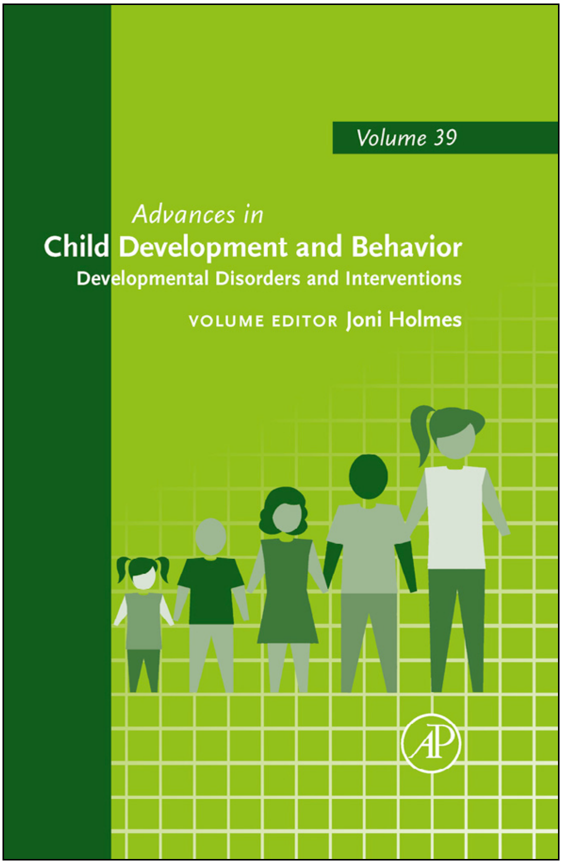

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POOR WORKING MEMORY: IMPACT AND INTERVENTIONS

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I. Introduction

Poor working memory is not yet a recognized developmental disorder. However, children with poor working memory function are at very high risk of educational underachievement (e.g., Gathercole & Alloway, 2008) and it has recently been suggested that deficits in working memory might be a cognitive phenotype for children who make slow progress at school, but who do not have general learning difficulties (Gathercole, 2010). Moreover, working memory impairments are associated with a wide range of developmental disorders of learning, including attention-deficit hyperactivity disorder (ADHD), dyslexia, specific language impairment (SLI), Down syndrome, and reading and mathematical difficulties (see Alloway & Gathercole, 2006). The early recognition of working memory difficulties and the provision of effective educational support and targeted intervention are therefore paramount to improving the long-term outcomes for a vast number of children.

So, what is working memory and how can we identify children with *poor* working memory? The term working memory describes our ability to hold in mind and manipulate information for brief periods of time during complex cognitive activities. There are several theoretical models of working memory which differ in their views of the nature, structure, and function of the system (for a review, see Conway, Jarrold, Kane, & Towse, 2007; Miyake & Shah, 1999). The primary distinction between these models is whether working memory is conceived as a distinct entity (e.g., Baddeley, 2000; Baddeley & Hitch, 1974) or a limited capacity process of controlled attention that acts to activate existing representations in long-term memory which then become the current contents of working memory (e.g., Anderson & Lebiere, 1998; Barrouillet, Bernardin, & Camos, 2004; Cowan, 2005; Engle, Kane, & Tuholski, 1999; Kintsch, Healy, Hegarty, Pennington, & Salthouse, 1999). Most accounts of working memory distinguish between the storage-only capacities of short-term memory (STM) and the storage and processing functions of working memory. They also agree that the capacity of working memory is limited, meaning there is an upper limit to the amount of information that can be stored and processed at any given moment in time.

According to one of the most widely accepted models (Baddeley, 2000; Baddeley & Hitch, 1974), working memory is a multicomponent system. There are two domain-specific STM stores, the phonological loop and the visuospatial sketchpad, that are specialized for the temporary maintenance of verbal and visual and spatial information, respectively. These are governed by a domain-general central executive system linked to attentional control, responsible for holding and manipulating information from long-term memory, coordinating performance on dual tasks, switching between retrieval strategies, and inhibiting irrelevant information (e.g., Baddeley, 1996; Baddeley, Emslie, Kolodny, & Duncan, 1998; Engle & Kane, 2004; Engle *et al.*, 1999; Kane, Conway, Hambrick, & Engle, 2007, Kane & Engle, 2000; Kane, Hambrick, & Conway, 2005). The fourth component, the episodic buffer, is responsible for integrating information from the subcomponents of working memory and long-term memory (Baddeley, 2000).

An individual's working memory capacity can be assessed using both simple and complex span tasks. Simple span tasks, also known as STM tasks, involve the storage of either verbal or visuospatial material. These assess the phonological loop and visuospatial sketchpad components of the Baddeley and Hitch (1974) working memory model, respectively. Complex memory span, or "working memory," tasks impose significant demands on both storage and processing, and require the support of both the central executive, plus the respective storage components of working memory. Thus, verbal working memory tasks such as reading and listening span (Daneman & Carpenter, 1980; Daneman & Merickle, 1996) rely on both the central executive and the phonological loop, whereas working memory tasks involving visuospatial material draw upon the central executive and the visuospatial sketchpad (Alloway, Gathercole, & Pickering, 2006; Kane *et al.*, 2004).

There are currently two standardized test batteries designed to assess children's working memory capacities, the Automated Working Memory Assessment (Alloway, 2007) and the Working Memory Test Battery for Children (Pickering & Gathercole, 2001). Both provide multiple assessments of the different aspects of short-term and working memory and, because age norms are available, can be used to identify children who have poor working memory for their age. In our own research, we typically classify children as having poor working memory skills if their standard scores on two separate tests of working memory are at least one standard deviation below the mean (bottom 15th centile, standard scores < 86). It is these children who we know are at substantial risk of poor educational progress. When diagnosing a child with poor working memory, it is important to take into account potential non-memory causes of low test performance. For example, factors such as speech-motor dysfunction and hearing or sight problems might give rise to inaccurate encoding or recall, which will affect performance negatively. The Working Memory Rating Scale (Alloway, Gathercole, & Kirkwood, 2008) can also be used to identify children with working memory impairments. This is a behavioral rating scale consisting of 22 statements, which are rated by a child's teacher. It provides a quick and efficient method for the early identification of working memory problems in a school setting.

II. Cognitive Profile

Poor working memory is associated with a wide range of cognitive difficulties that primarily relate to learning, but which we have recently seen extend to other executive functions including planning, problem solving, and sustained attention (Gathercole *et al.*, 2010). Low working memory is also related to below-average intelligence (IQ) and deficits in working memory are key markers of a number of developmental disorders of learning. Each of these issues is considered in the following sections.

A. POOR WORKING MEMORY AND LEARNING IMPAIRMENTS

Working memory skills are highly associated with children's abilities to learn in key academic domains such as reading, mathematics, and science (Gathercole & Pickering, 2000; Geary, Hoard, Byrd-Craven, & De Soto, 2004; Holmes & Adams, 2006; Jarvis & Gathercole, 2003; Swanson & Saez, 2003). Children's performances on tests of working memory are also significantly associated with the developmental precursors of reading, writing, and mathematics as children commence formal schooling (Gathercole, Brown, & Pickering, 2003) and are excellent prospective indicators of academic performance, predicting children's attainment on National achievement tests at 7, 11, and 14 years of age (Gathercole, Pickering, Knight, & Stegmann, 2004; Jarvis & Gathercole, 2003).

Working memory is used to process and store information during complex and demanding activities (Just & Carpenter, 1992). It therefore supports many activities children routinely engage in at school. Imagine, for example, attempting to read and comprehend a passage of text. The process of reading sentences, holding them in mind, and integrating the information to uncover the meaning relies heavily on the ability to simultaneously process and store information over the short term. Similarly, solving a mathematics problem, such as multiplying two numbers together, involves the temporary storage of digits whilst simultaneously retrieving learned rules of multiplication and stored number facts from long-term memory.

Beyond support for everyday mental activities, working memory also provides vital support for learning across the school years. Children with poor working memory characteristically underachieve at school (Gathercole & Alloway, 2008) and, conversely, children who underperform at school typically have working memory impairments. Gathercole and colleagues found that 41% of children who achieved below-average scores on National English tests at 6 and 7 years of age had working memory scores in the deficit range, as did 52% of children who achieved the same low levels in National Mathematics tests at this age. Similar proportions were reported for adolescents who scored in the below-average range on National tests in English, Mathematics, and Science at 14 years of age, with more severe working memory impairments associated with below-average performance in Science and Mathematics. Across both age groups, STM scores for low achievers did not differ significantly to average and high achievers, suggesting it is working memory rather than STM that limits learning opportunities (Gathercole *et al.*, 2004). Overall, these data show that the incidence of poor working memory is more than three times higher in low achievers compared to the normal school population, in which approximately only 16% would be expected to show working memory deficits.

