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Working Memory and Learning During the School Years

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IN THIS LECTURE I take the opportunity to draw together recent findings and ideas concerning the nature and function of short-term memory during childhood. The issue of the primary function of short-term memory—in other words, why we have it and what it does for us—is particularly intriguing. The majority of systems of behaviour studied by psychologists fulfil obvious biological functions. The visual and auditory sensory systems, for example, support our abilities to perceive and interpret sensory inputs. Language, another human faculty extensively investigated by psychologists, represents our primary means of communication, the one that marks us as distinct from our mammalian relatives.

It is less obvious what functions are served by short-term memory, a system whose time span is limited to seconds only, and is characterised by the greatest fragility. Here I suggest that the primary function of short-term memory is to support learning—probably across the lifespan, and certainly during the childhood years when so much knowledge and so many complex skills are acquired in a relatively short period of time.

Working memory as a mental workspace

The theoretical account of short-term memory that has guided the work reviewed here is the 'working memory' model originally advanced by

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Baddeley and Hitch in 1974. Although the model has undergone substantial development in the subsequent thirty years, its basic organisation has not changed substantially, and is summarised in Figure 1. At the heart of the model is the central executive. This is a limited capacity system with high-level functions that include coordinating the flow of information both within working memory and other more permanent memory systems, the attentional control of action, shifting between cognitive activities, and updating the contents of working memory (e.g., Baddeley, 1986, 1996; Miyake *et al.*, 2000). The central executive is linked with three other components of working memory: the phonological loop, specialised for the maintenance of material that can be represented in phonological form (Baddeley, 1986); the visuo-spatial sketchpad, which processes and stores nonverbal material; and the episodic buffer, responsible for the integration of cognitive events across different representation domains (Baddeley, 2000).

Baddeley and Hitch's (1974) article was also ground-breaking in its conceptualisation of the role of short-term memory. In contrast to the traditional emphasis on short-term memory as a relatively passive and highly specialised storage device, these authors proposed that the short-term memory system plays an active and highly flexible role in supporting complex cognitive processing in everyday life, and should therefore be viewed as a 'working' memory. This concept of short-term memory as a workspace capable of storing and processing information in the course of ongoing cognitive activities is now widely accepted (Case *et al.*, 1982; Daneman and Carpenter, 1980; Engle *et al.*, 1999; Just and Carpenter, 1992).

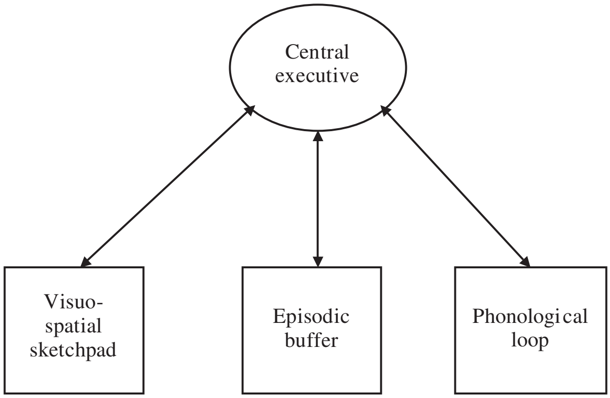

Figure 1. The working memory model (adapted from Baddeley, 2000).

In this lecture, I argue that the role played working memory in everyday life extends far beyond that of meeting the storage demands of current cognitive activities. The ease of acquiring new knowledge and skills during childhood is directly constrained by the capacity to store and manipulate information in working memory. In this way, working memory is a crucial element of the cognitive system that supports learning.

Development and variation in working memory

Many insights into the role of working memory in supporting learning have been gained from studies that have capitalised upon the substantial degree of individual variation in working memory function in the general population. Working memory capacity increases steadily from about four years of age (the youngest point at which it can probably be reliably assessed) to fourteen years (Gathercole *et al.*, 2004), at which time performance is close to adult levels.

