Working memory and classroom learning

Susan E. Gathercole and Tracy P. Alloway

University of Durham

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Contact information:

Working Memory Research Group

Department of Psychology

University of Durham

Science Laboratories

South Road

Durham DH1 3LE

Email: s.e.gathercole@durham.ac.uk

Tel: 0191 3343255

www.psychology.dur.ac.uk/research/wm/index.htm

What is 'working memory'?

The term 'working memory' refers to the ability to hold and manipulate information in the mind for a short period of time. It has often been described as a flexible mental workspace in which we can store important information in the course of complex mental activities. A good example of our use of working memory in everyday life is mental arithmetic. Consider, for example, attempting to multiply two two-digit numbers (*e.g., 27* and *48*) without using a paper and pencil, or a calculator. To do this successfully, it is necessary to store the two numbers, and then systematically apply multiplication rules, storing the intermediate products that are generated as we proceed through the stages of the calculation. It is only if we manage to meet both the storage and processing demands of the activity that the correct answer can be reached. Carrying out such mental activities is a process that is effortful and error-prone. A minor distraction such as an unrelated thought springing to mind or an interruption by someone else is likely to result in complete loss of the stored information, and so in a failed calculation attempt. As no amount of effort will allow us to remember again the lost information, the only course of action is to start the calculation afresh. Our abilities to carry out such calculations are limited by the amount of information we have to store and process. Multiplying larger numbers (*e.g., 142* and *891*) "in our heads" is for most of us out of the question, even though it does not require greater mathematical knowledge than the earlier example. The reason we cannot do this is that the storage demands of the activity exceed the capacity of working memory.

This example illustrates some important features of working memory. First, it is an extremely useful and flexible system that we use in everyday life. Second, working memory requires attention and is prone to catastrophic loss if attention is

shifted away from its contents, for example when we are distracted by an interruption. As information cannot be recovered once it has been lost, it is an extremely fragile system. Third, working memory capacities are limited. Capacities vary across individual, but for any person there is a limit to what can be held in this mental workspace; if this limit is exceeded, information is lost. Finally, we have conscious access to the contents of working memory: we know what we have successfully stored, and we know when information has been lost. Our subjective experience of using working memory is of effortful mental juggling, trying to keep all of the crucial information in mind at once.

Working memory in childhood

There is substantial evidence that working memory plays an important role in learning, especially during the childhood years. Relevant studies have typically investigated the relation between children's working memory capacity and their learning achievements in areas such as literacy, language, and mathematics. Working memory capacity is usually measured by complex memory span tasks in which the child has to both store and process information simultaneously. An example of such a task is *listening recall*. In this task, the child has to listen to a series of sentences, to decide whether each sentence is true or false (e.g., *rabbits have ears* – "true", *bananas can fly* – "false"), and then at the end of the block of sentences to recall the last word of each sentence in correct sequence ("ears, fly"). The number of sentences in each block is increased until the point at which the child can no longer accurately recall the final words. Performance is scored in terms of the number of trials correct, and a child with greater working memory capacity will obtain higher scores. Not all complex span tasks involve processing the meaning of sentences and remembering words. Another commonly used complex memory span task is *counting recall*, in

which the child counts the number of dots in a series of arrays, and then attempts to recall the tally number in sequence.

Insert Figure 1 about here

Working memory capacity shows a steady developmental increase across the early and middle childhood years. This is demonstrated in Figure 1, which shows mean scores on the listening recall test of *Working Memory Test Battery for Children* (*WMTB-C*, Pickering & Gathercole, 2001) for children aged 5 to 15 years in the standardisation sample. Performance improves from 5 years until the teenage years, when it starts levelling off. Adult levels of performance are typically reached by about 15 years. One important feature of working memory capacity during childhood is the extent to which it varies very widely across individuals of the same age. This is illustrated by the considerable distance between the two bars shown for each age in Figure 1, which mark the 10th and 90 centiles. At some ages, the distance between these bars is equivalent to four or five years' variation in terms of age-appropriate performance. This amount of variation in working memory capacity would be expected between the three children with the highest and lowest working memory skills in an average class.

