	**Cluster size**	**Peak Z**	**Talairach Coordinates**		
			x	**y**	**z**
Right Heschl's gyrus (BA42)	794	6.57	62	-20	11
Right superior temporal gyrus (BA22)		6.51	60	-24	3
Right superior temporal gyrus (BA22)		5.33	58	-6	7
Left Heschl's gyrus (BA42)	425	6.57	-62	-17	7
Left superior temporal gyrus (BA22)		5.43	-60	-9	6
Left superior temporal gyrus (BA22)		4.22	-57	-1	3
Left cerebellum	601	6.42	-38	-47	-31
		4.13	-27	-68	-24
		3.79	-16	-67	-19
Right caudate head	1787	5.95	7	25	3
Left caudate head		5.73	-6	23	3
Right putamen		5.02	6	13	6
Left primary motor cortex (BA4)	198	5.56	-59	-8	30
Left postcentral gyrus (BA3)		5.46	-50	-13	47
Left primary motor cortex (BA4)		4.79	-55	-14	40
Left cerebellum	99	5.10	-8	-63	-41
Right cerebellum	97	5.00	10	-63	-45
Bilateral cuneus (BA19)	129	4.43	9	-87	29
		4.09	-7	-85	32
Right cerebellum	63	4.10	10	-27	-27
Right lingual gyrus (BA18)	107	4.05	3	-81	-9
Right cerebellum		3.68	8	-71	-19
Right cerebellum	52	3.95	44	-51	-29
Right cerebellum	38	3.77	35	-50	-43
Left cerebellum	62	3.76	-17	-23	-25
		3.33	-12	-33	-26
Right cerebellum	39	3.56	5	-38	-14

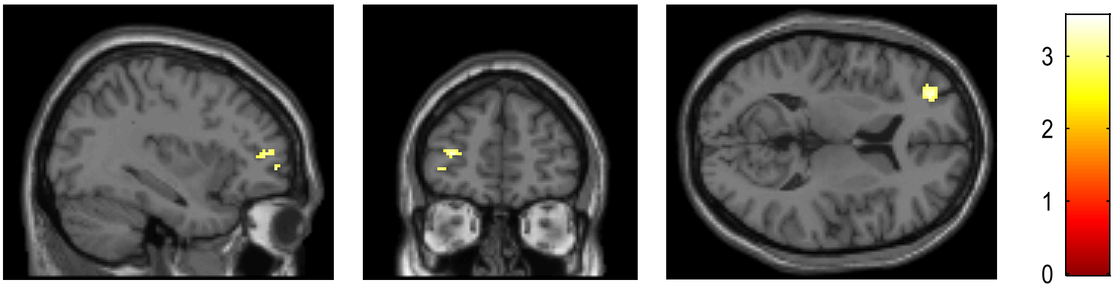

Figure 4.2. Significantly decreased activation in two areas of the left middle frontal gyrus for grouping compared to rehearsal. Origin: (-30, 47, 8)

Table 4.5. ROI Comparison of Grouping and Rehearsal Strategies as a Function of Span Length.

Brain Region	**Cluster size**	**Peak Z**	**Talairach Coordinates**		
			x	**y**	**z**
Grouping > Rehearsal					
No significant clusters					
Grouping < Rehearsal					
Left middle frontal gyrus (BA10)	27	3.30	-34	51	8
Left middle frontal gyrus (BA46)		3.01	-42	39	7
Left middle frontal gyrus (BA10)	55	3.13	-27	42	17
Left middle frontal gyrus (BA46)		2.73	-36	37	14
Span 6: Grouping > Rehearsal					
No significant clusters					
Span 6: Grouping < Rehearsal					
Left middle frontal gyrus (BA10)	27	3.28	-34	51	8
Left middle frontal gyrus (BA46)		3.04	-42	39	7
Left middle frontal gyrus (BA10)	56	3.11	-29	42	17
Left middle frontal gyrus (BA46)		2.75	-36	37	14
Span 7: Grouping > Rehearsal					
No significant clusters					
Span 7: Grouping < Rehearsal					
Left middle frontal gyrus (BA10)	26	3.30	-34	51	8
Left middle frontal gyrus (BA46)		2.98	-42	39	7
Left middle frontal gyrus (BA10)	50	3.15	-27	42	17

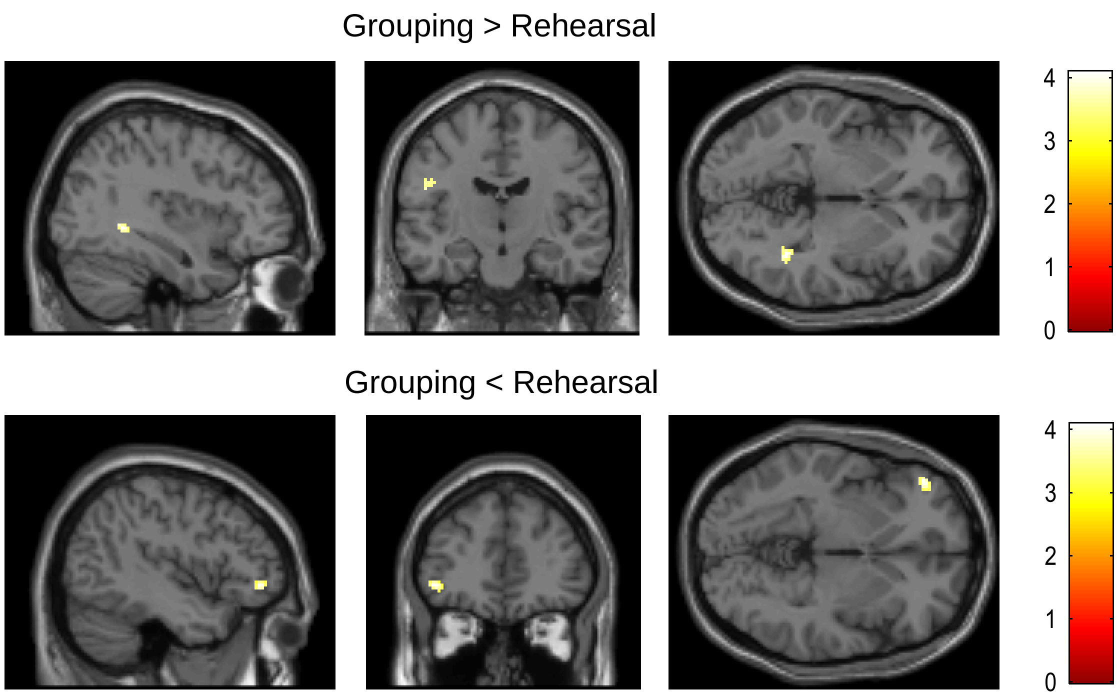

Figure 4.3. Whole brain comparison of grouping and rehearsal. Grouping>rehearsal origin: (34, -17, -1), rehearsal<grouping origin: (-41, 38, 4).

Table 4.6. Whole Brain Comparison of Grouping and Rehearsal strategies as a Function of Span Length.

Brain Region	**Cluster size**	**Peak Z**	**Talairach Coordinates**		
			x	**y**	**z**
Grouping > Rehearsal					
Right parahippocampal gyrus (BA19)	45	3.72	34	-46	-1
Right lingual gyrus (BA19)		3.47	27	-52	0
Left premotor cortex (BA6)	24	3.39	-46	-15	27
Grouping < Rehearsal					
Left inferior frontal gyrus (BA46)	38	3.94	-43	38	4
Span 6: Grouping > Rehearsal					
Right parahippocampal gyrus (BA19)	30	3.68	34	-46	-1
Left premotor cortex (BA6)	24	3.38	-46	-15	27
Span 6: Grouping < Rehearsal					
Left inferior frontal gyrus (BA46)	38	3.89	-43	38	4
Span 7: Grouping > Rehearsal					
Right parahippocampal gyrus (BA19)	49	3.74	34	-46	-1
Right lingual gyrus (BA19)		3.52	27	-52	0
Left premotor cortex (BA6)	25	3.39	-46	-15	27
Span 7: Grouping < Rehearsal					
Left inferior frontal gyrus (BA46)	37	3.97	-43	38	4

4.4. Discussion

This was the first investigation of the neural correlates of grouping in childhood, and extends upon previous investigations of grouping in adults by keeping stimulus presentation constant between conditions. Furthermore, this was the first study to instruct children to use grouping for ungrouped sequences and to examine the association between children's self-reported grouping and recall accuracy on short-term memory tasks. Overall, the findings suggested that children who reported grouping performed equally as well as children who reported rehearsal or other strategies. In addition, there was no significant difference in recall accuracy between children who received grouping instruction and children who received the control instructions. Functional MRI revealed that self-reported grouping was associated with decreased activation of the left middle/inferior frontal gyri compared to rehearsal, suggesting some differences in encoding between these two strategies.

4.4.1. Strategy and Recall Accuracy

It was predicted that self-reported grouping would be associated with greater recall on the short-term memory tasks compared to rehearsal and other strategies. However, recall accuracy did not significantly differ according to what strategy children reported. Previous studies have shown that adults who report grouping, imagery, and chaining strategies on short-term and working memory tasks perform better than adults who report reading or rehearsal (Bailey et al., 2008, 2011; Dunlosky & Kane, 2007). If strategy is the cause of these high scores, then grouping should have been associated with greater recall on the short-term memory tasks in the present study. However, this was not the case and the findings may be more in keeping with the strategy-as-effect hypothesis, which proposes that high working memory capacity affords the production and implementation of more normatively effective strategies, such as grouping (Dunlosky & Kane, 2007). Accordingly, no difference in performance was found between children who reported grouping and those who reported rehearsal because both groups of children had high working memory capacities, approximately one standard deviation above the normative average. Therefore, whilst high working memory capacity afforded the use of grouping, and many children spontaneously reported using this strategy (in the control group, 58% on the digit recall task and 46% on the letter span task), it was not a significant predictor of performance. Future research should establish whether there is an association between strategies and short-term memory performance in children of mixed ability. The high rates of grouping spontaneously reported by children could indicate this strategy has developed by the age of 11-14; however, it should be considered that this high ability sample may not be representative of children this age.