The substantial degree of individual variation is illustrated in Figure 2, based on data from the Working Memory Test Battery for Children

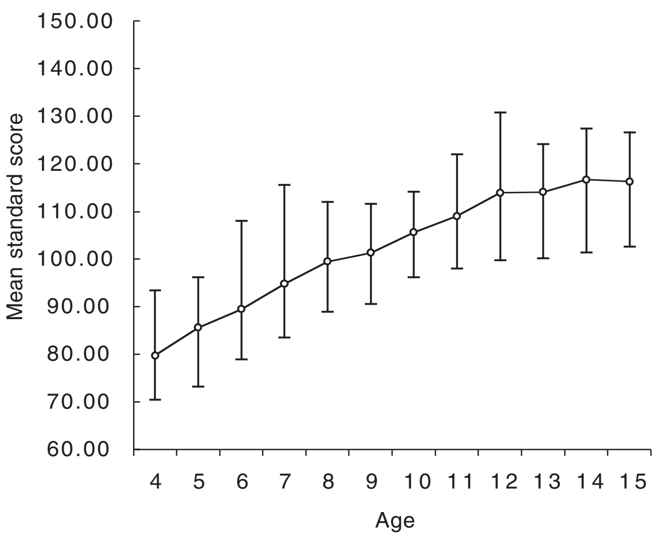

Figure 2. Composite working memory span scores from the Working Memory Test Battery for Children (Pickering and Gathercole, 2001) as a function of age. Values shown are means tenth and ninetieth centile points. Scores are standardised across the entire sample, with a mean of 100 and a standard deviation of 15.

(Pickering and Gathercole, 2001). The figure shows the mean scores of groups of children aged between five and fourteen years on memory span measures associated with the central executive. The bars correspond to the levels of performance attained by the children falling at the tenth centiles at each age (the lowest ten per cent, with levels below the mean) and at the ninetieth centiles (top ten per cent, with levels above the mean). Within each age, individual differences are so great that in a regular class of schoolchildren, age-appropriate levels of working memory performance will vary by several years.

The scores in Figure 2 are derived from scores on three complex memory span tasks. Each task imposes simultaneous processing and storage demands. For example, one task is listening recall, in which the child listens to a series of spoken sentences, decides whether each one is true or false, and then at the end of the sequence of sentences attempts to recall the final word from each sentence in order. The task therefore involves both storage (of the sentence-final words) and processing (of the meaning of each sentence). The processing and coordination element of this and other verbal complex span tasks, such as backwards digit recall, and counting recall taps the central executive, whereas the phonological loop supports the verbal storage component of the task (Baddeley and Logie, 1999).

There are several theoretical accounts of developmental changes and individual variation in performance on complex span tasks. According to one influential view, both processing and storage are supported by a single limited resource. As the efficiency of processing increases with age, more resource is available to support storage, leading to improvements in task scores. An alternative view is that developmental increases in complex memory span result from faster processing times that in turn reduce time-based forgetting in the course of switching between the processing and storage elements of the tasks (e.g., Towse and Hitch, 1995; Towse *et al.*, 1998). More recent evidence suggests that the developmental function arises from a complex interplay of factors that include time-based forgetting, intrinsic memory loads and attentional processes (Barrouillet and Camos, 2001; Conlin *et al.*, 2003; Towse *et al.*, 2002).

The principal focus of this lecture is the relationship between working memory and successful learning. In the following sections, I examine evidence that learning abilities and working memory capacities are closely linked in a number of different populations—in unselected samples, in children with special educational needs, and in children with specific difficulties with language. To anticipate, failure to show normal rates of learning is accompanied by poor working memory function in each case.

Working memory and academic achievement

National assessments of children's achievements at particular points in their school careers (termed 'Key Stages') were introduced following the implementation of a National Curriculum for state schools in England. Key Stage 1 assessments take place at 6/7 years, Key Stage 2 assessments at 10/11 years, and Key Stage 3 at 13/14 years. At each stage, the performance of each child is evaluated against expectations of normal levels of attainment at each age, with expected levels being 2 at Key Stage 1, 4 at Key Stage 2, and 5 or 6 at Key Stage 3. There are three areas of assessment: English (including literacy), mathematics, and science. Levels of achievement are based on measures ranging from teacher-based assessments to standardised tests.