Working memory and Key Stage performance

Children's working memory abilities are closely related to their performance in Key Stage assessments of the national curriculum. In an initial study, we assessed working memory skills in a sample of six- and seven-year old children who were about to complete Key Stage 1 assessments (Gathercole & Pickering, 2000). The children who subsequently failed to reach expected levels of attainment for their age – levels W or 1 – scored very poorly on working memory measures, and particularly on verbal complex memory span tests.

Insert Figure 2 about here

This association between working memory skills and Key Stage performance has been replicated and extended in a series of further studies. Gathercole, Pickering, Stegmann & Wright (2004) found that working memory skills were excellent predictors of whether children would obtain low, average or above high scores on both English and maths assessments at Key Stage 1 (6/7 years) and maths assessments at Key Stage 3 (13/14 years). Mean standard scores on working memory measures (100 is average for age, with a standard deviation of 15) are shown in Figure 2 for three Key Stage 1 ability groups in English (low, average, and high). Scores under 100 reflect performance below the national average on the memory measures, and scores above 100 are above average. It can clearly be seen from the figure that children with low attainment levels on the English assessments typically had poor working memory scores, and that children with the highest attainment levels tended to have working memory skills that were considerably above the average for their age.

Close links between working memory and learning attainments were also demonstrated in a longitudinal study in which working memory skills were measured shortly after school entry. Gathercole, Brown, & Pickering (2003) assessed working memory within two months of children commencing full-time education in reception class. At the same time, the children were evaluated by their school using the local baseline assessment scheme on their emerging abilities in the areas of reading, language, speaking and listening, mathematics, and social skills. We were interested in comparing the extent to which the children's levels of attainments at Key Stage 1 almost three school years later were predicted working memory scores. The results were intriguing. Both working memory and baseline assessments scores predicted

Key Stage 1 attainment levels in English. However, the two predictive paths from both working memory and baseline assessment scores at 4/5 years and later English attainment levels were independent of one another, as shown in the diagram of causal paths in Figure 3.

Insert Figure 3 about here

The different pathways leading to Key Stage 1 performance seem to reflect fundamental differences in the abilities being measured in the working memory assessments and the baseline assessment schemes, both of which make important contributions to later attainments. Baseline assessments largely measure knowledge that the child has already gained in the course of their 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 recognize printed letters or digits. Children's scores highly on such test items will reflect whether or not they have already acquired the relevant knowledge, and this is likely to be strongly influenced by their prior experiences both in the home and in pre-school education as well as their basic learning abilities.

Working memory assessments are quite different in nature. Children's performance on these measures does not reflect what they have or have not learned prior to the tests, as the test materials are designed to be equally unfamiliar to all participants. No child will therefore benefit from knowledge acquired previously in performing these tests. Consistent with this, performance on working memory tests is independent of general background factors such as socio-economic status and preschool education (e.g., Alloway, Gathercole, Adams, & Willis, 2003). Baseline assessments, on contrast, are significantly associated with such factors. What constrains performance on working memory measures is working memory capacity. We suggest that the

predictive pathway from working memory skills to curriculum attainments reflects the role of working memory in supporting learning, and provides a relatively pure indication of a child's learning potential that is independent of more general environmental factors. The most effective way of identifying children at risk of low educational attainment is therefore likely to be assessments that combine children's knowledge in key areas at school entry (such as Foundation Stage profiles) with purer tests of learning ability that are independent of prior experience, such as working memory measures.

Working memory and special educational needs

If poor working memory skills do limit a child's capacity to learn complex skills and acquire new knowledge, individuals with extreme deficits of working memory should experience marked learning difficulties. We had the opportunity to test this possibility in the course of our standardisation of the Working Memory Test Battery for Children (Pickering & Gathercole, 2001). Approximately 750 children aged between 4 and 15 years participated in this study and of these, almost 100 children had special educational needs recognised by their schools. Once the test scores were standardised on the entire sample, we looked at the working memory profiles of the children with different kinds of special educational needs (Pickering & Gathercole, 2004). In the group with learning difficulties in both literacy and mathematics, low scores on both working memory and phonological loop tests were 31 times more common than in the remainder of the standardisation sample who had no special educational needs. In a small group of children whose learning difficulties were specific to language, this profile was 43 times more common than in the comparison sample. The degree of working memory impairment of these children with recognized learning difficulties

was therefore very unusual in the general population. In contrast, children with recognized special educational needs of a non-cognitive origin (such as children with behavioural problems) had normal working memory skills.