The strategy-as-effect hypothesis also predicts that children with high working memory capacity should be capable of learning and implementing effortful strategies (Dunlosky & Kane, 2007). Indeed, children that received grouping instruction reported using grouping significantly more on the digit recall and letter span tasks than children in the control group. However, there was no significant effect of grouping instruction on performance. Similar findings have been reported in another study where instruction in rehearsal, imagery, and chaining strategies did not improve working memory performance in adults with high capacity (Turley-Ames & Whitfield, 2003). These high capacity individuals were already engaging strategically with the tasks before instruction and so it is possible that they were already using the optimal mnemonic strategy for their individual capacity. It was suggested that in some cases instruction to use a different strategy may have impeded performance. The present study provides some comparable findings in children, suggesting that individuals with high working memory capacity may have been capable of using the most effective strategy without instruction. However, this hypothesis could be more directly investigated in future studies by sampling children of low, average, and high working memory capacity. This would afford a novel examination of whether grouping is associated with children’s working memory capacity and whether grouping instruction is effective in children with low and average capacity.

There is also reasonable cause to doubt previous investigations of grouping instruction in adults. Previous studies have found that instructing adults to group improves their recall accuracy (Farrell, 2008; Farrell et al., 2011). However, these findings were confounded by practice and expectation effects, because there was no control group or counterbalancing. Children in the current study had equal practice, regardless of whether they were using a grouping or rehearsal strategy. Using a similar design in adults, one study failed to find a significant effect of grouping instruction compared to no instruction (Ryan, 1969a). Furthermore, other previous work in adults compared grouping to single item repetition (Wickelgren, 1964) rather than sequential rehearsal, which is the most commonly reported short-term memory strategy in adults (Morrison et al., 2016). Therefore, another interpretation of the data is that grouping instruction may not improve children’s recall when practice and expectation are controlled for.

The only previous work to investigate grouping in children found that eight year olds recalled temporally grouped sequences of digits and letters more accurately than ungrouped sequences (Towse et al., 1999). One account of the temporal grouping effect is that it is a product of rehearsal, such that grouping items in rehearsal improves recall (Ryan, 1969b). However, studies have shown that articulatory suppression does not eliminate the temporal grouping effect (Frick, 1989; Hitch et al., 1996), suggesting that it is not entirely mediated by rehearsal. Another account suggests that temporally grouped sequences recruit an additional timing signal that codes for the within-group position of stimuli (Hitch et al., 1996). Accordingly it is the timing of stimulus presentation that produces the effect, rather than rehearsal processes. In the present study, the timing of stimulus presentation was constant between conditions because stimuli were presented simultaneously and ungrouped. Therefore children were grouping the items in rehearsal, which may not have been sufficient to afford an additional timing signal that would facilitate recall. However, this is not necessarily the only mechanism by which grouping might facilitate recall. Grouped rehearsal may be more efficient than sequential rehearsal and may serve to reduce cognitive load, as will be discussed in the next section.

4.4.2. The Neural Correlates of Grouping in Childhood

Performance on the digit recall task was associated with activation in bilateral areas of the anterior cingulate (BA24/BA32), superior temporal gyri (BA22), Heschls’ gyri (BA42), visual cortex (BA19), caudate head, and cerebellum, as well as the left motor cortex (BA4) and right putamen. This pattern of activation in primary (BA42) and secondary auditory and language processing areas (BA22), the caudate, and cerebellum is consistent with previous studies of verbal short-term memory in adults (Buchsbaum et al., 2011; Kalm et al., 2012).

The primary aim of the fMRI analysis was to compare brain activation between children that reported grouping and children that reported rehearsal. It was predicted that grouping would be associated with reduced activation in the middle frontal gyrus and increased activation in the left inferior parietal lobe. Grouping was associated with significantly decreased activation in two areas of the left middle frontal gyrus compared to rehearsal, corresponding to the neural correlates of temporal grouping in adult studies (Henson et al., 2000; Kalm et al., 2012). This not only suggests that grouped rehearsal recruits similar processes to temporally grouped sequences, but also that these processes are similar between adults and children aged 11-14 years. Furthermore, as there were no differences in stimuli, performance on the digit recall task, working memory capacity, age, or gender, activation in the left middle frontal gyrus can be confidently attributed to the strategy that children reported using.

The ROI activations in the left middle frontal gyrus were more precisely localised to BA10 and BA46. The whole-brain analysis also revealed that grouping was associated with significantly decreased activation in an adjacent region of BA46, in the inferior frontal gyrus. The dorsolateral prefrontal cortex, comprising of BA9 and BA46, is an essential region for working memory as evidenced by lesion studies in non-human primates (see Petrides, 2000, for a review). A meta-analysis has shown that activation in the dorsolateral prefrontal cortex is correlated with increased memory load in working memory tasks (Rottschy et al., 2012). Therefore, decreased recruitment of the left dorsolateral prefrontal cortex in the present study may suggest that grouping reduced memory load. The dorsolateral prefrontal cortex has also been suggested to play a specific role in the organisation of items in working memory (see Blumenfeld & Ranganath, 2007, for a review). Relatedly, activation in the dorsolateral prefrontal cortex is associated with encoding sequences of digits that can be easily chunked according to mathematical rules (Bor et al., 2004; Bor & Owen, 2007). Therefore decreased recruitment of the left dorsolateral prefrontal cortex may also reflect the organisation of items into groups. Studies of temporal grouping in adults have not previously reported activation of the dorsolateral prefrontal cortex (Henson et al., 2000; Kalm et al., 2012). However, this may be because the stimuli were already grouped during presentation, whereas stimuli in the present study and chunking experiments (Bor et al., 2004; Bor & Owen, 2007) required organisation into groups.

Decreased activation was also found in BA10 for grouping compared to rehearsal. This region has been associated with a large number of processes (see Ramnani & Owen, 2004, for a review), however a meta-analysis of various tasks and paradigms suggested that activation in the lateral BA10 is more strongly associated with working memory and episodic retrieval than other proposed functions (Gilbert et al., 2006). In adults, temporal grouping has been associated with decreased activation of BA10 (Kalm et al., 2012), and chunking has been associated with increased activation of BA10 (Bor et al., 2004). It has been suggested that decreased activation reflects increased neural efficiency, which may stem from a sharper neural response or more specific activation of neurons in a functional network (Kelly et al., 2006). In the context of the current findings, decreased recruitment of the left dorsolateral prefrontal cortex and BA10 may suggest that grouping afforded a more efficient use of working memory capacity. Interestingly, a meta-analysis of adult studies showed that brief training on working memory tasks was associated with decreased recruitment of the dorsolateral prefrontal cortex (Li et al., 2015). Similar to strategy instruction, it is possible that brief practice on working memory tasks affords the production of task-specific strategies that make more efficient use of working memory capacity.

The whole brain analysis also revealed that grouping was associated with greater activation of the left ventral premotor cortex (BA6) compared to rehearsal. This region was slightly inferior and anterior to the ROI, however previous studies in adults have shown that encoding of temporally grouped sequences of six letters is associated with decreased recruitment of the left dorsal premotor cortex, compared to ungrouped sequences (Henson et al., 2000; Kalm et al., 2012). This region was also associated with increased activation for sequential rehearsal, leading to the suggestion that temporal grouping modulates activity in the dorsal premotor cortex through recruitment of an additional timing signal (Henson et al., 2000), according to the connectionist account of temporal grouping (Burgess & Hitch, 1996). However this was not the case at high load, temporally grouped sequences of nine letters were associated with increased activation in the left ventral premotor cortex, near to the activation in the current study (Kalm et al., 2012). Chunking of digit sequences has also been associated with increased activation of the left dorsal premotor cortex in adults (Bor et al., 2004; Bor & Owen, 2007). Consistent activation of the left premotor cortex across all existing neuroimaging studies of grouping and chunking in verbal short-term memory, suggest that it plays an important role. However, differences in specific anatomical locations (dorsal versus ventral) and activation (decrease versus increase) currently constrain inferences regarding the underlying processes.

Counter to predictions, grouping did not activate the inferior parietal lobe greater than rehearsal. Previous studies in adults have found greater activation in the inferior parietal lobe for encoding of temporally grouped sequences of nine letters (Kalm et al., 2012) and chunking sequences of eight digits (Bor et al., 2004; Bor & Owen, 2007). However, these effects have only been found at high load, whereas temporally grouped sequences of six letters have not been associated with increased activation in the inferior parietal lobe (Henson et al., 2000; Kalm et al., 2012). These effects were also only evident when grouping or chunking was associated with greater recall. Therefore, the lack of activation in the present study may be because memory was not tested at a high load and there was no recall advantage of grouping. It is unlikely to reflect limited power because the sample size in the current study was much greater than the previous studies mentioned. However, it is not possible to rule out developmental differences in grouping, as there are no comparable studies in children.

4.4.3. Strengths, Limitations, and Future Directions

Another possible explanation for the absence of a behavioural effect of grouping on short-term recall is that the tasks were insensitive. The tasks may have been too easy for grouping to be an effective strategy, indeed studies in adults have shown that grouping is not associated with greater recall at span six or lower (Bailey et al., 2011; Kalm et al., 2012). However, an effect of grouping instruction has been shown at span six in adults (Farrell, 2008), the digit recall task included trials at span seven, and the letter span task could potentially progress to span 10, depending on performance. Therefore, the tasks included a range of difficulties which should have afforded grouping. The tasks may also be criticised because some stimuli required irregular group sizes, whereas recall is optimal for regular group sizes of three in adults (Ryan, 1969a). A fixed number of trials at span nine could have been used, however this is likely to be very difficult for children and lead to high error rates.

The classification of strategies for both short-term memory tasks was in perfect agreement with a second rater, suggesting that the strategy reports were reliable. However, it could be argued that reports of children who received grouping instruction did not reflect the strategy they were using, but the strategy that they ought to be using. This is unlikely to be true for the majority of participants, because only two children in the control group repeated the instructions that they were given, and many instead reported grouping. Therefore, it seems more probable that children reported the strategy that they used and thought to be most effective. Furthermore, questions regarding strategy-use were open-ended, encouraging children to reflect on the task rather than choosing an option that might appear to be the correct response. This was particularly telling for children in the control condition who reported grouping, as they received no instruction or information about grouping during the study. Re-running the analysis with only children in the control group did not change the results, grouping was still not significantly associated with performance.

A limitation of the current study is that the strategy-reports were only collected once, retrospectively, after each task. It is possible that children may have forgotten what strategy they were using, remembered a few trials and over-generalised, or used different strategies throughout the task (Dunlosky & Kane, 2007). A previous study showed that reports after each block of trials were more strongly associated with working memory performance (Dunlosky & Kane, 2007). This is certainly a consideration for further research, however it is important to point out that there was much less variation in the strategies between children in the current study. Children either reported grouping or rehearsal on the digit recall task, whereas in the previous study adults reported reading, rehearsal, imagery, sentence formation, grouping, and other strategies on the operation span.