Across a series of studies, we have evaluated the extent to which children's levels of attainment in these national curriculum assessments are related to working memory function. In an initial study, we investigated the relationships between working memory function skills and Key Stage 1 assessments at six and seven years of age (Gathercole and Pickering, 2000). Working memory was measured using complex memory span tasks in which the children were required both to process and store incoming information. One example of such a task is listening span, in which the child judges whether or not a spoken sentence is true or false, for a series of sentences, and then subsequently attempts to remember the final words of each of the sentences in sequence. The results of our study were clear. The children who failed to meet the expected levels of achievement in English and mathematics for their age (obtaining below a level 2) performed more poorly on complex working memory measures than children obtaining levels 2 and 3.

Subsequent studies have replicated these findings, and extended the relationships between working memory and scholastic attainment to subsequent Key Stages. Gathercole, Pickering, Knight, and Stegmann (2004) found that at both Key Stages 1 and 3 (ages seven and fourteen years), scores on complex memory span tests were below average levels for children failing to achieve expected levels for their age in mathematics and science, and above average for those children exceeding nationally expected levels. English assessments at age seven were also directly related to working memory skill, although not at fourteen years of age. Thus children's working memory capacities were closely related to their levels of scholastic attainment.

A recent study by Jarvis and Gathercole (2003) illuminated further the nature of the relationship between working memory and scholastic attainment. This study investigated the relations between children's learning achievements and two different aspects of working memory. In previous studies, we had employed complex memory span measures involving verbal stimuli and linguistic processing, such as the listening span task. In this new study, we also included complex memory span tasks involving the storage and processing of visuo-spatial material, such as unfamiliar shapes in different orientations. Previous evidence from studies of adults indicated that verbal and visuo-spatial working memory had separate capacities, and represented different components of the central executive (Shah and Miyake, 1996). Our findings indicated that visuo-spatial as well as verbal working memory contributed to learning. At both Key Stages 2 and 3 (ages eleven and fourteen, respectively), measures of verbal and visuo-spatial working memory were strongly and independently associated with attainment levels, as shown in Figure 3. A degree of subject-specificity to the associations was found, with unique links between nonverbal working memory scores and both mathematics and science levels (but not English), at both key stages.

The studies described so far have used cross-sectional designs to establish associations between working memory skills and school-based achievements at particular ages. However, if there is a genuine causal link between working memory and learning, working memory skills early in the child's school career should effectively predict later levels of achievement. We tested this prediction in a longitudinal study in which children's verbal working memory abilities were assessed at school entry at four years and related to their later attainment levels at Key Stage 1 (Gathercole, Brown, and Pickering, 2003). Shortly after school entry, the children were also

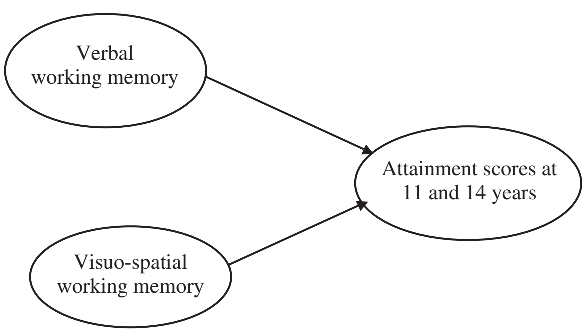

Figure 3. Causal paths between working memory and attainment levels, at eleven and fourteen years (Jarvis and Gathercole, 2003).

tested on local education authority 'baseline assessments' in the areas of language, reading, writing, mathematics and social skills.

The resulting causal paths between measures at age four and attainment levels in English and mathematics at Key Stage 1 are shown in Figure 4. Both the working memory and baseline assessment scores were directly linked to children's later achievements in the English assessments. Mathematics achievements at this stage, in contrast, were uniquely associated only with the school's own baseline assessments.