A further important finding is that working memory skills tend to be most impaired in children whose learning difficulties are pervasive rather than specific in nature. Across two studies, we have found that the most severe deficits of working memory are found in children whose learning difficulties include both literacy and mathematics (Alloway, Gathercole, Adams, & Willis, 2004; Pickering & Gathercole, 2004). Individuals with problems specific to literacy, in contrast, have working memory skills that typically fall in the low normal range. The clear implication is that children with very poor working memory function experience difficulties in learning that are of a relatively general nature.

Working memory and Specific Language Impairment

Working memory deficits also appear to be a key feature of Specific Language Impairment (SLI). SLI is diagnosed in children whose language development falls significantly behind that expected on the basis of age, despite normal general cognitive function, sensory abilities, and other developmental experiences.

In a recent study, we investigated working memory abilities in children with SLI (Archibald & Gathercole, 2003). Deficits on verbal working memory tasks were present in our group of SLI children, and the majority also performed very poorly on measures of verbal short-term memory. These deficits were 50 times more common in this group of children in the general population. It should be noted that this finding of a close link between working memory deficits and language impairments is not in conflict with the claim above that poor memory function leads to general rather than

specific deficits in learning: all of the SLI children in this sample showed impairments in mathematics and literacy as well as language.

Case studies

We have recently begun to explore in more detail the learning difficulties experienced in the classroom by children with very poor working memory skills. To do this, we observed three children in Year 1 who were selected on the basis of very low scores on working memory assessments administered early on in Reception class (Gathercole, Lamont, & Alloway, in press).

At the time of the observations, Jay, Andrew and Nathan were working in the lowest ability groups in the class. All three children had good social skills, and were relatively popular with their peers and teacher. They were, however, reserved in group discussions. In each case their teachers viewed their main problems as relating to lack of attention and motivation (e.g., "*He doesn't listen to a word I say*"), although the children showed no consistent evidence of attentional deficits using a diagnostic test based on teacher ratings of behaviour. Interestingly, the teachers did not identify memory as a problem for any of the children.

The children showed frequent task failures in four aspects of routine classroom activities that we consider to impose significant burdens on working memory. These areas of failure are summarised below.

Forgetting instructions

The most commonly observed memory-related failure in all three children was an inability to follow instructions from the teacher. The failure appeared to be due to forgetting the content of the instruction, particularly when it was fairly lengthy and

did not represent a routine classroom activity. Here are three examples of this kind of failure.

On one occasion, the teacher gave the following instruction to Jay: *"Put your sheets on the green table, put your arrow cards in the packet, put your pencil away and come and sit on the carpet"*. Jay failed to put his sheet on the green table. Teacher asked Jay if he could remember where he was supposed to put it; he couldn't, and needed reminding.

A second example involved Nathan. His teacher handed him his computer login cards and told to go and work on computer number 13. He failed to do this, because he had forgotten what computer he had been told to use.

Finally, Andrew was asked to go back and put an *n* in the word *bean*. He went back and asked the classroom assistant what he had been asked to do.

Considered individually, these failures to remember instructions may seem to have relatively trivial consequences. However, the children's frequent forgetting of general instructions and specific task guidance was noted to impair both their individual successes in completing learning activities and the smooth running of the classroom.

Losing track in complex tasks

All three children experienced marked difficulties in writing a sentence either generated by the child himself or provided by the teacher. The task structure of writing a sentence accurately consists of a hierarchy involving three levels – letters, words, and the sentence. If the sentence is internally generated by the child or spoken by the teacher, its surface form needs to be maintained to guide the writing of the words and their individual letters, and the child has to keep track of the position in the sentence while writing. If the task involves copying a sentence the burden of sentence

representation in working memory is reduced, but the child still needs to keep track of their position while writing.

Two types of failure were observed in writing. The first type of error involved the child forgetting either some or all of the sentence content. This was relatively easy to identify, as it was common practice for teachers to check with children in lower ability groups if they were able to repeat the sentence before beginning to write it. Jay, Nathan and Andrew all demonstrated on occasion that they were unable to do this. The second type of error involved the child losing track of his position in the sentence. This resulted in omission of words, repetition of words (when the child forgot that the word has already been written), intrusion of words that were not in the target sentence, and (frequently) abandonment of the task.