4.4.4. Conclusion

The novel findings of this investigation demonstrate that children's brain activity is modulated by the strategic use of memory. Strategic grouping in children was associated with similar neural processes as temporal grouping in adults. It was suggested that decreased recruitment of the middle frontal gyrus was a more efficient strategy compared to sequential rehearsal, which effectively reduced cognitive load. It was suggested that the left premotor cortex has an important role in grouping and chunking in verbal short-term memory, which warrants further investigation. Specifically, how activation in the left dorsal and ventral premotor cortex is associated with strategic grouping compared to temporal grouping, and how this interacts with load. Finally, it was recommended that future studies investigate the association between strategies and short-term memory in children with low, average, and high capacity.

Chapter 5: General Discussion

This thesis investigated methods to improve children's working memory through task-based training and instruction in strategies. The primary aims were to examine the cognitive and neural mechanisms of near-transfer, far-transfer to academic outcomes, and the neural correlates of grouping in typically developing children. Cogmed working memory training was found to improve performance on a battery of working memory tasks and these improvements were maintained three months after training. Cogmed was also associated with improvements in mathematical reasoning immediately after training but this was not maintained three months later. MetaCogmed, combined Cogmed and metacognitive strategy training, was found to facilitate near-transfer but not far-transfer to maths or reading compared to Cogmed alone. The findings from fMRI suggested that Cogmed increased recruitment of the middle frontal gyrus on an executively demanding working memory task and increased functional connectivity within the dorsal attention network and between areas of the posterior parietal cortex. Finally, grouping was not associated with better recall from short-term memory, however it was associated with reduced activation in the left middle frontal gyrus and left ventral premotor cortex compared to sequential rehearsal, which may suggest grouping was a more efficient strategy. This chapter will discuss theoretical and methodological conclusions, strengths and limitations, future directions, and recommendations for the field.

5.1. Theoretical Conclusions

5.1.1. Near-Transfer and Cognitive Mechanisms

A key distinction between the mechanisms of working memory training concern whether training leads to an increase in capacity, a change strategy, or both (von Bastian & Oberauer, 2014). Working memory capacity is associated with a range of cognitive abilities and predicts children's academic achievement (Alloway & Alloway, 2010), whereas strategies are typically task-specific (e.g. Bailey et al., 2008). Training capacity, therefore, may have generalisable cognitive and academic benefits, whereas training memory strategies may only benefit performance on memory tasks with similar structure.

In Chapter 2 Cogmed improved typically developing children's overall performance on the working memory tasks when compared to a non-adaptive control group. Chapter 3 demonstrated that these improvements in working memory performance were robust when compared to an adaptive control group, which better accounts for motivation and expectancy, and were maintained three months later. These findings may be explained by a change in working memory capacity, but they can also be explained by the acquisition of mnemonic strategies during training and transfer of these strategies to tasks that have similar structure to those trained on.

Increased working memory capacity would also be expected to improve performance on near-transfer tasks that are less similar to the training. The exploratory analysis of near-transfer effects in Chapter 3 showed that working memory training significantly improved performance on the Backwards Digit Recall and Dot Matrix tasks, which have very similar structure to the training tasks. Working memory training also significantly improved performance on the Digit Recall task, which would afford similar strategies to the Backwards Digit Recall task. However, there was no significant improvement on the Spatial Span task, which was the least similar to the training tasks, but involved similar visuospatial storage and mental rotation processes. Interestingly, near-transfer to the Spatial Span task was found for the group that received working memory and metacognitive training, suggesting that metacognitive training may have facilitated the production or application of strategies to less similar tasks. Another study showed that Cogmed improved performance on a simple and complex span task, but not an updating task, whereas updating training only improved performance on the updating task (Ang et al., 2015). Similarly, complex span training has been found to improve performance on complex span tasks but not structurally dissimilar tasks, such as an updating task (von Bastian & Eschen, 2016). On the other hand, it has been shown that complex span training improves performance on long-term recollection tasks (Harrison et al., 2013); however, these tasks have been shown to afford the same strategies as complex span tasks (Bailey et al., 2008).

A very recent meta-analysis of 50 Cogmed studies in children and adults directly investigated the degree of near-transfer to tasks that are directly related to the training tasks and memory tasks that are less similar (Aksayli, Sala, &

Gobet, 2018). Medium effects were observed on the nearest transfer tasks immediately and several months after training, which could be explained by practice effects and the transfer of task-specific strategies. A small-medium effect was observed on other memory tasks immediately after training and a small effect several months after training. Although the effects on the nearest transfer tasks were significantly greater than the effects on other memory tasks, the effects of working memory training were not entirely task-specific. However, it is unclear to what degree these effects may be explained by increased working memory capacity versus general strategies or approaches to complete memory tasks that were developed during training. A more detailed evaluation of transfer to memory tasks that do and do not afford similar strategies may be necessary to determine to what extent near-transfer can be explained by changes in capacity versus changes in strategy.

Similar to the findings of near-transfer in Cogmed studies, a recent meta-analysis of 33 randomised controlled trials of n-back training found a significant medium effect on performance on untrained n-back tasks and a small significant effect on other working memory tasks (Soveri et al., 2017). Type of control group moderated training effects, but near-transfer was still significant when this was controlled for. Furthermore, a more comprehensive meta-analysis of 87 working memory training programmes, mostly consisting of Cogmed and n-back studies, found large near-transfer effects on untrained working memory tasks that were similar or identical to the training and small but significant effects on other measures of verbal and visuospatial working memory, compared to active control groups (Melby-Lervåg, Redick, & Hulme, 2016). At the follow-up, on average five months post-training, the effects on similar near-transfer tasks were large and there were small effects on other measures of working memory, although this was not quite significant for verbal working memory. Interestingly, near-transfer did not correlate with degree of far-transfer to non-verbal reasoning or verbal abilities, which undermines the purported theoretical mechanisms of transfer from working memory training. However, there was no evidence that working memory training increased verbal ability and the evidence for far-transfer to non-verbal reasoning is highly contentious, as will be discussed in Section 5.1.3. The evidence for far-transfer to academic skills is more promising and the association with near-transfer should be investigated in future.

A very recent randomised controlled trial of updating and binding training with 197 young adults utilised Bayesian analyses, which can determine the strength of evidence for the null as well as the alternate hypothesis (De Simoni & von Bastian, 2018). Updating training included four adaptive tasks that required memory for stimuli that had to be updated through either a process (e.g. +2) or replacement with a new stimulus. Binding training included four adaptive tasks that required recognition of associations between pairs of stimuli. The training programmes were compared to an adaptive control group, who completed training on four visual search tasks. Near-transfer was only assessed on structurally different working memory tasks; the updating training group were assessed on the binding tasks whereas the binding group were assessed on the updating tasks. There was moderate evidence for a null effect of near-transfer, suggesting that the effects of training did not transfer to structurally different tasks. Although performance on these tasks were highly correlated at baseline they were less, although still significantly correlated, immediately after training. It is possible that training effects may have been specific to certain working memory process that were not shared between the tasks; only updating training tapped executive components of working memory whereas binding training required relatively passive storage of information.

De Simoni and von Bastian (2018) further investigated the mechanisms of transfer using measures related to the three embedded components model of working memory (Oberauer & Hein, 2012). ‘Focus switching’ refers to the ability for the focus-of-attention to shift between single items in memory, ‘removal of no longer relevant information’ refers to the unlearning of an item to reduce its interference with relevant information, and ‘interference resolution’ refers to the ability to identify the correct item by recollecting the context and inhibiting interference from highly familiar items. Although there was moderate to strong evidence for a null effect of binding training on these process-specific measures, there was inconclusive evidence that updating training may have improved focus switching and interference resolution. However, further analyses of the pattern of errors suggested that the process-specific changes in performance on the training tasks were highly specific and that they did not transfer to other tasks. One suggestion is that participants may have developed stronger stimulus representations through repetitive encoding and retrieval of the same stimuli during training. Lastly, over 80% of the participants in the working memory training groups reported using specific working memory strategies (most commonly rehearsal) to complete the training tasks. However, these strategies are unlikely to benefit performance on structurally different tasks and the difference in response modes (recall versus recognition) may be a contributing factor (Bailey, Dunlosky, & Hertzog, 2014).

Evidence suggests that working memory training increases the use of memory strategies that may improve performance on near-transfer tasks. One study in young adults showed that Cogmed improved performance on three near-transfer tasks, relative to non-adaptive training, and also increased the use of grouping on two of these tasks (Dunning & Holmes, 2014). However, improvement was found on one near-transfer task without a significant change in strategy, and a significant increase in grouping was found on another near-transfer task without a significant improvement in performance. This suggests that there is a relationship between strategy-use and working memory training, and studies have shown that children can recall more information when they have been instructed to use rehearsal (Asarnow & Meichenbaum, 1979), imagery (Pressley & Levin, 1977), or semantic sorting strategies (Schleepen & Jonkman, 2012).

A very recent randomised controlled trial of n-back training in adults directly investigated the effects of self-generated and instructed strategies during training (Laine, Fellman, Waris, & Nyman, 2018). One group were instructed to use a visuospatial strategy to mentally align subsets of size n and allow easier identification of matches. The strategy group showed larger overall improvements on the training task than a passive control group as well as the group who completed n-back training without strategy instruction. These improvements were fairly immediate as performance differences were already evident after the fourth training session. The strategy group also showed significantly greater improvements on two untrained 3-back tasks compared to the other n-back training group. However, there were no significant improvements in performance on the forward digit span, a running span task, or a selective updating task (some items are carried forward and some are replaced) where the visuospatial strategy would be inappropriate. These findings demonstrate the highly task-specific nature of some working memory strategies, which may only improve performance on one task but not other tasks that measure the same underlying construct. Furthermore, strategy-use and the level of detail provided in strategy reports by the other two groups significantly predicted performance on the n-back tasks at post-test. These findings suggest that self-generated strategies during training may explain improvements in performance. However, there was no analysis of how strategy-use in the n-back training group changed over time, which would have afforded investigation of how self-generated strategies may improve performance during training.