These findings indicate firstly that working memory measures and baseline assessments tap different underlying constructs, and secondly that both constructs contribute significantly to learning in the area of literacy. We have argued that a fundamental distinction between the two types of assessment concerns the extent to which they tap previously acquired knowledge (Gathercole, Brown, and Pickering, 2003). Baseline assessments largely measure knowledge that the child has already gained in the course of his or her experiences and learning achievements prior to school. Examples of typical test items on baseline scales are whether or not the child can write his or her own name, or recognise printed letters or digits. These are tasks that the child either can or cannot do, on the basis of previously acquired knowledge. In contrast, it is unlikely that any child has either encountered working memory tasks or the specific stimulus materials they employ before. Thus, performance on these measures is constrained by a limited cognitive resource (working memory) rather than prior knowledge. Consistent with this analysis, working memory assessments are relatively independent of general background factors such as socio-economic status and preschool education (e.g., Alloway,

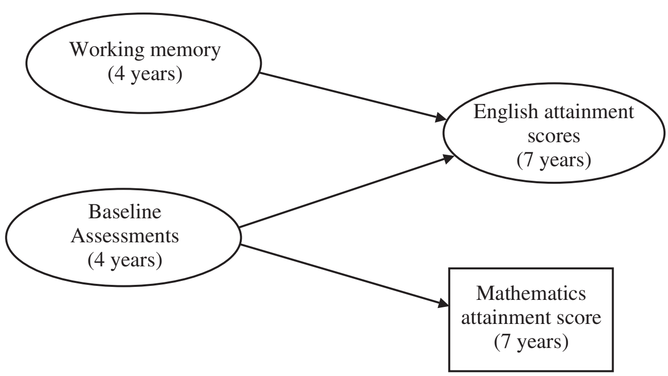

Figure 4. Causal paths between working memory and baseline assessments at four years, and Key Stage 1 attainment levels at seven years (Gathercole, Brown, and Pickering, 2003).

Gathercole, Willis, and Adams, in press; Dollaghan *et al.*, 1997), whereas baseline assessments are significantly associated with such factors (e.g., Lindsay and Desforges, 1999; Strand, 1999).

Working memory and special educational needs

If poor working memory function does indeed directly constrain the capacity to learn complex skills and acquire new knowledge, children with extreme deficits of working memory should experience significant learning difficulties. Initial support for this hypothesis was provided by findings from a longitudinal study that working memory scores predicted later special needs status in a sample of children aged between seven and eight years (Gathercole and Pickering, 2001).

The opportunity to test on a larger scale the hypothesis that severe working memory deficits may be a direct cause of recognised learning difficulties was provided by the standardisation study of the Working Memory Test Battery for Children (Pickering and Gathercole, 2001). Over 700 children aged between four and fifteen years participated in this study. Of these, approximately eighty children had special educational needs that were identified by their schools. We looked separately at the working memory profiles of the children with special educational needs, grouped according to their areas of learning difficulty (Pickering and Gathercole, 2004). The findings were striking. In the group with learning difficulties in both literacy and mathematics, low scores on both working memory measures and tests of phonological loop capacity were thirty-one times more common than in children with no special educational needs. Phonological loop measures involve storage of verbal material, such as lists of spoken digits, for immediate recall. In a smaller group of children whose learning difficulties were specific to language, this profile was forty-three times more common than in the comparison sample. The degree of working memory impairment of these children with recognised learning difficulties was therefore very unusual in the general population. In comparison, children with recognised special educational needs of a non-cognitive origin (such as children with behavioural problems) failed to show significantly inflated incidence of working memory deficits.

An important feature of this study is the direct comparison of working memory profiles in children with special needs with those of the larger population from which they were drawn. This eliminates many of the usual biases of sampling in studies of special populations, and reinforces other evidence for a close association between working memory ability and learning success. The finding of unusually low general working memory function in children with special educational needs has also been replicated in an independent sample of sixty-four children aged between seven and eleven years (Alloway, Gathercole, Adams, and Willis, in press).