Jay provided an example of both types of writing failure when he was working with his teacher and the rest of the low ability group. The teacher decided that the children should write *He had 36 barrels of gunpowder*. The sentence was repeated until the children appeared to remember it. Jay successfully wrote *he* and *had*, and then could not remember what to write next. The teacher asked him to read what he had already written and then to say what word came next, but he could not. The teacher reminded him of the sentence. Jay then got stuck after writing several letters of the word *gunpowder*, attempted and failed to get the teacher's attention to help him, and then forgot that the word needed completing.

A further example of a place-keeping error was provided by Andrew. The teacher wrote on the board *Monday 11th November* and, underneath, *The Market*, which was the title of the piece of work. Andrew lost his place in the laborious attempt to copy the words down letter by letter, writing m*oNemarket*. It appeared that he begun to write the date, forgot what he was doing and began writing the title instead.

Failing to cope with simultaneous processing and storage demands

Jay, Nathan and Andrew all frequently struggled in structured activities whose successful completion involved engaging in a relatively demanding processing activity at the same time as storage of information. Many of these activities involved counting. Although all three children were capable of counting accurately in the context of a simple task, many classroom activities combined counting with other cognitive processes. One frequent activity in literacy sessions involved counting the numbers of words in a sentence, often prior to writing the sentence down. Nathan was unable to recall the sentence, isolate each word and count it without assistance from the teacher. A group activity in Andrew's class was to count the number of sentences in a text. Andrew was unable to keep track of the tally number while reading aloud the text. In both cases, the task failure appeared to result from combining the memory demands of counting (keeping track of the tally number) in the context of a concurrent and fairly demanding processing activity.

There was frequent use in each classroom of number aids, designed to facilitate children's grasp and mastery of counting and basic arithmetic. Examples include number lines, number fans, and Unifix blocks. In each case, the device provides a means of representing number physically. The children in the low working memory group struggled to take full advantage of the support potentially provided by these number aids. Number lines are designed to facilitate counting, by allowing the child to jump one step at a time from a starting number. Nathan was encouraged to use a number line when counting up the number of ducks shown on two cards, but struggled to coordinate the act of jumping along the line with counting up to the second number. He abandoned the attempt, solving the sum instead by counting up the total number of ducks on the two cards. Similarly, Andrew was observed to choose not to use the

number line when available, but instead to count on his fingers. In both cases, the unfamiliar activity of counting along the points of the number line to a stored target number appeared to impose a greater working memory load than simple counting of the physical events.

Further failures were observed in activities that involved the detection of target items in spoken or written text. These tasks imposed significant processing demands (analysis and comprehension of spoken language, or text reading) in conjunction with the storage of multiple items. For example, the children in Nathan's class were asked to identify the rhyming words in a text read aloud by the teacher. They had to wait until all four lines had been read before telling the teacher the two words that rhymed: *tie*, and *fly*. This task involves matching the sound structures of a pair of words, and storing them. Nathan was unable to do this. A related activity in Jay's class involved the teacher writing number sequences on the white board with some numbers missing. She counted the number aloud, and asked the class what numbers she had missed out. In each case, there was more than one number missing (*e.g., 0, 1, 2, 4, 5, 7, 8*). Here, the child has to use their number knowledge to identify each missing number, and store them. Jay was unable to tell the teacher the numbers she had missed out on all occasions.

All of the tasks discussed here share the common feature of imposing significant processing demands on the child, combined with a storage load. In themselves, the storage loads do not appear to be particularly excessive. In the case of counting-based activities, the child simply has to retain the tally number and sometimes the target number to which he must count, and in the examples of the detection tasks supplied above the child had only to store two items in each case. In isolation, it seems likely the child would be able to meet these storage requirements without difficulty. The

task failures appear to arise from the combining storage with the significant processing demands of the task.

Longer-term forgetting

Memory failures that extended beyond the duration of working memory were observed on a number of occasions, with all three children failing on several occasions to remember information that they had encountered in an earlier activity in the day. This raises the possibility that poor working memory skills may limit the flow of information through to longer-term memory systems, leading to poor functioning in several memory systems.

Two examples illustrate this point. Jay's teacher discussed bonfire night and read the story of Guy Fawkes to the class. When Jay was asked "*What might you see in the sky tomorrow night*?" he failed to answer *fireworks.* He was also unable to say what Guy Fawkes planned to do, even after writing the sentence in answer to the question. Similarly, in a class activity involving the teacher and class together reading from a big book, Nathan was unable to answer any questions asked about the text.