At the extreme end of the school distribution, distinctive working memory profiles characterize children with special educational needs (SEN). Pickering and Gathercole (2004) reported that children with general learning difficulties in English/literacy and mathematics were six times more likely to have both poor verbal and visuospatial STM and verbal working memory scores than children without SEN. Children with SEN specifically related to language were also impaired on tasks that measured short-term and working memory, although their STM deficits were limited to the verbal domain. Conversely, children with noncognitive SEN such as behavioral problems had working memory skills in the normal range. These distinctive profiles suggest that children with SEN have deficits in working memory that compromise their educational progress.

The severity of a child's SEN in literacy or mathematics is associated with the severity of their memory impairment. Children whose needs are of the greatest severity, indexed by requiring additional resources to support their learning, show commensurately greater cognitive deficits than children with milder learning difficulties. Their deficits are particularly marked in tasks measuring verbal working memory (Alloway, Gathercole, Adams, & Willis, 2005).

Studies of children identified solely on the basis of poor working memory, rather than poor educational progress or SEN, show that they are very likely to struggle at school. Gathercole and Alloway (2008) recently examined the academic profiles of a large group of children with poor working memory. Over 300 children aged 5 or 6 and 9 or 10 with scores in the bottom 10th centile were identified. Of these children, 75% of the 5 and 6 year olds and 83% of the 9 and 10 year olds had difficulties in both reading and mathematics. An additional 5% of the 5 and 6 year olds were struggling in mathematics only. These figures clearly illustrate impaired rates of learning in children with poor working memory.

These children also struggle to successfully complete a range of tasks that are designed to aid learning at school. Common classroom activities that require large amounts of information to be held in mind are particularly challenging for children with poor working memory. One of the most crucial aspects of classroom learning is following spoken instructions given by the teacher, and this is particularly difficult for children with small working memory capacities. Teacher instructions are often multistep, directing children where they or their classroom objects should be, contain vital information about learning activities, or relate to a sequence of actions that must be carried out. To perform these actions, children must be able to remember the different parts of the instruction whilst carrying out the various steps to complete the action successfully. Children with poor working memory typically either carry out the first command of a multistep instruction, skip straight to the last step, or simply abandon the task all together as they are unable to remember all the necessary parts of the sequence (Gathercole & Alloway, 2008; Gathercole, Lamont, & Alloway, 2006). Children with low working memory have also been shown to be poorer in laboratory tasks that involve carrying out the actions described by a multistep instruction and remembering the content of the instruction (Gathercole, Durling, Evans, Jeffcock, & Stone, 2008).

These children also experience difficulties in classroom activities that require information to be both processed and stored. For example, writing activities that require children to count the number of words in a sentence, write down the sentence, and then check that what they have written contains the same number of words as were originally counted require children to store the number of words in mind, remember the sentence, and also engage in the mentally challenging processing of writing down the sentence (Gathercole & Alloway, 2008).

Children with poor working memory also make characteristic errors in their classroom work. These include failing to keep track of their place in demanding and complex activities and mistakes in writing and counting. In their written work, they miss out letters, skip whole words, or blend parts of different words from different sentences. So, for example, if they were asked to copy the title of a piece of work "My Holiday" and the date "17th June," they might write down "My Holune." In counting tasks, they lose track of which numbers they are working with and where they are in the calculation. For example, if they were adding the numbers 28, 7, and 11, they might miss out the 7 and only add together the numbers 28 and 11. In most cases, children fail to self-correct which ultimately leads to failure (Gathercole & Alloway, 2008).

These kinds of activities, which are common place in the classroom, typically overload the working memory capacities of many children. This memory overload causes problems in following teacher instructions, remembering information vital to individual tasks, and keeping track in structured learning activities (Gathercole & Alloway, 2008; Gathercole *et al.*, 2006). Over time, these frequent missed learning opportunities amount to slow educational progress and poor academic attainment (Gathercole & Alloway).

B. LOW WORKING MEMORY AND IQ

There is considerable overlap between performance on tests of working memory and IQ, with correlations as high as 0.8 reported between working memory and reasoning tasks (Kyllonen & Christal, 1990) and similarly high levels of association observed between executive function and IQ tests (Miyake, Friedman, Shah, Rettinger, & Hegarty, 2001). One explanation is that the two domains are overlapping but dissociable and that the shared variance between working memory and IQ occurs because methods of assessing IQ are strongly influenced by working memory (e.g., Jurden, 1995). Carpenter, Just, and Shell (1990) first suggested that working memory capacity may be a main factor underpinning individual differences on the Raven's Progressive Matrices test, a commonly used nonverbal IQ test, in the early 1990s. Since then, working memory has been reported to predict performance on various tests of general IQ (Engle *et al.*, 1999; Kane *et al.*, 2004) and assessments of working memory are now an integral part of one of the most widely used IQ assessments, the Wechsler Intelligence Scales for Children IV (Wechsler, 2004).

There are, in fact, clear distinctions between IQ and working memory. First, working memory tasks assess different aspects of a single, well-understood memory system. IQ assessments, however, aggregate performance across a wide range of abilities, which includes language and nonverbal reasoning. The two domains are also separate in the extent to which a child's prior knowledge and experiences contribute to performance. Verbal IQ assessments rely heavily on a child's knowledge of words and language, which are influenced by background factors such as their home language environment and level of education (Brooks-Gunn, Klebanov, & Duncan, 1996; Hoff & Tian, 2005; Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991). Working memory tasks, however, are equally unfamiliar to all children, conferring no obvious advantages or disadvantages to children from different backgrounds. Studies have shown that children from minority ethnic groups and poor economic circumstances score poorly on tests of vocabulary knowledge but not on measures of either verbal STM (Campbell, Dollaghan, Needleman, & Janosky, 1997; Ellis Weismer *et al.*, 2000; Engel, Santos, & Gathercole, 2008; Santos & Bueno, 2003) or verbal working memory (Engel *et al.*, 2008).

Working memory and IQ also make distinct contributions to learning. Working memory predicts unique variance in children's attainment above and beyond what can be predicted by IQ (Gathercole, Alloway, Willis, & Adams, 2006). Furthermore, associations between working memory and attainment persist after differences in performance IQ or verbal IQ have been statistically controlled both in children with and without learning difficulties (e.g., Cain, Oakhill, & Bryant, 2004; Siegel & Ryan, 1989; Swanson & Sachse-Lee, 2001). For these reasons, working memory tests appear to provide culture-fair indices of a child's cognitive potential.

Despite differences between working memory and IQ, children with poor working memory typically have low range IQ, and vice versa. In a recent comparison of the cognitive profiles of 50 children with low working memory (standard scores below 86 on two tests of working memory) and 50 age-matched children with average working memory (standard scores over 90 on two working memory assessments), we found significant group differences in both verbal and performance IQ. In both cases, the average working memory group had significantly higher scores than the low memory group (see Figure 1).

Of the low working memory group, 14% had verbal IQ scores in the extremely low range (standard scores below 70), 30% scored in the poor range (standard scores in the 70–80 range), 54% in the average range (scores between 86 and 115), and a further 2% scored above average (standard scores in excess of 116). For performance IQ, 6% scored in the extremely low range, 50% in the poor range, and 44% in the average range. Overall, these data show that the majority of children with poor working memory have IQ scores in the poor average range, with very few in the extremely low IQ category (Gathercole *et al.*, 2010).

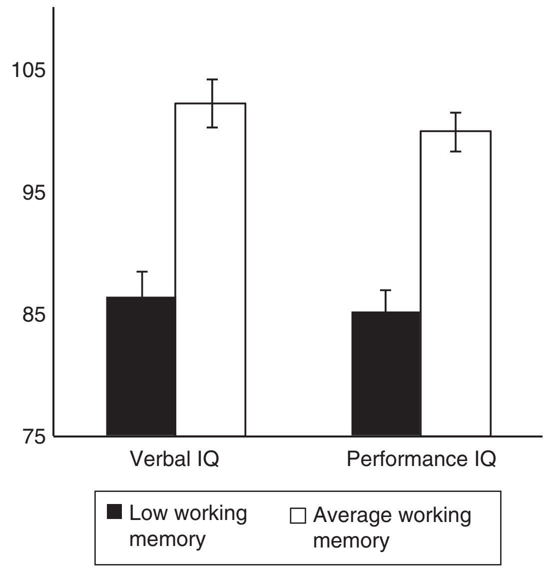

Fig. 1. Verbal and performance IQ scores of 50 children with poor working memory and 50 age-matched children with average working memory, from Gathercole et al. (2010).

C. WORKING MEMORY DEFICITS AND PERVASIVE EXECUTIVE FUNCTION IMPAIRMENTS

Working memory is one of several executive functions that support flexible goal-directed behavior. Others include inhibition, switching, planning, and problem solving (Pennington & Ozonoff, 1996). Inhibition involves controlling an overlearned or prepotent response (Stroop, 1935); switching/shifting is involved in changing between mental sets, multiple tasks, or from one situation, or aspect of a situation, to another (e.g., Monsell, 1996); planning involves setting goals, developing appropriate steps ahead of time, and anticipating future events; and problem solving allows us to initiate behavior to solve tasks by engaging in flexible thinking.