The development of strategies may be an important mechanism in working memory training but it does not entirely account for transfer effects. Chapter 4 showed that simply instructing children to use a grouping strategy increased their use of grouping on a near-transfer task, but it did not improve their recall. This may suggest that grouping is a product of high working memory capacity, rather than the cause. Working memory training may be associated with increased use of grouping because capacity has been increased and, therefore, afforded the use of grouping. However, it may be the case that the high working memory capacity sample in Chapter 4 were already capable of spontaneously using the most effective strategy for their individual capacity and, therefore, did not benefit from grouping instruction (see Turley-Ames & Whitfield, 2003). This was illustrated by the high rates of spontaneously reported grouping, without instruction.

5.1.2. Neural Mechanisms of Working Memory Training

Chapter 2 investigated the neural correlates of working memory training in 32 typically developing children using a range of MRI techniques. This novel approach afforded the examination of task-related brain activation, resting-state functional connectivity, and grey matter volume, as well as how these neural correlates may potentially interrelate. Working memory training increased recruitment of the middle frontal gyrus on a complex span task and increased functional connectivity within the dorsal attention network. However, there was no significant change in grey matter volume.

Increased recruitment of the middle frontal gyrus on the complex span task suggested that there was a change in how children's working memory was engaged on the task. This may reflect neuroplastic changes in the brain's response, for instance greater recruitment of neurons within a region or an increased spatial extent of the activation (Kelly et al., 2006). Increased recruitment of the lateral prefrontal cortex in children has been associated with increased working memory capacity (Klingberg et al., 2002a). Therefore, increased recruitment of the middle frontal gyrus may reflect increased working memory capacity. Interestingly, this was only the case for performance on the complex span task and not the simple span task. Meta-analyses have indicated that working memory tasks with greater executive demands are associated with greater middle frontal activation, whereas tasks requiring simple storage are associated with greater inferior frontal activation (Rottschy et al., 2012; Wager & Smith, 2003). As the complex span task required task switching and maintaining information in the face of competing processing, greater recruitment of the middle frontal gyrus may indicate greater executive control. However, it is not clear whether this reflects an increase in capacity or a strategic change in the way children approached or performed the task.

The complex span task used in Chapter 2 was visuospatial, but it could be verbally recoded into a sequence of positions, referring to 'left', 'middle', and 'right'. Therefore, the difference in middle frontal activation may reflect group differences in the use of a visuospatial or verbal strategy. Chapter 4 demonstrated that memory strategies modulate children's brain activity when performing a short-term memory task. Specifically, grouping was associated with decreased recruitment of the left middle frontal gyrus. The tasks were identical between the groups, which suggests that this change in activation was related to the particular strategy children were using on the task. As grouping is increasingly used after working memory training (Dunning & Holmes, 2014), this highlights how training may lead to changes in strategy and, therefore, changes in the recruitment of particular brain regions. However, different strategies are likely be associated with different neural correlates; for instance, chunking is associated with increased recruitment of the lateral prefrontal and parietal cortices (Bor et al., 2004, 2003; Bor & Owen, 2007). These findings highlight the value of measuring strategies to interpret mechanisms of change in future neuroimaging investigations of working memory training.

On the other hand, the observation of increased functional connectivity in the dorsal attention network after working memory training cannot be easily attributed to a change in strategy, because brain activity was measured at rest. This corroborated the findings of a similar study in typically developing children that also found Cogmed increased functional connectivity within the dorsal attention network, compared to a non-adaptive control (Astle et al., 2015). It was suggested that the increased connectivity may be the result of the repeated and demanding co-activation of this network during training. This may reflect enhanced attentional capacity that afforded greater performance on the training and transfer tasks. However, as these are measures of functional brain activity, other processes cannot be ruled out. For instance, both of these studies also included task-based functional brain imaging (see Barnes et al., 2016), which may have been associated with the use of strategies. In Chapter 2 the resting-state scan was acquired after the Odd-One-Out task and before the Dot Matrix task. Therefore, in the same context it could be possible that there was an after-effect of the task, where a particular strategy may have still been active, or a preparation effect, before starting the next task.

Other investigations have suggested that training shifts network dynamics within the fronto-parietal network towards those observed in individuals with high working memory capacity (Langer, von Bastian, Wirz, Oberauer, & Jancke, 2013). In this study 66 young adults were randomised to receive adaptive or non-adaptive working memory training on a complex span task, task-switching paradigm, and a relational integration task that required verbal reasoning and storage of relevant information. Near-transfer was measured on three structurally similar working memory tasks that used different materials and far-transfer was assessed fluid intelligence. Electroencephalography (EEG), a technique that measures cortical postsynaptic potentials on the scalp, was conducted at baseline and post-training when the participants were at rest. At baseline, overall working memory capacity was associated with increased power in the theta frequency band and increased small-worldness within the fronto-parietal network, which indicates that nodes within a network are more closely integrated and more efficient.

Adaptive training was found to improve performance on the complex span near-transfer task (von Bastian et al., 2013) and, crucially, it increased theta power and small-worldness in the fronto-parietal network relative to non-adaptive training. By demonstrating that training-related changes in the fronto-parietal network were similar to the differences between high and low working memory capacity individuals, it suggests that training may lead to neural changes that afford greater working memory capacity.

Structural brain imaging may provide an additional insight into neurological changes that are indicative of cognitive capacity. Chapter 2 found no evidence of changes in grey matter volume following working memory training, which corroborates the absence of change in a recent study in adults (Metzler-Baddeley et al., 2016a). This may suggest that working memory training does not affect the structure of grey matter, but it is also possible that these studies lacked power to detect an effect. Indeed, a larger study found reduced grey matter volume in a number of fronto-parietal regions following adaptive mental arithmetic training (Takeuchi et al., 2011). Although it is unclear why training may reduce grey matter volume, it could be caused by a relative increase in white matter density (Draganski et al., 2006). White matter supports long-range connections between remote brain regions, which may also underlie changes in functional connectivity (see Kelly & Castellanos, 2014).

Diffusion Tensor Imaging (DTI) is an MRI technique that measures fractional anisotropy, which indicates the structural integrity of white matter tracts (Beaulieu, 2002). Maturation of white matter in the fronto-parietal network has been shown to predict future working memory capacity (Darki & Klingberg, 2015) and working memory training has been associated with increased fractional anisotropy in frontal and parietal regions of the brain in adults (Román et al., 2017; Salminen, Martensson, Schubert, & Kuhn, 2016; Takeuchi et al., 2010). Specifically, one study reported increased fractional anisotropy in the intraparietal sulcus (Takeuchi et al., 2010), which was the same region that showed increased functional connectivity in Chapter 2. Therefore, it is possible that working memory training may lead to structural changes in white matter tracts that connect nodes within functional networks that support working memory.

Evidence also suggests that the neural mechanisms of working memory training change over time. Working memory training has previously been shown to increase fronto-parietal activation after two weeks and decrease activation after four weeks (Hempel et al., 2004). Similarly, brief training has commonly been associated with decreases in fronto-parietal activation whereas longer working memory training programmes have been associated with both decreases and increases in activation (Li et al., 2015). Repeated assessment of children's brain activation, working memory performance, and strategies over the course of training may provide useful insights into the cognitive and neural mechanisms of working memory training.

5.1.3. Far-transfer

A controversial topic in the working memory training literature concerns whether training leads to generalisable cognitive benefits. When considering studies with active control groups and randomisation, there is minimal evidence that working memory training improves children's academic achievement. Therefore, Chapter 3 explored the potential of concurrent working memory and metacognitive strategy training ('MetaCogmed') to facilitate far-transfer to mathematical reasoning and reading comprehension in a double-blind randomised controlled trial. The intervention included standard Cogmed training and a novel metacognitive workbook that was designed to be feasible for a teacher to deliver in an after-school club. MetaCogmed was compared to a group receiving Cogmed and a placebo workbook, and to an adaptive control group, who completed adaptive visual search training and a placebo workbook.

Both Cogmed and MetaCogmed were associated with significant improvements in mathematical reasoning immediately after training, but these effects were not maintained three months later. Importantly, these improvements were relative to an adaptive control group who were challenged and received feedback on their improvements during training. A meta-analysis of working memory training studies in typically developing children also found evidence for significant far-transfer to maths when considering all studies, but this was non-significant when only considering studies with active control groups (Sala & Gobet, 2017b). The active control groups included non-adaptive working memory training, as discussed above, but also maths training, which was found to improve maths ability (e.g. Kuhn & Holling, 2014; Passolunghi & Costa, 2016). Maths training as a control group is useful for specifically determining which intervention is more effective at improving maths ability. However, there is an important distinction between near-transfer from maths training and far-transfer from working memory training. Near-transfer may indicate a practice effect or the acquisition of task-specific knowledge and strategies, which would have limited generalisability. On the other hand, far-transfer is more indicative of an increase in cognitive capacity that may generalise further. In other words, if the improvements in maths are the result of increased working memory capacity, then the benefits may generalise to other cognitive and academic outcomes.

A more recent meta-analysis of 50 Cogmed studies, also discussed earlier, found no evidence of any far-transfer effects immediately or several months after training (Aksayli et al., 2018). Specifically, null effects were observed across far-transfer measures and there was no significant heterogeneity within or between studies when accounting for baseline differences, suggesting that there were no effects regardless of measure, age, population, or type of control group used. However, measures of far-transfer were broadly grouped according to four arbitrary domains: cognitive and attentional skills, academic skills (language and maths), IQ, and miscellaneous. As previous work by the same authors has suggested that working memory training may have a specific short-term effect on maths but not reading (Sala & Gobet, 2017b), any specific effects on maths in this meta-analysis would have been averaged with, presumably, null effects on reading. Therefore, whilst this report suggests that Cogmed does not have broad benefits to cognitive and academic skills that may be expected from increasing working memory capacity, it does not rule out the possibility that Cogmed may have more specific benefits for maths, at least in certain populations and experimental conditions, i.e. for typically developing children when compared to an adaptive control group.

A recent investigation described earlier (De Simoni & von Bastian, 2018), demonstrated moderate to strong evidence for null effects of updating and binding training on measures of reasoning, shifting, and inhibition in young adults, compared to an adaptive control group. These findings are particularly compelling because far-transfer was assessed at the construct level by averaging performance on four tasks of each construct. Furthermore, the latent factors for updating and binding moderately correlated with reasoning, suggesting that increased working memory capacity through training should theoretically support reasoning ability. However, it should be noted that the correlation between working memory and shifting was weak and that the inhibition tasks did not load on a single latent factor that would allow for such an analysis. There was also inconclusive evidence for the effect of updating training on processing speed, which was moderately correlated to with updating ability at baseline. Despite finding large effects on the training tasks there was very little evidence for far-transfer to constructs related to working memory. Similarly, a large study in older adults found moderate to strong evidence for null effects on reasoning, shifting, and inhibition after training on complex span, binding, and updating tasks, compared to adaptive visual search training (Guye & Bastian, 2017). As above, these findings suggests that working memory training does not have broad effects on cognition as might be expected if working memory capacity was increased. However, it is possible that there may be more specific effects on certain constructs that may be related to changes in specific working memory processes and the underlying neural systems.