Implications for classroom practice

We suggest that these frequent failures of low memory children to meet the working memory demands of classroom activities may be at least one cause of the poor academic progress that they typically make. In order to reach expected attainment targets, the child has to succeed in many different structured learning activities designed to build up gradually across time the body of knowledge and skills that they need in areas of the curriculum such as literacy and mathematics. If the children frequently fail in individual learning situations simply because they cannot store and manipulate information in working memory, their progress is acquiring

complex knowledge and skills in areas such as literacy and mathematics will be slow and difficult.

As yet, no ways of improving working memory skills have been identified. However, we suggest that the learning progress of children with poor working memory skills can be improved dramatically by reducing working memory demands in the classroom. Here we consider a number of ways in which this can be achieved in school, summarised in Table 1.

Table 1 about here

First, it is important to ensure that the child can remember what he or she is doing. On many occasions, we observed children with low working memory simply forgetting what they had to do next, leading to failure to complete many learning activities. Children's memory for instructions will be improved by using the instructions that are as brief and simple as possible. Instructions should be broken down into individual steps where possible. 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 the child of crucial information for that particular phase of the task 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 them to repeat it back. Our observations indicate that the children themselves have good insight into their working memory failures.

Second, in activities that involve the child in both processing and storage information, working memory demands and hence task failures will be reduced if the processing demands are decreased. For example, sentence writing was a source of particular difficulty for all of the children with low working memory that we

observed. Sentence processing difficulty can be lessened by reducing the linguistic complexity of the sentence. This can be achieved in a variety of ways, such as simplifying the vocabulary, and using common rather than more unusual words. In addition, the syntax of the sentence can be simplified, by encouraging the child to use simple structures such as active subject-verb-object constructions rather than sentences with a complex clausal structure. The sentences can also be reduced in length. A child with poor working memory skills working with short sentences, relatively unfamiliar words and easy syntactic forms are much more likely to hold in working memory the sentence form and to succeed in a reasonable attempt at writing the sentence.

Third, the problem of the child losing his or her place in a complex activity can be reduced by breaking down the tasks into separate steps, and by providing memory support. External memory aids such as useful spellings displayed on the teacher's board or the classroom walls and number lines are widely used in classrooms. In our observational study, however, we found that children with poor working memory function often chose not to use such devices, but gravitated instead towards lower-level strategies with lower processing requirements reduced general efficient *example*. In order to encourage children's use of memory aids, it may be necessary to give the child regular periods of practice in the use of the aids in the context of simple activities with few working memory demands.

Difficulties in keeping place in complex task structure may also be eased by increasing access to useful spellings will also help prevent them losing their place 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 spellings on key words on the

teachers' board was itself observed to be a source of error in low memory children in our study, with children commonly losing their place within the word. Making available spellings of key words on the child's own desk rather than a distant class board may reduce these errors by making the task of locating key information easier and reducing opportunities for distraction. It may also be beneficial to develop ways of marking the child's place in word spellings as a means of reducing place-keeping errors during copying.

A final recommendation for improving the learning successes of individuals with poor working memory skills is to develop in the children effective strategies for coping with situations in which they experience working memory failures. Strategies may include encouraging the child to ask for forgotten information where necessary, training in the use of memory aids, and encouragement to continue with complex tasks rather than abandoning them even if some of the steps are not completed due to memory failure. Arming the child with such self-help strategies will promote their development as independent learners able to identify and support their own learning needs.

Current research

Following the principles outlined above, we are now working on a programme designed to identify and provide learning support in the classroom for children with working memory deficits. In this programme, children will be screened for working memory impairments using the Automated Working Memory Assessment battery (*AWMA*). The *AWMA* is a computerised assessment package that requires minimal training prior to administration, and is designed for classroom use. It is suitable for children aged 4 to 11 years of age. A learning support programme will be offered to

children who are identified as having poor working memory skills. The programme will provide guidance for classroom and special needs teachers on ways of reducing excessive working memory loads in classroom activities, and on developing children's own strategies for coping with memory failures.