The extent to which problems in working memory extend to other executive functions is not at present well understood. In children as in adults, individual differences studies have distinguished working memory from inhibitory control and set-shifting behavior (Miyake *et al.*, 2000; St. Clair-Thompson & Gathercole, 2006). However, behavioral ratings of children with poor working memory include executive function difficulties such as monitoring the quality of their own work and generating new solutions to problems (Gathercole, Alloway, *et al.*, 2008).

To investigate whether the working memory problems faced by children with poor working memory are part of a more pervasive pattern of impaired executive function, we recently assessed 50 children with working memory deficits, and a comparison group of 50 age-matched children with average working memory, on a range of tests of executive function (Gathercole *et al.*, 2010). All children completed standardized tests of cognitive inhibitory control, set-shifting, planning, motor inhibition, and sustained attention. Where appropriate, measures of basic information processing were taken for comparison with higher level executive control. Performance for both groups on the primary higher level tasks is summarized in Table I.

Overall, we found that children with poor working memory had difficulties that extended to other executive functions, but which did not reflect higher level executive impairments in set-shifting or inhibition. Children with poor working memory were characterized by significantly higher error rates on a set-shifting task and an inhibition task, a greater number of rule violations on a planning task, and a higher incidence of omissions on a sustained attention task in comparison to the average working memory group. They also had significantly slower completion times on the inhibition task and were significantly impaired relative to the comparison group on measures of motor inhibition and problem

Table I
Mean Executive Function Scores for Low and Average Working Memory Children, from Gathercole et al. (2010)

Measure		Low WM		Average WM	
		M	SD	M	SD
Set-shifting	Time	9.50	3.11	10.56	2.92
	Errors	30.17	21.62	45.51	18.31
Inhibition	Time	9.38	3.02	11.68	2.92
	Errors	44.30	27.37	65.00	25.07
Planning	Total	12.54	4.88	12.94	3.83
	Errors	38.60	39.33	61.54	41.11
Sustained attention	Omissions	40.56	29.40	23.36	21.21
	Commissions	74.40	74.36	48.04	51.65
Motor inhibition	Total	4.14	3.57	9.28	3.69

Note: Set-shifting, inhibition time scores, and planning and motor inhibition total scores are scaled scores ($M=10$, SD$=3$); set-shifting, inhibition, and planning error scores are cumulative centiles-lower scores indicate a higher number of errors; sustained attention scores are counts.

solving. However, their performance on the inhibition and set-shifting tasks was not disproportionately greater in conditions that required executive intervention compared to their performance on tasks that tapped the basic cognitive processes necessary for completion of the higher level task. For example, although they performed poorly on the Stroop-like inhibition task, their performance on this higher level task was not disproportionately poorer than on the basic color naming and word reading aspects of the task. Thus, their weaknesses in basic processing underpinned their impairments in the higher level executive tasks. These data show that children with low working memory have deficits that are manifest in a variety of cognitively demanding activities, but that they do not have selective impairments in high-level executive functions of inhibition or set-shifting.

In summary, there is evidence from these standardized cognitive assessments that executive function impairments that extend beyond working memory are present in these children. This is also strongly reflected in teacher ratings of classroom behavior, which point to problems in monitoring and planning, problem solving, and shifting (Gathercole, Alloway, *et al.*, 2008). Although they struggle in cognitive tasks designed to measure planning, problem solving, and sustained attention, children with poor working memory do not have specific deficits in inhibition and set-shifting (Gathercole *et al.*, 2010).

Working memory and executive difficulties might co-occur because limited working memory capacities constrain performance on tasks that explicitly require the storage and processing of information. For example, problems in planning and monitoring may result from the loss of task information and goals from working memory. It is also possible that the inattentive profile of children with poor working memory results from the loss of goal-critical information from working memory (this is discussed in detail later in this chapter). By this account, poor working memory function underpins deficits in a range of executive tasks. However, the issue of causality is one that needs further exploration as it is equally possible that executive function failures may be the cause rather than the consequence of poor working memory.

D. WORKING MEMORY AND DEVELOPMENTAL DISORDERS OF LEARNING

The cognitive profiles of children with poor working memory overlap with a number of developmental disorders of learning. These include reading and mathematical difficulties, dyslexia, SLI, Down syndrome, William's Syndrome, and ADHD.

Very low levels of performance on working memory tasks are common in children with specific difficulties in reading (Gathercole, Alloway, *et al.*, 2006; Pickering & Gathercole, 2004; Swanson, 1993, 2003). Verbal STM is significantly associated with reading development during the early years (Gathercole & Baddeley, 1993) and deficits in this component of the memory system are common among children with reading difficulties (Siegel & Ryan, 1989; Swanson & Siegel, 2001). Verbal working memory skills have also been found to be consistently associated with children's reading skills (e.g., de Jonge & de Jong, 1996; Engle, Carullo, & Collins, 1991) and explain unique variance in reading comprehension over and above verbal STM, word reading, and vocabulary knowledge (e.g., Cain *et al.*, 2004; Swanson & Jerman, 2007). Furthermore, impairments in complex span tasks that tap working memory extend across both the verbal and nonverbal domain, indicative of a modality-general impairment in working memory in poor readers (Chiappe, Hasher, & Siegel, 2000; de Jong, 1998; Gathercole, Alloway, *et al.*, 2006; Palmer, 2000; Swanson, 1993).

Individuals whose reading problems satisfy the more stringent criteria for dyslexia also perform below average on both short-term and working memory tasks in the verbal domain (Jeffries & Everatt, 2003, 2004). Children with SLI show the same pattern of highly specific deficits in the verbal domain, with severe impairments in both verbal STM (Archibald & Gathercole, 2006; Edwards & Lahey, 1998; Ellis Weismer, Evans, & Hesketh, 1999; Gathercole & Baddeley, 1990; Montgomery, 1995) and verbal working memory (Archibald & Gathercole, 2007; Ellis Weismer *et al.*, 1999; Montgomery, 2000a, 2000b). It has been suggested that poor verbal storage skills underlie impairments in verbal working memory in this group (Archibald & Gathercole).

Children with mathematical difficulties also show signs of working memory deficits (Bull & Scerif, 2001; Geary, 1993; Mayringer & Wimmer, 2000; Passolunghi & Siegel, 2004; Siegel & Ryan, 1989; Swanson & Beebe-Frankenberger, 2004). These children typically perform poorly on measures of visuospatial STM and working memory (Gathercole & Pickering, 2000; Geary, Hoard, & Hamson, 1999; McLean & Hitch, 1999; Siegel & Ryan), but not on measures of verbal STM (McLean & Hitch; Passolunghi & Siegel).Working memory appears to play an important role in the development of counting, with children with poor working memory using primitive finger-counting strategies that have relatively low working memory demands (Geary *et al.*, 2004). Their continued use of these early strategies prevents them establishing networks of arithmetic facts in long-term memory, which are necessary to support the use of efficient retrieval-based strategies analogous to those used in adulthood (e.g., Hamann & Ashcraft, 1985; Kaye, 1986). Thus, poor working memory impedes the learning of number facts (Geary, 2004), the learning and efficiency of number transcoding (Camos, 2008; McLean & Hitch) and computational skills (Wilson & Swanson, 2001). It also causes difficulties in solving mathematical problems expressed in everyday language (Swanson & Sachse-Lee, 2001).

Impairments in working memory are also associated with a variety of genetic pathologies, including Down syndrome and William's syndrome. There is considerable evidence for marked deficits in verbal STM among children with Down syndrome (e.g., Jarrold, Baddeley, & Hewes, 1999). These children typically perform at age-appropriate levels on visuospatial STM tasks and do not appear to have deficits in working memory when compared to controls (Numminen, Service, Ahonen, & Ruoppila, 2001; Pennington, Moon, Edgin, Stedron, & Nadel, 2003). In marked contrast, children with William's syndrome have much stronger verbal STM than visuospatial STM skills (Jarrold, Baddeley, Hewes, & Phillips, 2001). This pattern of impairment is most likely related to the double dissociation between verbal and visual processing skills in William's syndrome.

Children with behavioral difficulties such as ADHD are also characterized by poor working memory function (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Children with ADHD perform poorly on tests of visuospatial STM (Barnett *et al.*, 2001; Martinussen *et al.*; Mehta, Goodyear,

& Sahakian, 2004) and both verbal and visuospatial working memory tasks (Martinussen & Tannock, 2006; Martinussen *et al.*; McInnes, Humphries, Hogg-Johnson, & Tannock, 2003; Roodenrys, 2006; Willcutt, Doyle, *et al.*, 2005). Their verbal STM appears to be relatively preserved, suggesting that verbal storage problems are not fundamental features of the disorder (e.g., Martinussen & Tannock). Our own data from a sample of 83 children aged 8–11 years with a clinical diagnosis of combined type ADHD concur with this pattern of impairment. We found that whilst verbal STM was relatively intact in this sample, visuospatial STM scores were in the low average range with substantial deficits in verbal and visuospatial working memory (Holmes, Gathercole, Place, Alloway, Elliott, & Hilton, 2009; Holmes, Gathercole, Alloway, *et al.*, 2010—see Figure 2). Of the total sample, 19.8% had impairments in verbal STM, which is close to the level of 16% that we would expect in the normal population. However, 38.6% had deficits in visuospatial STM, over half had impairments in verbal working memory (50.6%) and 63.9% had very poor visuospatial working memory.