Multiple meta-analyses of updating training have been conducted in recent years due to the contentious findings reported in one study (Au et al., 2014). This meta-analysis of 20 studies in healthy adults calculated a small but significant overall effect on fluid intelligence. However, several studies that met the criteria at the time were not included, baseline differences were not controlled for on a study-by-study level, and there was little emphasis given to the difference in effects for studies with active versus passive control groups (Melby-Lervåg & Hulme, 2016). This final point is crucial because far-transfer was only significant for studies with passive control groups, but not for studies that better accounted for the confounding effects of expectancy by using an active control group. A replication of the meta-analysis overcoming these limitations and including more recent evidence found a smaller but significant overall effect size, but this was only significant for studies with passive control groups and not for studies with active control groups (Melby-Lervåg & Hulme, 2016). Furthermore, a Bayesian re-analysis of the data by another group demonstrated strong evidence for an effect of n-back training when using a passive control group and strong evidence for a null effect when using an active control group (Dougherty, Hamovitz, & Tidwell, 2016). In response, the original authors showed that the within-group effect size in studies with passive controls was larger than that observed in studies with active controls, suggesting that n-back training was more effective in the former (Au et al., 2016). The authors suggest that differences in control for expectancy do not fully explain this pattern of results; however, it is possible that studies with passive control groups are limited by further methodological shortcomings which may inflate the effects, and may be more susceptible to publication bias. Furthermore, the authors suggest that some studies (e.g. Colom et al., 2010) were erroneously included in the re-analysis and had a negative effect size, which was particularly influential because of the large sample size.

A more recent meta-analysis included more n-back training studies than previous investigations (N=33) and only included randomised controlled trials, which are typically more methodologically rigorous and reliable (Soveri et al., 2017). Overall, there were small significant effects on cognitive control and fluid intelligence. However, type of control group (passive versus active) significantly moderated the transfer effects and controlling for this variable revealed that the far-transfer effects were non-significant. These findings are consistent with previous meta-analyses and the most parsimonious conclusion that can be drawn is that n-back training does not transfer to structurally different tasks when controlling for expectancy effects.

One of the most comprehensive recent meta-analyses of working memory training included 87 studies, multiple training regimens, and various populations (Melby-Lervåg et al., 2016). Far-transfer measures were categorised as non-verbal ability (i.e. reasoning), verbal ability (vocabulary and reasoning), word decoding, reading comprehension, or arithmetic and analysed separately for studies with active and passive control groups. Immediately post-training there was a small significant effect on reading comprehension and a small significant effect on non-verbal reasoning in n-back training studies, compared to active control groups. At the follow-up, an average five months later, a significant small effect was observed for arithmetic when considering studies with active control groups. The authors quite rightly raised concerns that in six out of the 10 comparisons for reading, four of five largest effects for n-back training on non-verbal reasoning, and three out of 15 comparisons for arithmetic at follow-up the control groups showed significant decreases from pre- to post-training. Whilst these decreases may counterintuitively contribute to the effect size, it is premature to disregard the overall effects as chance findings. For example, children who are participating in these interventions may do so at the expense of missing school lessons or after-school clubs, they may fall behind on their homework, or they may be more fatigued. The authors also noted that studies with passive control groups showed no effects on reading comprehension; however, this does not necessarily affect the interpretation of studies with active control groups, which may be generally more controlled than studies with passive control groups and, therefore, more able to detect true effects. There were, however, no significant overall effects on non-verbal reasoning, verbal abilities or word decoding immediately or five months after working memory training. Furthermore, there was evidence of publication bias in studies with active control groups, although this was only analysed for all far-transfer measures together. This meta-analysis again suggests that the effects of working memory training do not broadly contribute to cognitive functioning, but there is some evidence that it may improve academic skills, which is particularly relevant for children.

Considering interventions to improve typically developing children's academic skills more broadly, three meta-analyses conducted by Sala & Gobet (2017a) called into question the notion of far-transfer effects. Chess and music training were each associated with small overall far-transfer effects to cognitive abilities, and working memory and chess training were associated with small overall far-transfer effects academic abilities. However, the overall far-transfer effects for all three interventions were non-significant, either minimal or null, when considering only the studies with active control groups, although it should be noted that only one chess training study used an active control. Specifically, the size of the effects of music and working memory training were inversely related to the quality of the study, as indicated by the type of control group. These findings cast doubt on the presence of far-transfer from working memory training and other interventions such as music training, which are presumed to improve executive function and academic attainment. However, this analysis broadly categorised cognitive and academic measures, which may obscure more specific effects of the interventions or overlook measures that are more sensitive to training effects. Furthermore, as discussed earlier, the authors' meta-analysis of working memory training studies categorised control groups as either active or passive, when in fact some of these control groups actively trained a skill of interest. In future meta-analyses, distinctions should be made between further types of control groups in order to specify the possible positive effects of the control training and the possible negative effects that may occur at the cost of missing out on school or other activities.

5.1.4. Metacognitive Strategy Training

Chapter 3 revealed some preliminary evidence that MetaCogmed facilitated near-transfer at the three month outcome compared to Cogmed, indicating that the metacognitive workbook was effective to some extent. Metacognitive strategy training may have increased children's awareness of which strategies were most effective during working memory training, resulting in better consolidation of these strategies for retrieval at the three month outcome. Previously, working memory and metacognitive strategy training has been shown to improve children's working memory immediately (Carretti et al., 2014) and six months after training (Partanen et al., 2015), compared to reading comprehension practise or education as usual. However, this is the first time that working memory and metacognitive strategy training has been shown to have an additional near-transfer effect in children, compared to working memory training alone. Immediate improvements in the MetaCogmed group were also observed on the Spatial Span task compared to the Cogmed group, suggesting the effects of metacognitive strategy training may have been more immediate. Interestingly, this near-transfer task was the least similar to the training tasks, which may suggest that, to some degree, metacognitive strategy training increased the extent of transfer. This may have manifested from the generation or retrieval of an appropriate memory strategy or may be the result of the application of metacognitive strategies.

In contrast to the near-transfer effects, there was no evidence that metacognitive training facilitated far-transfer to academic outcomes. This may be because children had more time and, therefore, more opportunity to attempt different metacognitive strategies on the working memory training, which could then be readily applied to the near-transfer tasks. Furthermore, the working memory and metacognitive training were completed in the same context and children always had their workbooks to hand. In contrast, children had less time to practise metacognitive strategies on the maths and reading exercises, because there were only five examples of each. For further practice, it may have been necessary for children to apply these strategies in their Maths and English classes. However, the different context and different activities may have restricted transfer.

5.1.5. Neural Correlates of Grouping

Working memory training aims to increase capacity, but has also been shown to increase the use of grouping strategies (Dunning & Holmes, 2014). In adults, grouping is associated with greater recall on short-term memory, working memory, and long-term recollection tasks (Bailey et al., 2008, 2011; Dunlosky & Kane, 2007). Grouping may afford better performance on memory tasks or a high working memory capacity may afford the use of grouping. This has only been previously investigated in one study of children by examining the temporal grouping effect. However, the temporal grouping effect may be a product of the stimulus timing rather than reflecting a top-down strategic process. Chapter 4 investigated short-term recall and the neural correlates of self-reported grouping in typically developing children aged 11-14 years whilst keeping stimulus presentation constant between conditions.

Grouping was associated with decreased recruitment of the left middle frontal gyrus and increased recruitment of the left ventral premotor cortex, compared to sequential rehearsal. These findings were comparable to adult studies that reported decreased recruitment of the left middle frontal gyrus and increased recruitment of the left ventral premotor cortex for encoding temporally grouped sequences (Henson et al., 2000; Kalm et al., 2012). This suggests that strategic grouping may be similar to the processing of temporally grouped sequences and that these processes are similar between 11-14 year old children and young adults. Decreased recruitment of the middle frontal gyrus may reflect reduced load as a result of more efficient encoding or it may be related to the organisation of items in working memory (Blumenfeld & Ranganath, 2007). Consistent activation of the premotor cortex in studies of grouping and chunking (Bor et al., 2004; Bor & Owen, 2007), may suggest that is associated with the organisation of items in memory, the timing of rehearsal, or the timing of recall. However, the precise location and direction of activation in the premotor cortex has varied considerably across studies preventing any firm conclusions.

5.2. Methodological Conclusions

5.2.1. Control Groups

A critical discussion in the cognitive training literature, and psychological intervention research more broadly, concerns the type of control group used. As discussed earlier, in working memory training studies with children the size of far-transfer effects is related to the type of control group used (Sala & Gobet, 2017a); larger effects are observed in studies with passive control groups and smaller effects are observed in studies with active control groups. This pattern is also observed across populations (Melby-Lervåg et al., 2016), and when considering particular working memory training interventions such as Cogmed (Aksayli et al., 2018) or n-back training (Soveri et al., 2017). These findings suggest that passive control groups are not an appropriate comparison to evaluate the effects of working memory training because they do not control for participants’ expectancy. To elaborate, those who are receiving a training intervention may be more likely to believe that they should improve on the assessments after training, i.e. the placebo effect. However, if the control group are engaged in some form of training, that is unrelated to working memory, they may also believe that they should improve on the assessments after training. For these reasons, an active control group is essential when investigating working memory training or other psychological interventions.

Active control groups have typically consisted of non-adaptive working memory training where the difficulty of the training tasks remains at low level (e.g. Klingberg et al., 2005). However, these control groups have been widely criticised because the training is not challenging and, therefore, children may have lower expectations about its effects (e.g. Shipstead et al., 2012). Furthermore, non-adaptive training in children with poor working memory has been associated with improvements in working memory compared to a passive control group (Dunning et al., 2013), which may suggest that it has a small training effect. To remedy these possible confounds adaptive control groups have been recommended (e.g. Simons et al., 2016), which consist of adaptive training on tasks unrelated to working memory. Adaptive control training is challenging and provides feedback on the participant’s improvement on the training tasks over time. In Chapter 3, adaptive visual search training was developed for children and a recent study in adults has shown this to be an excellent control (De Simoni & von Bastian, 2018). At the latent factor level, the visual search tasks were not correlated with reasoning, processing speed, or working memory, and only weakly correlated with shifting. Furthermore, adults showed gradual improvements in the training tasks over time, they rated it as equally enjoyable, and they had similar expectations as in working memory training.