Working memory and Specific Language Impairment

There has been considerable interest in the working memory skills of children with a disorder known as Specific Language Impairment (SLI). SLI is diagnosed in children whose language fails to develop for no obvious reason. In an early study, we discovered that children with SLI perform at even lower levels on measures of the phonological loop than on the language measures that form the criterial basis for their clinical diagnosis (Gathercole and Baddeley, 1990; see also, Bishop *et al.*, 1996; Dollaghan and Campbell, 1998; Montgomery, 1995).

Children with SLI also perform poorly on verbal complex memory span measures associated with the central executive (Ellis Weismer *et al.*, 1999; Montgomery, 2000). In two recent studies, we have investigated whether the phonological loop and central executive deficits in SLI cooccur, or represent separable deficits (Archibald and Gathercole, 2003; Briscoe *et al.*, 2003). In both studies, deficits in verbal complex memory span were present in all of the SLI children that were unusual in the general population, and the majority also showed deficits in phonological loop function. In one study (Archibald and Gathercole, 2003), the cooccurrence of marked deficits in both the phonological loop and central executive was approximately fifty times more common than in the general population. This twinning of central executive and phonological loop deficits is also consistent with the working memory profiles of a small group of children with special educational needs that were specific to language (Pickering and Gathercole, 2004).

These findings suggest a core deficit of central executive function in SLI, with an additional impairment of the phonological loop in many of the cases. Despite the verbal storage demands of the complex memory span tasks used in these studies, the data cannot be explained in terms simply of an underlying phonological loop deficit. In a recent study we investigated the language abilities of children selected on the basis of consistently poor performance on phonological loop measures between five and eight years of age (Gathercole, Tiffany, Briscoe, Thorn, and

ALSPAC Team, in press). The memory deficits of this group were quite specific: their verbal complex memory span scores fell within the normal range. Importantly, their performance on a range of measures of language function—including vocabulary knowledge and language comprehension—was entirely normal. These data establish that a deficit of the phonological loop alone is not a sufficient condition for impaired language development. It should, however, be noted, that the low phonological loop group were impaired in learning of novel phonological forms, consistent with the view that the specific developmental function of the phonological loop is to support vocabulary acquisition (Baddeley *et al.*, 1998). It therefore appears that by eight years of age, the low phonological loop children were able to overcome their specific phonological learning impairment, possibly as a consequence both of the redundancy of language exposure and compensatory contributions of other intact cognitive learning systems.

We suggest that the more profound working memory deficits that characterise SLI cannot be overcome in these ways, and that such children cannot adequately meet the working memory demands of many learning situations. As a consequence, children with SLI fail to develop language and other high-level cognitive skills such as literacy and mathematics at a normal rate. The ability to hold information in mind for brief periods, possibly while carrying out effortful processing at the same time, is crucial to successful learning, and children with poor ability to do this will not be able to complete many learning activities successfully. In the following section, I examine more direct evidence that working memory constrains classroom-based learning in this way.

Observing working memory constraints on learning

I have argued the case so far for robust and substantial links between working memory and children's abilities to learn and acquire complex skills and knowledge. The links span the years of compulsory education, and also have a degree of specificity with respect to the particular links between the domain of central executive function and the area of learning. They extend from individual differences within unselected samples to groups with both general and specific learning difficulties.

Although the empirical relationship between working memory abilities and learning achievements across the childhood years is now well established, the ways in which poor working memory capacities constrain successful learning during specific learning activities have not to date been the subject of investigation. We have recently begun to address this issue in a study of children selected on the basis of very low scores on complex memory span measures at school entry at four years (Gathercole, Lamont, and Alloway, in press). The children were observed in the course of their regular classroom activities over a year later, when they were five or six years of age. The observations focused on learning situations in which the working memory demands were judged to be significant, in terms either of the storage or combined processing and storage loads.

At the time of the observations, all of the low working memory children were working in the lowest ability groups in the class. We observed them to fail in many routine classroom activities that imposed significant burdens on working memory. They encountered particular problems in tasks that required both memory storage and effortful processing, and in keeping track of their place in complex task structures. Examples of such activities include writing sentences from memory, carrying out numerical calculation abstracted from questions expressed in everyday language, and counting words in sentences. In these situations, children frequently lost track of their place in the complex task structure, resulting in repetitions, place-skipping, and task abandonment. The children also had poor memory for instructions given in the classroom, frequently failing to follow more than the first step in multi-step commands. This profile of classroom failures was not observed in children with normal working memory function.