It is possible that working memory problems may be the cause of the inattentive and distractible behavior associated with ADHD. To complete a task successfully, working memory resources support the maintenance of task goals as well as the different elements of the ongoing mental activity to achieve the goal—it enables us to stay on task and focus on the salient aspects of the task. Poor working memory function may therefore cause attention to shift away from the task at hand, resulting in the loss of part or all of the necessary information needed for task completion. This will

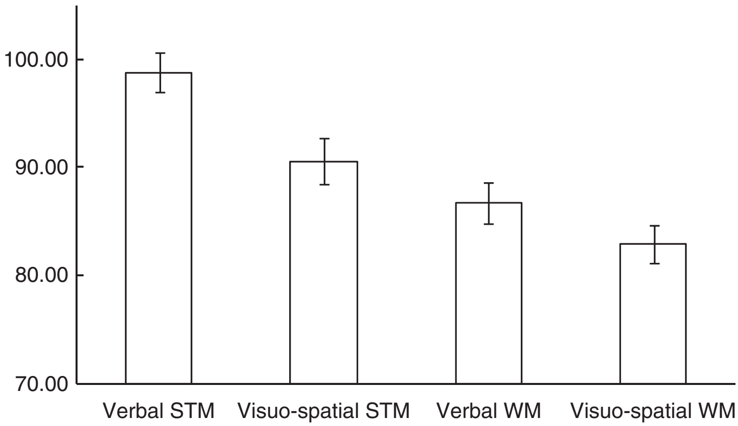

Fig. 2. Working memory profiles of 50 children with ADHD, from Holmes et al. (2010).

result in task failure, and as a consequence, individuals with ADHD may well appear to have short attention spans and to be distractible (Holmes, Gathercole, Alloway, *et al.*, 2010).

In summary, impairments in working memory are associated with a broad range of genetic and neurodevelopmental disorders of learning, with markedly distinct profiles of deficit characterizing different disorders. Deficits in the verbal domain are associated with specific language difficulties, such as SLI and dyslexia and are also characteristic of individuals with Down syndrome who experience severe language delays and difficulties. Conversely, children with William's syndrome exhibit domain-specific impairments in visuospatial memory. Unlike the other disorders discussed here, ADHD is associated with a domain-general impairment in working memory combined with deficits in visuospatial STM. There is now abundant evidence that tasks that require storage but no further processing of visuospatial material depend significantly on the domain-general resources of working memory (Miyake *et al.*, 2001; Wilson, Scott, & Power, 1987), rather than a distinct visuospatial store. This is particularly true in young children (Alloway *et al.*, 2006). Thus, the memory profile of children with ADHD corresponds to a singular impairment in the domain-general working memory system, which may cause the inattentive behavior that is characteristic of the disorder (Holmes, Gathercole, Alloway, *et al.*, 2010). Children with general reading difficulties have deficits in all aspects of working memory, whereas children with mathematical difficulties have severe impairments in verbal and visuospatial working memory and visuospatial STM, but not verbal STM. Children with poor working memory also have pervasive domain-general working memory deficits, akin to children with reading difficulties, mathematical difficulties, and ADHD. These are twinned with substantial impairments in visuospatial STM and poor verbal STM (see Figure 3).

E. COGNITIVE PROFILE—SUMMARY

To summarize, due to the key role working memory plays in supporting learning, both in classroom activities and in online mental activities, over 80% of children with small working memory capacities struggle in reading and mathematics (Gathercole & Alloway, 2008). Related to this, poor working memory function is characteristic of a number of developmental disorders of learning, including language, mathematical, and behavioral difficulties. Children with poor working memory also have deficits that are manifest in a variety of cognitively demanding activities, such as planning, sustained attention, problem solving, and IQ tasks. It is

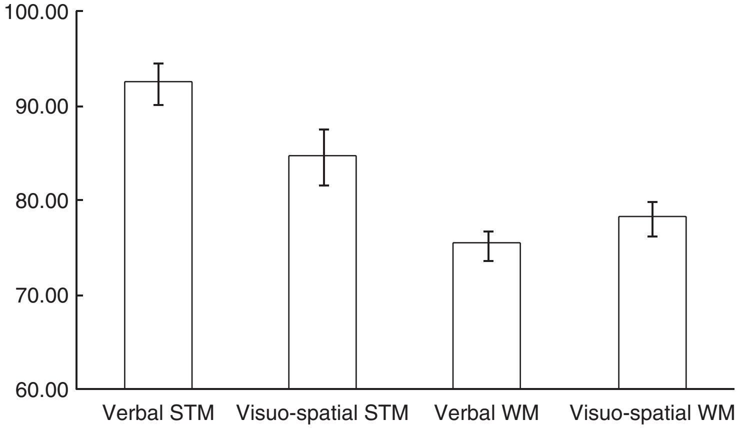

Fig. 3. Working memory profiles of 50 children with poor working memory, from Gathercole et al. (2010).

suggested, however, that they do not have selective impairments in high-level executive functions. Rather, limited memory resources constrain performance on a range of executive tasks (Gathercole *et al.*, 2010).

III. Social and Behavioral Profile

Poor working memory is associated with relatively normal social integration, self-esteem, and emotional control. However, high levels of inattentive and distractible behavior accompany working memory problems and individuals with poor working memory have difficulties maintaining focused behavior in practical situations.

It is now widely recognized that the majority of problems in individuals with poor working memory are related to inattentive and distractible behaviors. Both children and adults with low memory experience difficulties in practical situations that require maintained and focused attention. Kane, Brown, McVay, Silvia, Myin-Germeys, & Kwapil, (2007) found that typically developed adults with low working memory spans were more likely to "zone out" when engaged in demanding ongoing activities than individuals with higher working memory spans. They asked individuals to rate their behavior on several dimensions at eight random points during the day. Those with higher working memory spans were less likely to report instances of mind wandering and were able to maintain on task thoughts better during challenging cognitive tasks than those with poor working memory.

Poor working memory function is also closely associated with inattentive behavior in children. In a nonclinical sample, Aronen and colleagues found children with low working memory performance were reported by teachers to have more academic and attentional difficulties at school than children with good working memory performance (Aronen, Vuontela, Steenari, Salmi, & Carlson, 2005). Similarly, children identified solely on the basis of poor working memory skills have high levels of inattentive and distractible behavior. Teachers often describe them as having short attention spans and rarely say that they have memory problems (Gathercole, Alloway, *et al.*, 2006). Furthermore, when asked to rate behavior on commonly used checklists such as the Conner's Teacher Rating Scales (Conners, 1997), teachers typically judge children with poor working memory to be highly inattentive with high levels of distractibility. Over 70% of children aged 5 or 6 years with low working memory have markedly atypical scores on the cognitive problems/inattention subscale of the Conner's checklist (75% reported in Alloway *et al.*, 2009a, 2009b studies of 53 children; 79% reported in Gathercole, Alloway, *et al.*'s (2008) and Gathercole, Durling, *et al.*'s (2008) studies of 29 children). Figures for older children range from 58% (Alloway *et al.*, 2009a, 2009b) to 70% (Gathercole, Alloway, *et al.*, 2008). Gathercole, Alloway, *et al.* (2008) found that the majority of elevated scores were largely due to high ratings on problem behaviors that relate to inattention and short attention spans. In stark contrast, they found that none of the children in a comparison group of 20 children with typical working memory had atypically high levels of inattentive behavior.

ADHD in childhood is also characterized by both working memory deficits and inattentiveness (Holmes, Gathercole, Alloway, *et al.*, 2010; Klingberg *et al.*, 2005; Martinussen & Tannock, 2006; McInnes *et al.*, 2003; Willcutt, Doyle, *et al.*, 2005; Willcutt, Pennington, *et al.*, 2005). The co-occurrence of working memory and attentional problems in poor working memory and ADHD groups suggests there may be substantial overlap in the behavioral characteristics of the two groups. In a recent study, we directly compared teacher behavior ratings for 59 children with a diagnosis of ADHD and 27 children of the same age with low working memory (see Alloway, Gathercole, Holmes, Place, & Elliott, 2009). Teachers were asked to rate the extent to which a child has shown problem behaviors in school over the past month on the Conners' Teacher Rating Scale Revised Short-Form (Conners, 1997). Overall, teacher ratings of oppositional and hyperactive behaviors were significantly elevated in the ADHD group, while ratings of cognitive problems/inattention were elevated in both the ADHD and low working memory groups. As a consequence of high ratings on individual subscales, scores for both groups were also elevated on the ADHD index of the Conners' scale (Conners; see Figure 4). The inattentive symptoms observed in children with working memory deficits, which are also commonly associated with ADHD, most likely occur when overloaded working memory systems enable interference from irrelevant information to disrupt goal-directed behavior.