Whilst it is suggested that adaptive control groups are best suited to evaluate the specific effects of cognitive training, other control groups may also be appropriate in certain settings. It should be considered whether control training is ethically appropriate when evaluating cognitive training interventions in place of typical school lessons. Adaptive control training is known to be inert, but missing 20-25 school lessons could have considerable negative effects on children’s attainment. Education-as-usual is the most ecologically valid comparison group and it is ethically appropriate. This is similar to a ‘usual care’ control group frequently adopted in medical trials, which ensures that patients in the control group receive the best treatment based on current recommendations. Ethically this approach is far superior to a no contact or placebo control group. In medical trials, patients in the control and experimental groups both receive special attention, diagnosis, and treatment, and so they should have reasonably similar expectations. This differs in education research because schooling is the normal standard for all children, and by comparison children in an intervention may believe they are receiving special attention.

Therefore, whilst children in an education-as-usual control group are still actively engaged at school, this may be considered a passive control group because it does not control for expectancy. Section 5.5. will consider whether other school-based interventions can serve as an appropriate and ethical control to evaluate the academic outcomes of working memory training.

Notable randomised controlled trials have conducted working memory training in place of children's usual lessons and either reported null effects (Dunning et al., 2013; Hitchcock & Westwell, 2017) or a long-term decline in maths ability (Roberts et al., 2016). This suggests that missing lessons can be detrimental to academic achievement, which may counteract the effects of working memory training. Certainly this evidence suggests that working memory training cannot currently be recommended to take the place of school lessons. Studies have also reported no academic benefits of working memory training when it is delivered at home (e.g. Chacko et al., 2014). However, the findings of Chapter 3 suggest that working memory training may have academic benefits when offered in addition to the normal curriculum, after-school. Training after-school may have contextual benefits compared to home training, which might aid transfer, concentration, and peer support. Future research should investigate the potential of working memory training delivered after-school. If this finding can be replicated in typically developing children then it may also have important applications for children with poor working memory, poor academic attainment, or ADHD.

5.2.2. Common Features of Working Memory Training

A common feature of working memory training is that the difficulty adapts according to the individual's performance. This means that the individual is constantly training at a level that is close to their current capacity. Analogous to Vygotsky's zone of proximal development (Vygotsky, 1987), learning and plasticity is thought to occur when external demands repeatedly exceed current capacity limits (Lövdén et al., 2010). However, a recent study suggested that the adaptive difficulty of working memory training is not essential to outcomes (von Bastian & Eschen, 2016). One hundred and thirty young adults were randomly assigned to three working memory training groups where difficulty was either adaptive, randomised, or self-selected, or to an active control group. All working memory training groups improved on the training tasks, however there were no differences in performance on the training or near-transfer tasks between the groups. These findings instead suggest that exposing individuals to varying levels of difficulty during training was sufficient to improve performance. Although there were no significant differences in training effects, motivation, or engagement it should be considered whether there was sufficient power to detect more subtle effects and whether the different training schedules would be appropriate for children. Self-selected difficulty introduces more variability in the individuals' training levels and some children may not challenge themselves. Randomised difficulty resulted in more easy trials being presented and does not track training progress, which may be detrimental to children's engagement.

It is also common for working memory training programmes to prescribe 20-25 training sessions in an intensive five week period. This is a significant commitment for children and can be difficult for children to adhere to, as demonstrated by the significant drop-out in Chapters 2 and 3. In young adults, 10 sessions of Cogmed has been shown to significantly improve performance on the AWMA compared to non-adaptive training (Dunning & Holmes, 2014) and these effects are comparable to those observed after 20 sessions (e.g. Dunning et al., 2013). Furthermore, a reduced Cogmed training protocol which only included half the number of exercises per day was found to improve children's reading and spelling two years later, compared to education-as-usual (Söderqvist & Bergman-Nutley, 2015). These findings suggest that the effects of working memory training may be achieved in much shorter periods, although further investigation of far-transfer effects in comparison to active control groups is necessary in future.

5.3. Strengths

A major strength of all three studies presented in the thesis was the use of active control groups, which advanced previous evidence. Many previous investigations of the neural correlates of Cogmed in adults (Olesen et al., 2004; Westerberg & Klingberg, 2007) and children (Stevens et al., 2016) lacked a control group. Similarly, neuroimaging investigations of other working memory training programmes in children have lacked an active control group (Everts et al., 2015; Jolles et al., 2012). Chapter 2 utilised a non-adaptive control group, presented the first evidence of changes in working memory related activation and grey matter volume in children compared to an active control, and replicated functional connectivity changes in the dorsal attention network (Astle et al., 2015). Chapter 3 was the first and only investigation to examine the effects of working memory training on children’s academic outcomes in comparison to an adaptive control group. The addition of an adaptive control group extended upon much of the current literature that has typically used non-adaptive control groups. Findings in relation to a non-adaptive control group may be confounded by differences in expectancy and motivation. On the other hand, adaptive visual search training challenges individuals and provides feedback on improvement, and it has been shown to be an excellent control in adults (De Simoni & von Bastian, 2018). Chapter 3 demonstrated that the near-transfer effects of Cogmed observed in Chapter 2 were reliable and provided compelling evidence for a short-term improvement in children’s maths ability. Chapter 3 also utilised a placebo control for the metacognitive workbook, whereas all previous investigations of working memory and metacognitive training have lacked a control (Carretti et al., 2014; Partanen et al., 2015; van der Donk et al., 2015), which limits interpretation. Finally in Chapter 4, children in the control group were given non-specific strategy instructions about how to remember digit strings. Some previous investigations of grouping instruction in adults have lacked a control group, meaning that the effects are considerably confounded by practice and expectancy effects (Farrell, 2008, 2012). Chapter 4 contradicted previous findings, suggesting that grouping instruction was not effective, at least for 11-14 year old children with high working memory capacity.

A strength of the thesis was to evaluate an existing commercial cognitive training programme that is already widely used by children, parents and schools. By doing so, the findings presented here can directly inform consumers about the effectiveness of this product. A previous meta-analysis also suggested that Cogmed has the largest near-transfer effects and, therefore, it was logical to investigate possible neural mechanisms and whether it improves children’s academic outcomes. The thesis also uniquely contributes to a wide evidence base by presenting the only investigation of Cogmed's effects on children's brain activation and grey matter volume compared to an active control group, as well as the only investigation of Cogmed compared to an adaptive control group.

Composite assessments of working memory were used in Chapters 2 and 3 to investigate the effects of working memory training at the construct level rather than the task level. This approach allows measurement of multiple domains of working memory, i.e. verbal versus visuospatial and short-term versus working memory, and a more reliable estimate of overall working memory ability. The measurements are less task-specific; however, task-specific effects will still contribute to the overall score. Measures of academic skills were selected on the basis of their theoretical association with children's working memory capacity. Mathematical Reasoning predominantly contains word-problems and arithmetic, which are more strongly associated with working memory capacity than other aspects of maths (Peng et al., 2015), and Reading Comprehension is more strongly correlated with working memory capacity in older children, compared to basic word reading (Seigneuric & Ehrlich, 2005). Therefore, the standardised assessments selected from the WASI-II were hypothesised to be sensitive to the possible effects of working memory training.

5.4. Limitations

Chapters 2 and 3 used a battery of tasks on the AWMA to assess children's overall working memory performance. However, some of these tasks were very closely related to the training tasks, whereas others differed. A more recent development in the working memory training literature is the categorisation of near-transfer measures into very near-transfer or criterion measures, which describe tasks that are structurally very similar to the training tasks, and intermediate or near-transfer measures, which describe other working memory tasks that have a different structure to those trained on (Aksayli et al., 2018; De Simoni & von Bastian, 2018; Melby-Lervåg et al., 2016). Chapter 3 provided some analysis of the extent of near-transfer, but it was limited by the number of tasks used and their relative similarity to the training tasks. Future studies would benefit from using multiple simple span, complex span, running span, n-back, and binding tasks to estimate the extent of near-transfer.

Interpretation of the relationship between working memory training and strategies were limited in Chapters 2 and 3 because there was no measure of children's self-reported strategy-use. Future studies should investigate the relationship between improvements in children's working memory performance and change in strategy-use following working memory training. This would afford the examination of whether changes in strategy moderate improvements on near-transfer tasks following training. As in Chapter 3, predictions could be made regarding near-transfer effects based on the similarity of tasks to the training and whether they afford similar strategies. Such investigations would inform the extent of near-transfer and whether this depends on the transfer of memory strategies. Chapter 4 demonstrated a reliable measure of children's self-reported strategy use, which could be employed in these investigations. However, a more extensive classification of strategies would be required to assess strategy-use on a wider variety of tasks.

A general limitation of the studies presented is the limited power to detect more subtle effects. In Chapter 2, the behavioural analysis of 33 children was sufficient to detect a large near-transfer effect on a composite of eight working memory tasks but power may have been limited to detect an effect on the individual fMRI tasks. Furthermore, we used a 1.5T scanner which can detect approximately 1-2% of the signal change in the BOLD response (Gandolla et al., 2011), whereas a 3T scanner has improved signal-to-noise ratio (Soher, Dale, & Merkle, 2007). Combined with the relatively small sample, it is possible that the analyses of training effects on brain activation during the Dot Matrix task and changes in grey matter volume were underpowered. Furthermore, it may have been particularly difficult to assess neural changes because there are significant neurodevelopmental changes in children this age. Grey matter volume begins to decrease before puberty and white matter volume steadily increases through adolescence (Giedd et al., 2015). In Chapter 3, a large near-transfer effect and medium far-transfer effect to maths was observed; however, there was no significant difference in maths at the three month outcome. At the three month outcome, the Cogmed and MetaCogmed groups had numerically higher maths scores than the control group but is possible that this effect weakened over time. It is possible that there was still a small effect on maths at the three month outcome but the study was underpowered to detect small effects. Finally, although the overall sample size was sufficient, the high proportion of children that spontaneously reporting grouping in Chapter 4 meant that the group of children using a rehearsal strategy were somewhat underrepresented. This may have increased error or bias, limiting the power to detect group differences.