Working memory as a cause of errorful learning

Some insights into why classroom failures such as those described above may compromise learning is provided by research comparing learning under conditions where errors are prevented ('errorless' learning) with learning in situations in which the participant learns by trial and error ('errorful' learning). Studies of individuals with memory deficits resulting from acquired brain damage have consistently shown a substantial benefit to errorless learning (e.g., Baddeley and Wilson, 1994; Clare *et al.*, 2002; Parkin, Hunkin, and Squires, 1998). An explanation for this is that responses in specific situations are based on long-term memories from previous related episodes. The probability of a correct response being generated in a particular situation is therefore greater if the participant has consistently made correct responses in the past than if prior responses were inconsistent.

These findings and theoretical analyses imply that if a child has poor working memory, learning achievements will be improved by minimising task failures due to working memory overload. There are a number of ways in which this can be achieved in an educational context. In activities that combine significant processing and storage demands, it may be useful to simplify the processing activity. For example, sentence writing was a source of particular difficulty for all of the low working memory children that we observed. The processing loads involved in sentence writing can be diminished by reducing the complexity of the sentence—in terms either of the vocabulary (common versus lower frequency words) or of the syntactic structures (simple subject-verb-object constructions rather than relative clauses). The planned sentences could also be reduced in length. If the child has to work with lengthy sentences and difficult words, the chances of task failure will increase dramatically, and opportunities for learning will be lost.

The working memory demands of tasks with a complex structure that require accurate place-keeping can be reduced by breaking down the tasks into discrete steps, with memory support being made available where possible. External memory aids are in wide use in classrooms. In our observational study, however, we found that children with poor working memory function often choose not to use such devices in the context of relatively complex tasks, and gravitate instead towards lower-level strategies whose processing requirements may be less (such as simple counting) but less efficient (more error-prone, and time-consuming, for example). In order to facilitate children's effective use of such devices, it may be useful to give the child regular periods of practice in the use of the aids in the context of simple activities. Relevant spellings also function as useful memory aids in writing activities. Reducing the processing load and opportunity for error in spelling individual words will increase the child's success in completing the sentence as a whole. However, reading off information from such external aids was observed in itself to be a source of error in low memory children in our study, with children commonly losing their place within either the word or the sentence. Making available spellings of key words on the child's own whiteboard placed on their desk rather than a distant class board will reduce these errors by making the task of locating key information easier and reducing opportunities for distraction. Methods for marking the child's place in word spellings may also be useful, as loss of position within a word while copying was a frequent source of error and task abandonment.

It is also important to ensure that the child can remember the task that has been set—we observed many occasions in which children with low working memory failed to remember what was required of them. The child's memory for instructions is likely to be enhanced by keeping the instructions as brief and linguistically simple as possible. Instructions should be broken down into smaller constituent parts where possible, which will also have the advantage of reducing task complexity. One effective strategy for improving the child's memory for the task is frequent repetition of instructions. For tasks that take place over an extended period of time, reminding of crucial information rather than repetition of the original instruction is likely to be most useful. Finally, one of the best ways to ensure that the child has not forgotten crucial information is to ask him or her to repeat it back. Our observations indicate that the children themselves have good insight into their working memory failures.

Conclusions

There are two main conclusions to this lecture. First, working memory appears to act as a gateway to, and potential constraint upon, learning. It is an important element of the cognitive systems specialised to support the acquisition of knowledge and complex skills. Failures to meet the working memory demands of learning activities result in lost opportunities for learning, and limit the rate and ease with which children reach milestones of scholastic achievement. The second conclusion follows directly from the first. Learning will be most successful under conditions in which children's working memory capacities can match the memory demands of the situation. It is argued that conditions that alleviate excessive working memory demands in the classroom—where 'excessive' should be judged by the capacities of the individual child rather than normative expectations for age group—will therefore substantially promote learning.

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