Beyond attentional problems, children with low working memory are typically reserved in group discussions in the classroom, but integrate well with friends and peers in less formal situations outside of the classroom (Gathercole, Alloway, *et al.*, 2008). Outgoing and humorous children with poor working memory rarely volunteer information in the classroom or raise their hand to answer questions, possibly because their poor memory skills make it hard for them to participate—teachers typically ask questions about recent activities which they may be unable to answer because they have forgotten the relevant information (Gathercole, Alloway, *et al.*, 2008).

Related to this, poor working memory function is not strongly associated with low self-esteem. Of 113 children with low memory ability, Alloway *et al.*, 2009a, 2009b found that overall levels of self-esteem were either at the good or vulnerable levels (43% and 39% of the sample, respectively). Only 12% scored at the very low end of the scale, which is characterized by those who may be depressed and need constant support

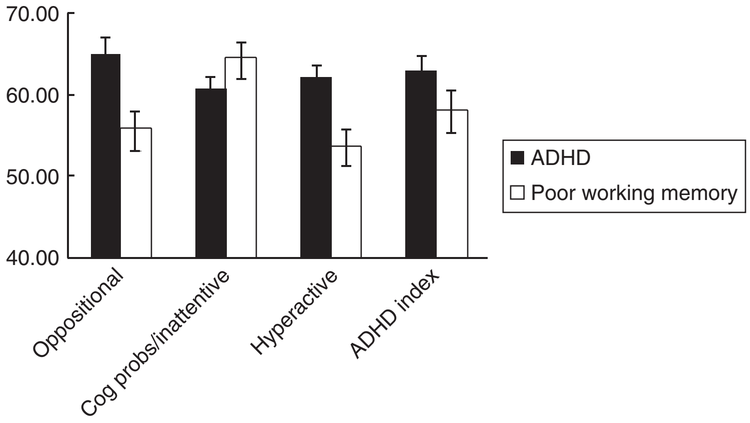

Fig. 4. Behavioral profiles of children with ADHD and children with poor working memory, from Holmes et al. (2010).

and encouragement (Morris, 2002). This demonstrates that very few children with poor working memory, who typically have poor academic success, have low self-esteem and is consistent with literature showing little association between global self-esteem and academic performance both in the general population (Baumeister, Campbell, Krueger, & Vohs, 2003; Marsh & Craven, 2006) and in those with learning difficulties (e.g., Snowling, Muter, & Carroll, 2007).

Emotional problems are not a hallmark characteristic of children with poor working memory, although studies that have examined teacher ratings report that approximately 50% of children identified as having poor working memory are also perceived to have problems with emotional control and regulation. Alloway *et al.* reported that 38% of their sample of 113 children had levels of emotional control problems that reached clinical significance (Alloway *et al.*, 2009a, 2009b). Likewise, Gathercole, Alloway, *et al.* (2008) reported that 45% of children aged 5/6 years with low working memory and 48% of children aged 9/10 years with low working memory obtained high ratings of problem behaviors relating to emotional control. It is possible that the incidence of emotional problems associated with poor working memory is a consequence of the number of children with poor working memory who have other comorbid disorders, such as ADHD or oppositional defiance disorder, which are more commonly associated with emotional and behavioral difficulties. Consistent with this view, children with low working memory have mildly elevated levels of oppositional and hyperactive behaviors in comparison to normative samples (Alloway *et al.*), and there is substantial overlap between the behavioral characteristics of children with low working memory and ADHD (e.g., Alloway *et al.*, 2009; Aronen *et al.*, 2005; Lui & Tannock, 2007).

Teachers of children with poor working memory rate them as having problem behaviors relating to a range of executive functions. In particular, they experience problems in monitoring the quality of their work, in generating new solutions to problems, planning/organizing written work, and large amounts of information, and in being proactive initiating new tasks (Alloway *et al.*, 2009, 2009a, 2009b; Gathercole, Alloway, *et al.*, 2008). As discussed earlier in this chapter, poor working memory may underpin this range of difficulties.

In summary, the key behavioral difficulties observed in children with poor working memory relate to inattention. Teachers view them as highly inattentive and distractible and judge them to have problem behaviors related to poor executive functioning. These behaviors are most likely the consequence of memory overload during complex and challenging mental activities, although further research is needed to test the direction of causality between poor attention, executive function problems, and working memory difficulties. In terms of social profiles, children with poor working memory are typically socially integrated, although they can be reserved in large group situations.

IV. Interventions

Three principal methods have been employed to reduce the difficulties that arise from poor working memory. One approach is to adapt the child's environment to minimize memory loads to facilitate classroom learning (e.g., Elliott, Alloway, Gathercole, Holmes, & Kirkwood, 2010; Gathercole & Alloway, 2008). The other two methods focus on improving working memory directly; one involves teaching children to use memory strategies to improve the efficiency of working memory (e.g., St. Clair-Thompson, Stevens, Hunt, & Bolder, 2010), the other involves directly training working memory through repeated practice on working memory tasks (e.g., Holmes, Gathercole, & Dunning, 2009; Holmes, Gathercole, Place, Dunning, Hilton, & Elliott, 2009; Klingberg *et al.*, 2005).

A. CLASSROOM INTERVENTION

This approach focuses on increasing teacher awareness of working memory problems and encouraging them to adapt their approach to teaching to reduce memory loads in the classroom. It also encourages teachers to help children with poor working memory to use strategies to overcome their cognitive weaknesses. Developed by Gathercole and colleagues, it is guided by seven key principles that are designed to decrease task failures, improve confidence, and accelerate rates of learning in children with low working memory.

The first stage of the intervention is to educate teachers about working memory and assist them in recognizing children who may be experiencing working memory failures. Teachers are often unaware that children with poor working memory have memory difficulties (Gathercole, Alloway, *et al.*, 2008). It is therefore paramount to teach them about the concept of working memory, to illustrate the contexts in which working memory plays a role in everyday classroom activities, and to emphasize the fact that working memory failures are often associated with inattentive behavior. This increased understanding can then be used to detect children who may have poor working memory (Gathercole & Alloway, 2008).

An integral part of supporting children with poor working memory in the classroom is to monitor how they cope with mentally challenging activities. This principle is closely related to detecting warning signs of memory overload, but goes further in that teachers and support assistants are encouraged to monitor whether children have forgotten crucial information during different activities. They can do this by asking simple questions such as “What were you going to write down?”

The third principle focuses on teachers evaluating learning activities to identify those that will be problematic for children with small working memory capacities. These include activities that place heavy demands on working memory, such as those that are overly long or include excessively long sequences, those that include large amounts of meaningless or unfamiliar material, and those that are complex and involve significant mental processing.

Directly related to this, the fourth aspect involves teachers developing and restructuring learning activities to reduce working memory loads. This can be done by reducing the amount of information a child has to remember, increasing the familiarity and meaningfulness of the material children are working with, and simplifying complex activities. So, for example, teachers might consider reducing the number of steps in an activity or breaking a long activity into several shorter activities, relating new material to previously acquired knowledge, simplifying linguistic structures, and reducing the length of sentences used to explain complex activities.

The fifth principle targets the profound difficulties children with poor working memory experience when trying to remember instructions and task information. It encourages teachers to frequently repeat important information, including classroom management instructions, task-specific instructions, and detailed information intrinsic to an activity. Teachers are encouraged to foster an environment in which children with poor working memory can ask for information to be repeated and to pair children with low working memory with those who do not struggle to remember information—this enables them to ask for information to be repeated in a less conspicuous way.

The final two principles involve teachers encouraging children to help themselves. First, teachers should provide and promote the use of memory aids such as wall charts and posters, lists of useful spellings and personalized dictionaries, counters, number lines, multiplication grids, calculators, memory cards, and audio recorders. Second, children with poor working memory should be encouraged to develop their own strategies to support their weak memory skills. These strategies include asking for help, rehearsing important information, note-taking, making links between new and previously learned information to activate support from long-term memory, and place-keeping and organizational strategies such as using flow-charts and diagrams.

Elliott and colleagues recently evaluated the effectiveness of this approach for boosting the learning outcomes of children with poor working memory (Elliott *et al.*, 2010). They found that the extent to which teachers implemented the principles of the working memory intervention predicted the children's literacy and mathematical skills and that teachers were enthusiastic about the ways in which their understanding and practice had improved as a result of the intervention. The long-term benefits for learning are not yet known, but this approach offers a practical starting point for teachers who are keen to help children with poor working memory.

B. STRATEGY TRAINING

The second approach to alleviating problems associated with poor working memory is to enhance working memory through training children to use strategies. Strategies are mentally effortful, goal-directed processes that improve the efficiency of working memory. These mechanisms include repeatedly rehearsing the to-be-remembered information aloud or in one's head, creating a sentence or story from the words, or generating visual images of the information. Individuals with high memory spans use strategies more than individuals with low spans (e.g., Engle, Cantor, & Carullo, 1992; Friedman & Miyake, 2004) and individual differences in strategy production account for individual differences in working memory task performance in adults (Dunlosky & Kane, 2007). Strategy use emerges during childhood, leading to the suggestion that developmental increases in working memory are at least partly mediated by their onset (Gathercole, 1999). For example, rehearsal does not emerge until about 7 years of age (e.g., Gathercole, 1998), with other strategies, such as organization and grouping (e.g., Bjorkland & Douglas, 1997) and chunking (e.g., Ottem, Lian, & Karlsen, 2007) developing later. Although strategy use is not spontaneous in young children, they will attempt to employ them when explicit instructions are given (e.g., Ornstein, Baker-Ward, & Naus, 1988; Ornstein & Naus, 1985). This has led to the suggestion that training children to employ memory strategies could facilitate their working memory functioning (e.g., St. Clair-Thompson & Holmes, 2008).