The metacognitive workbook was designed to be short add-on to working memory training to teach children metacognitive strategies in the context of working memory, reading, and maths tasks. However, this meant that there was less time, less diverse activities, no interactive work, and no classroom instruction compared to other metacognitive interventions in education (e.g. Adey & Shayer, 1993). It is recommended that future research allows more time to foster metacognitive awareness and strategies in a whole classroom setting; affording more diverse classroom activities, group work, and independent work. In addition, more efforts could be made to ensure children are practising these strategies in their lessons and homework. For example, children could be provided with a more durable strategy guide (see Chapter 3) and encouraged to use this day-to-day at school and at home.

A limitation of the study presented in Chapter 4 is that grouping was not associated with greater recall on the short-term memory task in or outside the MRI scanner. This has the advantage that the fMRI results are not confounded by performance, but the neural correlates of effective grouping may differ in meaningful ways (see Kalm et al., 2012). The absence of a behavioural effect may be because all of the children sampled had a high working memory capacity and there was no difference between those that used grouping and those that used rehearsal. Therefore, grouping may be associated with greater short-term recall when sampling children of low, medium, and high capacity. However, an interesting challenge for future work will be how to dissociate the neural correlates of grouping and working memory capacity.

5.5. Future Directions

5.5.1. Near-Transfer and Cognitive Mechanisms

The contributions of strategy and capacity to working memory training can be further examined with repeated measurements during training. It may be possible that children use normatively less effective strategies, such as rehearsal, at the beginning of training. Children may initially observe improvements on the training tasks with practice of this strategy and familiarisation of the tasks. However, rehearsal may constrain further improvements as capacity limits are reached, and a change in strategy may then be required to make more efficient use of working memory capacity. It is also possible that gradual increases in capacity afford the use of more normatively effective and effortful strategies, such as grouping (see Dunlosky & Kane, 2007). Repeated measurements of strategy-use during training may elucidate whether a change in strategy precedes performance or whether a change in performance precedes strategy.

Future work could also investigate the necessary requirements for near-transfer. First, it should be established whether grouping instruction would improve recall in children of low and average capacity. Second, strategy instruction and practice on a working memory task could be manipulated in a full factorial design. This would evaluate whether uninstructed practice or strategy instruction is sufficient for near-transfer, and whether strategy instruction in addition to task practice leads to greater improvement. As in Chapter 4, children should be asked to report what strategy they use on the near-transfer task so that the contribution of strategies to performance can be evaluated.

5.5.2. Neural Mechanisms of Working Memory Training

Although there were no significant changes in children's regional grey matter volume following working memory training, it may be possible that there were other changes in brain structure. Currently, there is no published investigation that has investigated whether cognitive training in children is associated with changes in white matter. However, white matter volume steadily increases in through childhood, adolescence, and early adulthood (Giedd et al., 2015), is related to the development of working memory (Darki & Klingberg, 2015), and may explain the protracted development of executive functions through adolescence and early adulthood (Luna & Sweeney, 2004). Therefore, an interesting avenue for future work would be to investigate whether working memory training in children affects structural connectivity, as measured by fractional anisotropy in white matter tracts using DTI. It is possible that repeated co-activation of attentional networks during training may lead to increased myelination of white matter tracts that connect regions within these networks. Indeed, these changes in structural connectivity may underlie the changes in functional connectivity observed in the posterior parietal cortex in Chapter 2 and previous research (Astle et al., 2015). Importantly, changes in brain structure would provide strong evidence for changes in processing capacity, rather than a change in strategy. Such findings may also inform about the extent of transfer to other cognitive processes that depend on the same neural systems. Critically, whereas previous research has suggested that far-transfer may occur to processes that activate similar regions of the brain as working memory, these findings may substantiate predictions about transfer to processes that are supported by the same brain regions that undergo structural changes during working memory training.

5.5.3. Approaches to Far-Transfer

If short-term improvements in maths following working memory training can be replicated in future work, then it will also be essential to investigate methods to maintain these improvements longer term. In Chapter 3, maths scores were still numerically higher than the control group after three months but no longer statistically significant. This may be related to the decline in working memory scores over the same period, which suggests it may be fruitful to investigate the potential of less frequent top-up sessions to maintain improvements in working memory over time. Finally, the generalisability of far-transfer effects should be explored when working memory training is conducted in addition to school and compared to an adaptive control group. It may be worth investigating other standardised assessments of reading comprehension that have multiple versions so as to avoid the test-retest effects observed in

Chapter 3. Furthermore, children's grades would provide ecologically valid measures of children's academic attainment.

Future research may wish to investigate a longer and more varied course of metacognitive strategy training in combination with a shorter course of working memory training (see Söderqvist & Bergman-Nutley, 2015). For example, it may be feasible to combine 30 minutes of metacognitive strategy training with 30 minutes of working memory training. Short courses of Cogmed have been found to have comparable effects to the standard programme in adults (Dunning & Holmes, 2014) and there is some unpublished evidence that shorter training sessions produce similar training effects and are more acceptable (Söderqvist, 2014). It is also recommended that future research employs objective measures of metacognitive awareness. For example, a post-task appraisal of difficulty would require children to reflect on how well they performed a task and this could be correlated with their performance (Krasny-Pacini et al., 2015). Alternatively a parent-report measure, such as the Behaviour Rating Inventory of Executive Function (Gioia & Isquith, 2011), may be appropriate if children and parents are blind to their treatment condition.

As the majority of current evidence for working memory training suggests that the effects are restricted rather than broad (e.g. Melby-Lervåg et al., 2016), new approaches to developing children's executive function should be explored. Given that working memory training is completed in a narrow context on tasks that do not represent real-world scenarios, we should perhaps not be surprised that the effects are narrow. Other approaches to improve children's executive functioning include aerobic exercise, martial arts, mindfulness practice, and classroom curricula (see Diamond, 2012; Diamond & Lee, 2011). For example, Tae-Kwon-Do has been shown to improve children's working memory and inhibitory control compared to standard physical education (Lakes & Hoyt, 2004). Another study recently showed that just 10 minutes of high-intensity exercise per day over a six week period improved children's' cognitive control and working memory, compared to an active control group who participated in quizzes and computer games for the same period (Moreau, Kirk, & Waldie, 2017). This highlights the potential of other interventions that can achieve cognitive improvements in very short periods of time that are acceptable to children and feasible for schools or parents to implement. Future research needs to explore the academic outcomes of such interventions and whether the diverse approaches to improving executive functions can be combined into a more effective programme or incorporated in school curricula.

5.5.4. Control Groups

As discussed in Section 5.2.1., control training in place of typical school lessons has significant ethical implications. Future studies may wish to consider other school-based interventions that can serve as a suitable control to evaluate the academic outcomes cognitive training. The most highly recommended interventions from the Education Endowment Foundation's teaching and learning toolkit include metacognitive strategies and self-regulation, reading comprehension strategies, and phonics (Higgins et al., 2016). It will be important to consider the magnitude and specificity of the effects of these interventions, as well as the particular aims of the study. For instance, reading comprehension strategies may specifically improve children's reading but it is unlikely to benefit other cognitive or academic skills. As working memory training is primarily of interest due to the potential for broad effects, metacognitive interventions may serve as a suitable control because they have been shown to have domain-general effects (e.g. Adey & Shayer, 1993). Metacognitive interventions are currently applied in schools and so may be considered as 'usual care' in terms of school-based interventions. However, rather than interpreting any effects of cognitive training in comparison to another school-based intervention in terms of whether cognitive training works or not, effects should be considered as cognitive training is either more or less effective than the control, whereas as no significant difference should be interpreted as the interventions are equally effective.

5.5.5. Neural Correlates of Grouping

Future studies may be able to differentiate whether the neural correlates of grouping are related to the organisation of items in memory or whether it is related to the temporal properties of rehearsal and recall. A previous study investigated the neural correlates of sub-vocal rehearsal by requesting participants to either rehearse a sequence of five random letters from memory or the letters ‘ABCDE’ (Logie et al., 2003). Interestingly, this study found rehearsal from memory was associated with increased activation of the left middle and inferior frontal gyri, similar to the findings presented in Chapter 4. Using a similar paradigm, one could investigate grouping of a random sequence of six numbers compared to grouping the numbers ‘123…456’. This could determine the neural correlates specific to grouping items in memory, as the conditions will be matched for their temporal properties during rehearsal and recall.

Another approach is to investigate which regions of the brain are essential for grouping items in short-term memory using Transcranial Magnetic Stimulation (TMS). TMS applied to the scalp produces a current on the underlying cortical surface, which is analogous to a virtual lesion. TMS could be used to disrupt activity in the dorsal and ventral premotor cortex in order to examine the effects on short-term recall and grouping. The dorsal premotor cortex has been associated with the temporal grouping effect and so TMS delivered to this region may knock out the effect, if this region is essential to performance. Similarly, the ventral premotor cortex was associated with strategic grouping in Chapter 4 and so TMS delivered to this region may impair the ability to group ungrouped sequences. This work should be carried out in adults where safety guidelines are well established (Rossi, Hallett, Rossini, Pascual-Leone, & The Safety of TMS Consensus, 2009).

5.6. Recommendations

5.6.1. Recommendations for the Scientific Community

Current evidence suggests that the generalisable effects of working memory training on cognitive and academic abilities is limited, yet the companies that sell these products still vouch for their efficacy. Commercial conflicts of interest gives rise to biases in study design, interpretation of findings, and marketing. Authors who have financial holdings in the training product may use less robust methods that may be more likely to produce positive results, run exploratory analyses without proper specification, or spin the results to fit their aims. Marketing may also conflict with a critical appraisal of the literature, leading to a superficial evaluation of positive findings and overly critical evaluation of negative findings. Indeed, companies' claims about the effectiveness of their training product will draw on studies using passive control groups and may not highlight the more compelling, and negative, findings presented in recent meta-analyses (e.g. Melby-Lervåg et al., 2016). This is particularly important as recent evidence has demonstrated that the study quality is inversely related to the size of effects, such that studies with active control groups show smaller and non-significant effects (Sala & Gobet, 2017a). Cherry-picking results biases the consumers' view of the product, who are not necessarily going to be aware of the scientific literature. Furthermore, there is a lack of transparency with commercial training products and the data that they collect, which hinders the advancement of science.

These are problems that also significantly affected the pharmaceutical industry and the field may learn from the approaches taken to reduce the bias and exploitation caused by conflicts of interest. The Prescription Medicines Code of Practice Authority (PMCPA) administers the code of practice for the pharmaceutical industry, which ensures the ethical and responsible promotion of medicines in the UK. Similar steps may be taken in cognitive training to ensure that the effectiveness of products are marketed fairly according to the best available evidence and current scientific opinion. Furthermore, the principles of OpenScience should be endorsed to allow transparency of methods and data, and to encourage further scientific discovery. Cognitive training companies and their employees should also be held accountable to the codes of best ethical practice by the British Psychological Society. They should be aware of the advances in the evidence, present evidence cautiously and honestly rather than making bold claims, and be responsible when recommending these products to wide audiences.

The same methodological issues and resolutions that are present in cognitive training interventions need to be taken forth to educational research as well. Although education-as-usual is an ecologically valid control group, it is passive in nature because it does not control for children's expectancy and the type of control group used significantly affects the interpretation of the results (Sala & Gobet, 2017a). Researchers should consider whether other evidence-based interventions can serve as a suitable and ethical control.

5.6.2. Recommendations for Parents and Educational Practitioners

Working memory training cannot currently be recommended as an educational intervention in place of school lessons. Evidence from a large randomised controlled trial showed that taking children out of lessons to complete working memory training was in fact detrimental to long-term outcomes in maths (Roberts et al., 2016). Chapter 3 showed that working memory training may have some short-term benefits to maths when provided after-school; however, this finding will need to be replicated in future research. Before working memory training can be recommended as an effective extracurricular intervention it will need to be demonstrated that these academic improvements are maintained longer term. Even as an extracurricular activity, one should consider the opportunity cost of participating in five weeks of cognitive training (Redick et al., 2015). Will the child be able to keep on top of their homework, will they have to withdraw from an after-school club, or will the training make them feel more fatigued at school? Schools should also consider the financial and time costs of supporting the training programme and what else may be achieved with same resources.

5.7. General Conclusions

This thesis has demonstrated strong evidence that working memory training improves typically developing children’s performance on near-transfer tasks. These improvements are maintained three months after training and are robust when compared to an adaptive control group. Near-transfer to structurally similar tasks to those trained on may reflect a practice effect and the transfer of task-specific strategies, rather than a change in capacity. Using a range of MRI techniques it was demonstrated that working memory training increased recruitment of the middle frontal gyrus on a complex span task and increased functional connectivity in the posterior parietal cortex. These findings may reflect increased attentional capacity as well as greater executive control on a demanding working memory task. However, the change in task-related brain activation may also reflect a change in strategy, and it was shown that activity in the left middle frontal gyrus was reduced when children used a grouping strategy on a short-term memory task. Future research should use DTI to investigate whether structural changes in white matter underlie these functional changes, as they may provide greater insight into whether and how training increases working memory capacity.

Working memory training was also associated with improvements in mathematical reasoning in the short-term. It is suggested that far-transfer to academic outcomes may only occur when training is provided in addition to school as usual and training conducted after-school may have additional contextual benefits. Furthermore, these effects may be best identified by comparison to an adaptive control group that it is unlikely to lead to any improvement in working memory. Future research will need to replicate these findings, explore methods to maintain these improvements longer-term, and determine the extent of far-transfer to academic outcomes.

Appendices

Appendix 1. Maths and Reading Workbook Exercises

12. Maths Problem Solving 2

In this section you are going to practice some maths exercises. In the first exercise, you need to read the question and solve the maths problem. In the second exercise, you need to find numbers hidden amongst other numbers.

Maths Exercise

Spinner

A fair spinner has eight equal sections with different colours on each section. Two sections are blue, one is green, three are red, and two are yellow. What is the probability that I spin red or blue?

Show all your working.

Answer: _______

3. Reading Comprehension 1

In this section you are going to practice some reading exercises. In the first exercise, you need to read the passage and answer some questions based on the information in the passage. In the second exercise, you need to find words that are related to the passage in a word search.

Reading Exercise

Read the passage and answer the questions below. As you read, think about how you are making sense of the information.

All About Meerkats

Meerkats are small mammals that live in the desert. The desert is their habitat. They are very well adapted to it. They are very small, between 9 and 14 inches high. Their fur is a tawny colour and they have a long, thin tail, with a red or black tip. Their faces are long and thin. They have black patches round their eyes, pointed brown noses and ears which can close when they are digging sand. They have long, sharp claws, good for digging their burrows and hunting for prey.

Meerkats are very social. They live in family groups of between 5 and 50 meerkats. An average size group is 20. They look out for each other. They like to groom each other and this strengthens family bonds. While the group goes hunting, one meerkat stays on guard duty. He stands on his hind legs, looking out for trouble. He barks or whistles if he sees anything worrying. Meerkats also babysit for each other and the adult will protect the baby against any predators.

Meerkats have a hard life, living in the desert, but they can eat almost anything! Their diet consists of: insects, lizards, snakes, spiders, plants, eggs, millipedes and centipedes. Tasty! They are immune to scorpion stings and they are very good at dealing with snakes.

Meerkats look very cute, they look after each other and so people love them. They are very popular in zoos and there are many documentaries about them. Also, there is a very popular TV programme, called Meerkat Manor, which is about a family of meerkats in the Kalahari Desert, named the Whiskers.

Reading Comprehension Questions

1) Circle one of the letters below to complete this sentence "Meerkats live…

a) in the desert."
b) in forests."
c) near water."
d) in cold climates."

2) Name three things that meerkats eat:

3) Explain two ways meerkats protect each other:

4) What does the passage suggest makes meerkats so popular?

5) Describe three of the meerkat's physical features.

6) How do meerkats bond with their family?

Appendix 2. Metacognitive Workbook

Sections of the metacognitive workbook:

Section	Content
1	Introduction and goal setting
2-4	Reflection exercises on working memory, reading, and maths exercises
5-6	Psychoeducation: Planning, monitoring, and evaluating
7	Personal strategy guide
8	Motivation and concentration strategies
9-20	Practising planning, monitoring, and evaluating on working memory, reading, and maths exercises

Metacognitive questions: Planning

Plan – Complete before the task

Goals

What is your goal in the Data Link task? Be specific.

Difficulty

What level are you on? ______ How difficult is it going to be?

Very Easy	Easy	Neither	Hard	Very Hard
1	2	3	4	5

How long will it take you to complete? ________ minutes

Progress

What steps do you need to take to complete the Data Link task?

Metacognitive questions: Monitoring

Monitor – Complete during the task

Goals

Are you remembering your goals? **Yes / No**

Progress and Strategies

Are you following your plan? **Yes / No**

Are your strategies working well? **Yes / No**

Have you changed your plan or strategies? How?

Mind-set

Are you in the right mind-set to complete the task to the best of your ability? **Yes / No**

Metacognitive questions: Evaluating

Evaluate – Complete after the task

Goals

Have you completed your goals? **Yes / No**

How well do you think you did on the Data Link task?

Very Poorly	Poorly	Neither	Well	Very Well
1	2	3	4	5

Progress & Strategies

How much of your plan did you follow?

None	Some	About Half	Most	All
1	2	3	4	5

When you were doing the Data Link task, what went well? Think about the steps you took and the strategies that you used.

Appendix 3. Placebo Workbook

Example Word Search Exercise

Word Exercise

In the word search below, try to find as many of the words related to the passage as you can. The words can go in any direction: to the right, left, up, down or diagonally. See how many you can cross off as you find them.

Classifieds

N	C	A	C	L	E	A	R	A	N	C	E	R	V
I	O	P	S	P	U	P	P	Y	V	O	E	H	I
S	N	P	S	C	L	A	S	S	I	F	I	E	D
N	S	O	L	P	G	O	D	P	E	E	H	S	A
I	I	I	R	C	R	W	L	A	C	T	I	V	E
C	D	N	E	Y	S	S	P	E	E	E	T	E	S
T	E	T	V	S	V	I	Y	D	S	A	D	H	T
C	R	M	L	O	A	S	E	F	S	O	E	N	A
S	E	E	I	V	H	L	D	O	N	P	O	P	E
S	D	N	S	I	I	L	E	M	U	T	S	O	C
R	I	T	M	O	O	R	W	O	H	S	N	Y	I
N	R	E	L	U	C	T	A	N	T	L	Y	E	N
A	U	S	T	I	N	O	S	S	A	E	A	C	P
E	G	A	T	N	I	V	N	T	S	A	O	U	Y

CLASSIFIED
AUSTIN
RELUCTANTLY
COSTUME
SALE
APPOINTMENT
SHOWROOM
VINTAGE
SHEEPDOG
SILVER
ACTIVE
CONSIDERED
CLEARANCE
PUPPY

Play this puzzle online at : http://thewordsearch.com/puzzle/89482/

Example Number Search Exercise

Number Exercise

In this exercise you need to search for the number 2016. It can be written horizontally, vertically, diagonally and in reverse! There are 20 in total, see how many you can find!

2	0	1	6	3	6	1	0	2	4	2	5
3	5	9	8	6	0	2	0	1	6	0	8
2	6	1	0	2	1	1	5	6	7	1	6
3	2	5	7	6	6	0	2	3	4	6	1
6	6	1	0	2	6	0	2	4	3	8	0
2	2	2	2	2	1	2	0	1	6	4	2
2	2	0	1	6	3	4	2	0	1	6	7
0	3	2	4	7	8	9	6	5	1	2	3
1	5	5	0	2	6	2	3	0	4	2	6
6	7	7	4	1	0	1	2	5	6	0	1
9	5	8	6	1	6	2	0	4	5	1	0
5	2	6	6	4	1	1	0	2	0	6	2

Appendix 4. Training Acceptability Questions

1. I enjoy doing the training.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

2. I think the training could be valuable to me.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

3. I think the training programme is easy to use.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

4. I am not trying very hard to do well on the training.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

5. I think the training is important.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

6. I think the training programme is difficult to use.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

7. I would do this training programme again.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

8. The training is fun to do.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

9. I believe doing the training could be beneficial to me.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

10. I am trying hard in the training.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

11. I don’t find the training very engaging.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

12. I think the training is boring.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

13. I put a lot of effort into the training.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

14. I don’t think the training is very important.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

15. The training programme is very interesting.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

16. It is important to me to do well on this training.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

17. I find the training very challenging.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

18. The training is very easy.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

19. I find the training programme very engaging.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

20. I am not putting much effort into the training.

Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
1	2	3	4	5

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