Training adults to use strategies facilitates their short-term and working memory abilities. Improvements in STM tasks have been reported when participants engage in strategies, such as rehearsal (e.g., Broadley, MacDonald, & Buckley, 1994; Gardiner, Gawlick, & Richardson-Klavehn, 1994; Rodriguez & Sadoski, 2000), visual imagery (e.g., De La Iglesia, Buceta, & Campos, 2005), grouping or chunking information (e.g., Black & Rollins, 1982; Carr & Schneider, 1991; Lange & Pierce, 1992), or creating stories from the to-be-remembered information (e.g., McNamara & Scott, 2001). Rehearsal, story generation, and visual imagery strategies also improve performance on working memory span tasks (Turley-Ames & Whitfield, 2003; McNamara & Scott). These gains, however, often do not extend beyond trained tasks and are not sustained, meaning they are unlikely to yield substantial benefits for the multiplicity of situations in which we depend on working memory.

Recently, St. Clair-Thompson and colleagues have shown that providing memory strategy training significantly improves working memory in children (St. Clair-Thompson & Holmes, 2008; St. Clair-Thompson *et al.*, 2010). In their first two studies, they measured the impact of strategy training on short-term and working memory in small groups of 6 and 7 and 7 and 8 year olds (St. Clair-Thompson & Holmes, 2008). The strategy training was provided in the form of a computerized adventure game called Memory Booster (Leedale, Singleton, & Thomas, 2004), which taught and encouraged the use of rehearsal, visual imagery, story generation, and grouping. Children completed two training sessions per week, each lasting approximately 30 minutes, for 6–8 weeks. In the first study, children were assessed on measures of verbal and visuospatial STM and verbal working memory both before and after training. There were no significant gains in STM for either age group. There were, however, significant gains in verbal working memory for the younger group of children (6 and 7 year olds). This pattern of improvement was reflected in a second study, in which a measure of children's ability to remember and follow instructions was also included. Again, there was no impact of training on STM for either age group, but both verbal working memory and performance on the following instructions task improved in the younger children (St. Clair-Thompson & Holmes).

Together, these initial studies demonstrated that working memory could be improved in young children through strategy training and there was preliminary evidence that gains generalized to a working memory-loaded classroom activity. There were no benefits of strategy training for older children, who were aged 7 and 8 years. It is possible that these children were already using efficient memory strategies meaning strategy training was unlikely to benefit their memory performance.

In a more recent study, St. Clair-Thompson and her colleagues investigated the potential usefulness of memory strategy training further

(St. Clair-Thompson *et al.*, 2010). A total of 254 children aged 5–8 years participated in the study. Half of the children completed Memory Booster strategy training and half received no intervention. All children were tested on measures of verbal and visuospatial STM and verbal working memory before and after training and subgroups completed a following instructions task, a mental arithmetic task and standardized assessments in reading, arithmetic, and mathematics. This time, significant training gains were found in verbal short-term and working memory, but not in visuospatial STM. Significant improvements were also reported in mental arithmetic and following instructions, but no improvements were found in standardized ability measures either immediately after training or 5 months later. The same patterns of gains were observed both in children aged 5/6 and 7/8 years, and also in children with average working memory and poor working memory (in this case classed as standard scores below 70; see St. Clair-Thompson *et al.* for further details).

This recent work on memory strategy training in children suggests it could provide a means of improving working memory in children. However, the transfer of benefits to other tasks seems limited. Although there is some evidence of transfer to tasks that allow for the use of memory strategies, such as following instructions, there is no evidence that gains transfer to standardized ability measures.

C. WORKING MEMORY TRAINING

The final approach to remediating poor working memory function is to train it through repeated practice on working memory tasks. Studies that attempted to improve working memory using this method in the 1970s and 1980s only reported moderate training gains, which were in the form of faster reaction times, not increases in working memory capacities *per se*, and there was no evidence that gains were transferable to nontrained working memory tasks or to other cognitive measures (Kristofferson, 1972; Phillips & Nettlebeck, 1984). Other training studies, such as those conducted by Hulme and Muir (1985), have demonstrated that training processes crucial to efficient processing in working memory such as articulation and rehearsal rate improve memory span, although only very slightly. More recent evidence indicates that intensive adaptive working memory training specifically on tasks that tax working memory may lead to more dramatic gains on trained and nontrained working memory tasks and also on other cognitive measures.

Jaeggi and colleagues found improvements on trained working memory tasks that transferred to marked increases in performance on a general

IQ test in healthy adults, using a paradigm known as *n*-back. This involves the continuous presentation of sequence of stimuli. Participants are required to indicate whether the current stimulus matches the one that was presented *n* steps earlier in the sequence. The task can be adjusted by increasing or decreasing the number of steps to make the task more or less difficult. Jaeggi and colleagues used an extremely cognitively demanding version of this task in which participants were presented with two rows of stimuli simultaneously. The top row showed individual spatial locations marked in a box, the bottom showed a string of individual letters. Participants were required to decide for each string whether the current stimuli matched the one presented *n* items back in the series. The number of items back varied according to participants' performance, increasing by one if performance improved and decreasing by one if performance dropped (Jaeggi, Buschkuel, Jonides, & Perrig, 2008).

Five groups of participants were included. Four groups completed between 8 and 19 training sessions and a fifth group was not trained. IQ was assessed pre- and post-training. Overall, there was a significant training effect, with all four training groups improving on the working memory tasks. Importantly, there was a transfer effect to performance on the general IQ test. This was strictly training related and could not be attributed to individual differences in pre-training working memory or IQ scores, gains in working memory as measured by changes on complex span tasks, or to the training itself. The gains in general IQ were dose dependent, with more training equating to bigger gains.

Jaeggi *et al.* (2008) suggest the transfer effect may result from the shared features between the training tasks and IQ measure, such as attentional control and the requirement to hold multiple goals in mind. However, they also propose that changes in performance on the IQ test may result from improvements in skills that were not working memory capacity related but that were also trained by the dual *n*-back task, for example, multiple-task management skills. It should be noted, however, that other researchers have proposed these findings do not represent a true transfer effect; rather they are a consequence of testing procedure used to administer the IQ test (see Moody, 2009).

Using a similar but less cognitively challenging program, Jaeggi and colleagues have also demonstrated that working memory can be improved through training in older adults (Buschkeuhl *et al.*, 2008). In this study, 13 women aged 80+ years trained on three working memory tasks and two speed of processing tasks two times a week for 3 months. The working memory tasks included recalling sequences of colors or animals in the correct order. Some of the tasks included an explicit processing element, which, for example, required participants to decide if the animals were in the correct orientation prior to recalling the sequence. The processing speed tasks were forced reaction time tasks in which participants had to make a decision and respond as quickly as possible to stimuli presented on the screen. A control group of 19 women aged 80+ years formed an active control group who completed a physical intervention, training on a bicycle ergo meter for the same amount time as the memory training group. Working memory and episodic memory were assessed before, immediately after and 1 year after training for both groups.

Performance on the trained tasks improved significantly for those in the memory training condition. There was evidence of transfer to nontrained visual working memory tasks immediately after training, although these transfer effects did not extend to a digit span task or measures of episodic memory. There were no significant differences between the memory and physical training groups 1 year after training. These results suggest it is possible to improve visual working memory in old–old adults through training in the short-term, but that it is unlikely these gains will be sustained. Furthermore, due to the complex nature of the training, which included both speed of processing and working memory training, it is difficult to determine the source of the gains in visual working memory.

An alternative method that has also produced positive results is the Cogmed Working Memory Training Program (CWMT), which was developed by Klingberg and colleagues at the Karolinska Institute in Sweden. In this program, individuals train intensively over several weeks on adaptive working memory tasks. The training tasks require the immediate serial recall of either verbal or visuospatial information, with some of the tasks requiring explicit processing prior to recall. Participants train for 20–25 days, each day completing 8 different tasks selected from a bank of 13, which takes approximately 30–45 minutes. The tasks vary across training days to maintain interest and positive verbal and visual feedback is given on some trials. The difficulty of the training tasks is automatically adjusted on a trial-by-trial basis to match the participant's current working memory capacity, which maximizes the training benefits.

The Cogmed program is perhaps the most widely validated memory training program, with studies showing dramatic improvements in working memory following training in both children and adults. Crucially, it is the only program to date that has been used to directly train working memory in children. In the very first trials, Klingberg's team used an early form of the training program that included only four training tasks: a Corsi block-like visuospatial memory task; two verbal tasks—backward digit and letter span; and a choice reaction time task. In a double-blind, placebo-controlled study, this primitive form of intensive and adaptive working memory training significantly improved performance on nontrained STM tasks, digit recall and Corsi block, and a test of nonverbal reasoning in a small sample of children with ADHD (treatment group $n=7$, control group $n=7$). Motor activity, as measured by the number of head movements during a computerized test, was significantly reduced in the treatment group, and performance on a response inhibition task also significantly improved following training. There were no significant changes in performance for the control group, who completed a placebo version of the program in which the difficulty of the training tasks was set a low level throughout the training period (span of 2 or 3 items for each task). In a second experiment, they used the same adaptive training program with four healthy adults. Significant improvements in performance were reported both on the trained tasks and on a nontrained visuospatial memory task, a Stroop task and a nonverbal reasoning task (Klingberg, Forssberg, & Westerberg, 2002).

Klingberg's team later extended their work to evaluate the effects of training in a larger group of children with ADHD ($n=53$) in a randomized controlled trial. The intensity of the treatment training program was increased to 90 trials per day on three working memory tasks (remembering the position of objects in a 4×4 grid or remembering phonemes, letters, or digits) for 20–25 days. As before, the placebo version included an identical set of tasks to the treatment program, which were set at a low level throughout training. Children were randomly assigned to each condition, with 27 completing the adaptive treatment program and 26 completing the placebo version. Overall, the treatment group improved significantly more than the comparison group on a nontrained measure of visuospatial STM. These effects persisted 3 months after training. In addition, significant treatment effects were observed in response inhibition, complex reasoning, and verbal STM, and there were significant reductions in parent ratings of inattention and hyperactivity/impulsivity following training. Reductions in ratings of cognitive problems following training were also reported in a pilot study with 18 adults more than 1 year after a stroke. As before, there were significant improvements in trained and nontrained working memory tasks and there was also a significant decrease in the patients' self-ratings of cognitive problems in daily life (Westerberg *et al.*, 2007).

The team at the Karolinska Institute has now extended their work on memory training to preschool children (Thorell, Lindqvist, Bergman, Bohlin, & Klingberg, 2009). On the basis of the strong theoretical connection between inhibition and working memory (see Engle & Kane, 2004; Roberts & Pennington, 1996), the overlapping areas of neural activation during working memory and inhibition tasks (McNab *et al.*, 2008) and the transfer of training effects to the Stroop task in their early studies, they decided to compare the effects of visuospatial working memory training and inhibition training in very young children.

Four groups of preschool children aged 4 and 5 years were included in the study. One group completed visuospatial working memory training ($n=17$). A second group completed inhibition training ($n=18$), the third ($n=14$) completed a placebo version of the memory training, as per previous studies, and a fourth group formed a passive control group ($n=16$). Those in the training groups completed adaptive training of either visuospatial working memory or inhibition for 15 minutes a day every day that they attended preschool over a 5-week period. Each day they completed three of five possible tasks, which rotated across the training period to maintain interest. The five visuospatial working memory training tasks required children to recall sequences of nonverbal information in the correct order. The inhibition training consisted of five tasks that mirror well-known inhibition paradigms—two go/no-go tasks and two stop signal tasks designed to train response inhibition and a flanker task designed to train interference control. Outcome measures for all groups included nontrained measures of interference control, response inhibition, forward and backward Corsi block, forward and backward digit recall, sustained attention, and problem solving.

Children in the working memory training group improved significantly on all trained tasks, whilst those in the inhibition training group improved only on the trained go/no-go and interference control tasks. Working memory training led to significant gains in both nontrained verbal and visuospatial memory tasks and attention, but there was no significant transfer to performance on nontrained inhibition tasks. There was no significant change in performance on nontrained tasks for children in the inhibition training, placebo, or passive control groups. Overall, the data from this study show that working memory can be trained in typically developing children as young as 4 years and, perhaps most importantly, demonstrates that different cognitive functions vary in how easily they can be modified by intensive practice (Thorell *et al.*, 2009). The results of this study point to generalized benefits of training working memory, but of limited effects of training other executive functions such as inhibition.

On the basis of the early success of working memory training with children, we have recently conducted our own independent evaluations of the CWMT program. Like Klingberg, our first study was with children with ADHD, who we know have significant and substantial deficits in working memory (Holmes, Gathercole, Alloway, *et al.*, 2010; Holmes, Gathercole, Place *et al.*, 2010; Martinussen *et al.*, 2006).

The primary treatment option for reducing the behavioral symptoms of ADHD is psycho stimulant medication in the form of methylphenidate or amphetamine compounds, which also enhance visuospatial working memory (Bedard, Jain, Hogg-Johnson, & Tannock, 2007). The aim of our first study was to therefore compare the impacts of working memory training and psycho stimulant medication on the separate subcomponents of working memory. We recruited 25 children aged 8–11 years with a clinical diagnosis of combined type ADHD, who were receiving quick release medication for their ADHD symptoms. All children completed assessments of verbal and visuospatial STM and working memory both before and after training and on and off medication. The training paradigm consisted of 20–25 sessions on the adaptive program developed by Cogmed, which this time consisted of 10 different working memory tasks. Children trained on 8 of the 10 tasks every day, completing 115 trials per session.

Both interventions had a significant impact on children's working memory, but differential patterns of change were associated with each approach. While medication led to selective improvements in visuospatial working memory, training led to improvements in all aspects of working memory. Crucially, these gains were sustained 6 months after training ceased (see Figure 5).

Children's IQ was not affected by either intervention. The impact of medication on nonverbal aspects of working memory only most likely reflects the predominant influence of medication on right hemisphere brain structures that are associated with visuospatial working memory (e.g., Bedard *et al.*, 2007). The generalized impact of working memory training in this group may have very practical benefits for learning in children with ADHD. Although medication helps to control the adverse behavioral symptoms of the disorder, providing improved working memory resources through working memory training holds the promise of providing improved support for learning for in this group (Holmes, Gathercole, Place, Dunning, *et al.*, 2009).

We also have encouraging preliminary data to suggest that working memory training benefits other groups of children. In a recent study, we trained 25 typically developing children aged 9/10 years in a large group in school and found significant improvements in the aspects of working memory that are most strongly associated with learning, namely visuospatial STM and verbal and visuospatial working memory (Holmes, Dunning, & Gathercole, 2010a; see Figure 6).

Furthermore, we have some indication that memory training will benefit children with dyslexia (Holmes, Dunning, & Gathercole, 2010b). Figure 7 summarizes data showing the impact of working memory training on the

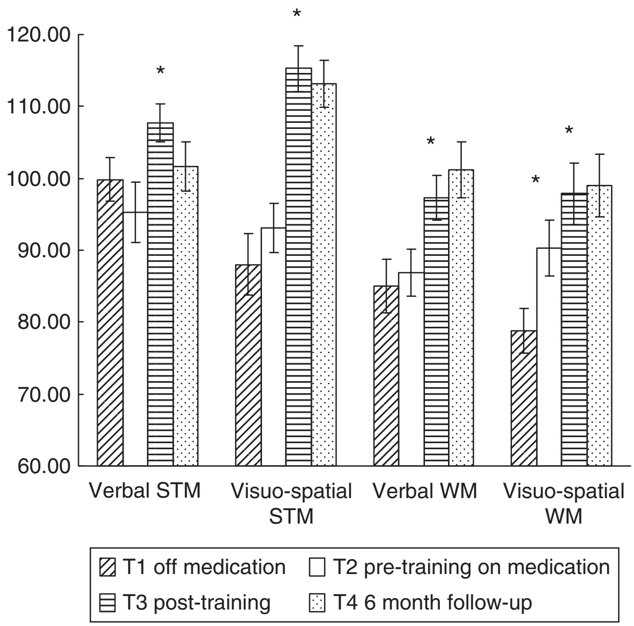

Fig. 5. Impact of medication and training on different aspects of working memory, from Holmes, Gathercole, Place, Dunning, et al., 2009. Note. *Asterisk above a bar denotes a significant change in scores from the previous testing point.*

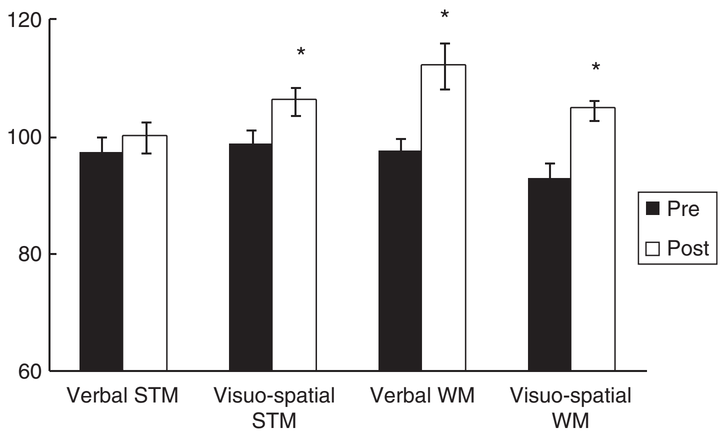

Fig. 6. Impact of working memory training in a group of typically developing children, from Holmes et al. (2010a). Note. *Asterisk above a bar denotes a significant change in scores from the previous testing point.*

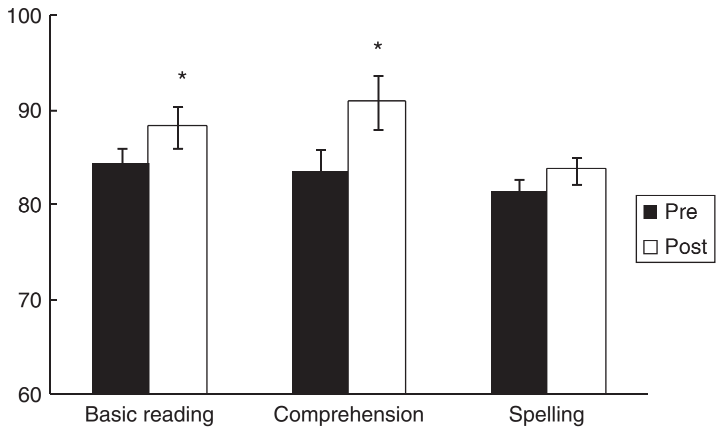

Fig. 7. Impact of working memory training on the language skills of a group of children with dyslexia, from Holmes et al. (2010b). Note. *Asterisk above a bar denotes a significant change in scores from the previous testing point.*

reading skills of a group of 19 children aged 8–11 years with dyslexia. In this study, we found significant improvements in both single word reading and reading comprehension following adaptive training, with reading comprehension scores improving from the deficit to average range. There was no significant improvement in spelling post-training.

Thus far, the benefits of focused working memory training have been discussed in terms of improvements in adults, typically developing children and children with developmental disorders such as ADHD and dyslexia. So, the big question remains—is this intervention beneficial to children who are selected solely on the basis of poor working memory? The answer is yes.

In a direct test of the utility of working memory training for this group, we identified 42 children aged 9/10 years with low working memory skills and assessed them on measures of working memory, IQ, and academic attainment before and after training either on the standard adaptive program or the placebo non-adaptive program used by Klingberg *et al.* (2005). We also included a measure of children's performance on a following instructions task pre- and post-training, which was included as a more practically based measure of working memory use in the classroom. Immediately after training, there were significant gains in all aspects of working memory and on the following instructions task for children in the adaptive condition ($n=20$). In all cases, the gains were significantly greater for the adaptive than the nonadaptive group ($n=22$). There was no immediate impact of training on standardized reading and mathematics tests or on IQ. Follow-up assessments revealed the training gains were sustained in the adaptive group 6 months after training, at which point performance on the standardized mathematics test also improved significantly. These results provide the first solid evidence that commonplace deficits in working memory and associated learning difficulties can be ameliorated, and possibly even overcome, by intensive adaptive training over a relatively short period (Holmes, Gathercole, & Dunning, 2009).

So, what is driving the changes in working memory following training? One possibility is that intensive training induces long-term plasticity in the brain regions that serve working memory. In two neuroimaging studies, Olesen, Westerberg, and Klingberg (2004) showed increased activation in the parietal and prefrontal cortices following memory training. In their first study, they reported an increase in brain activity in both of these regions in three subjects following training on both verbal and visuospatial working memory tasks. In the second study, eight adults were scanned five times during training on three visuospatial working memory tasks over a 5-week period. Again, increases in neuronal activity were observed in the prefrontal and parietal regions. In a single-subject analysis, Westerberg and Klingberg (2007) showed training-induced changes were not due to activations of any additional area that was not activated before training. Rather, they observed that areas where task-related activity was seen increased in size following training. Related to this, changes in the density of prefrontal and parietal cortical dopamine receptors have been reported after memory training. Either too much or too little stimulation of D1 receptors results in impaired working memory task performance (Cai & Arsten, 1997; Lidow, Williams, & Goldman-Rakic, 1998; Vijayraghavan, Wang, Birnbaum, Williams, & Arnsten, 2007; Williams & Goldman-Rakic, 1995). Thus, training-induced decreases in the binding potential of the receptor D1 associated with increases in working memory capacity were interpreted as demonstrating a high level of plasticity of the D1 receptor system (McNab *et al.*, 2009).

Overall, Klingberg's team has shown that training induces changes in two brain regions, the parietal and prefrontal cortices, which are both associated with working memory. Prefrontal activation is positively correlated with children's working memory capacity (Klingberg *et al.*, 2002; Kwon, Reiss, & Menon, 2002) and fronto-parietal networks are related to success on working memory tasks (Pessoa, Gutierrez, Bandettini, & Ungerleider, 2002; Rypma & D'Esposito, 2003). Their work suggests cortical and biochemical changes result from practice on working memory tasks.

The working memory training program may also promote self-awareness and the development of compensatory strategies to overcome areas of weakness. Introspective reports from children in our own training studies support this notion. When asked what they thought had helped them to improve on the training activities, 27% of children with low working memory and 27% of children with ADHD reported focusing more on the presented information or concentrating harder. A further 37% of children with low working memory and 67% of children with ADHD reported using a variety of other strategies, including rehearsal or tracing the patterns on the computer screen with their eyes (Holmes, Gathercole, & Dunning, 2009; Holmes, Gathercole, Place, Dunning, *et al.*, 2009). These verbal reports support the idea that training may enhance attentional focus and stimulate the development of a range of strategies that capitalize on relative cognitive strengths.

The data presented in this section demonstrate that it is possible to train working memory through repeated practice on working memory tasks. Importantly, they provide an early indication that the learning difficulties that so often accompany working memory deficits can be ameliorated, to some extent, by training. This finding is highly relevant to professionals looking for effective interventions for children with poor working memory and also for children with a wide range of disorders that are associated with both low working memory and poor academic performance. Although we have some insight into the nature of the cognitive and neural changes that underpin the gains in working memory, further research is needed in this area.

D. INTERVENTIONS—SUMMARY

The difficulties faced by children with low working memory can be targeted in different ways: (i) by adjusting the child's environment to reduce working memory loads, (ii) by training and promoting the use of effective strategies to improve the efficiency of working memory, and (iii) by training working memory directly using an adaptive, computerized program. The latter approach appears to be the most direct, useful, and well-validated method for boosting both poor working memory and learning in children. Strategy training has also been shown to boost working memory, both in children with low and average working memory, but the evidence for transfer effects to improved academic outcomes is far less persuasive. The classroom-based intervention, which focuses on changes in the ways children with poor working memory are taught, is perhaps the most practical approach as it builds upon and promotes good teaching practice. Although the extent to which teachers apply the principles of the intervention correlates with attainment, the benefit of this method for improving learning outcomes is as yet somewhat unclear. All three approaches require further investigation to determine the long-term effects on working memory and learning.

V. Summary and Future Directions

In conclusion, poor working memory affects approximately 15% of children. It is characterized by inattentive, distractible behavior that is accompanied by failures to complete everyday activities that require focused or sustained attention. Typically, children with poor working memory have normal social integration and normal levels of emotional control and self-esteem. They may, however, appear reserved in large group situations. Over 80% of children with low working memory struggle in reading and mathematics and it has been suggested that they are likely to be those children who make poor academic progress, but who fall below the radar of recognition for SEN.

Beyond poor learning, children with poor working memory have a range of other cognitive problems that extend to low IQ and deficits in other executive functions including monitoring and planning, problem solving, and sustained attention. Although the direction of causality is uncertain, it is possible that limited working memory resources underpin this wide range of deficits.

There are three main approaches to alleviating the difficulties faced by children with poor working memory: a classroom intervention, strategy training, or direct working memory training. Of these, direct training is the most widely used and successful method. Dramatic gains in working memory have been reported following training in typically developing children and adults, adults following a stroke, children with developmental disorders such as ADHD and, most pertinent to this chapter, children with poor working memory. Importantly, the memory gains in children with poor working memory sustain over a 6-month period, at which point they transfer to gains in learning. This finding holds the promise for improving the long-term educational outcomes of children with poor working memory.

Although we now have a fairly comprehensive understanding of the social, behavioral, and cognitive profiles of children with poor working memory, there are a number of challenges for the future. The first is to investigate the long-term consequences of poor working memory. Do working memory problems persist into adolescence and adulthood? If so, how do they impact on everyday functioning? Do children with poor working memory go on to develop compensatory strategies as they age? The second challenge is to investigate further the future impacts of different interventions. For example, is there a long-range benefit to learning from the classroom intervention? Do the dramatic training-induced gains in working memory endure? Related to this, the third challenge lies in determining what is driving the changes in working memory following direct training. Finding that working memory can be improved through intensive practice poses a challenge to theories that suggest working memory has a relatively fixed capacity (e.g., Engle, Cantor, & Carullo, 1992), is highly heritable (Kremen *et al.*, 2007), and is relatively impervious to substantial differences in environmental experience and opportunity (Campbell *et al.*, 1997; Engel *et al.*, 2008). Although there is evidence that training may induce neural plasticity in the brain regions supporting working memory, or the development of compensatory strategies, further neuroimaging, cognitive, and behavioral research is needed to fully understand what underpins the changes in working memory performance.

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