We are currently seeking collaborations on this project with education professionals working with children, such as special needs and classroom teachers, and educational psychologists. Anyone interested in learning more about this study, and possible participation in it, should contact Tracy Alloway or Susan Gathercole either by email (t.p.alloway@durham.ac.uk or s.e.gathercole@durham.ac.uk) or at the Department of Psychology, University of Durham, Science Laboratories, South Road, Durham DH1 3LE. Further information about our research is available at www.psychology.dur.ac.uk/research/wm/index.htm.

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Figure legends

Figure 1: Mean scores, with bars showing 10th and 90th centile points, on listening recall task from the Working Memory Test Battery for Children, as a function of age

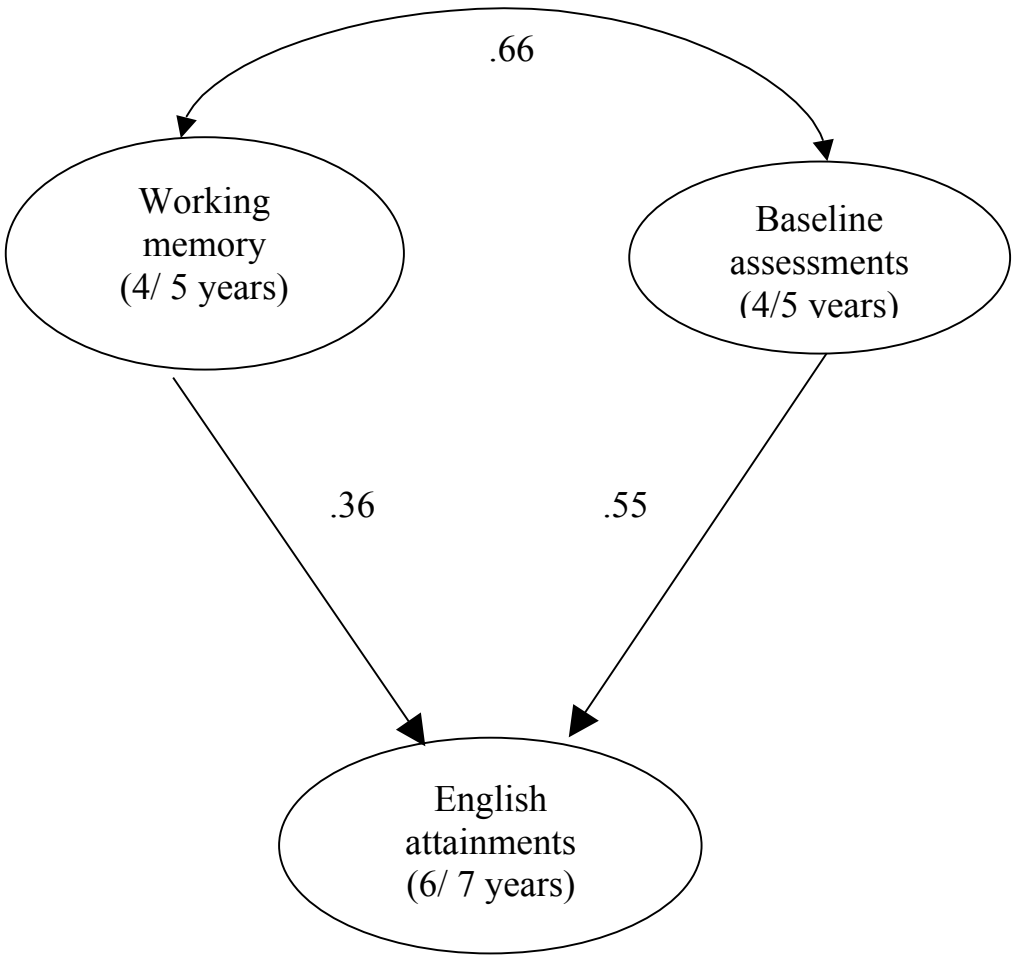
Figure 2: Mean complex memory span scores for low, average and high ability groups on English and mathematics assessments at Key Stage 2, from Gathercole et al. 2004.

Figure 3: Links between working memory and baseline assessment scores and subsequent attainments in Key Stage 1 English assessments, from Gathercole et al 2003.

Table 1

Working memory demands in classroom activities: Some problems and solutions

Problem	Solutions
Child forgets the task	• Give brief and simple instructions, broken down into separate steps if task is very complex. • Check the child can remember the instructions. Repeat instructions if necessary
Child cannot meet combined processing and storage demands of activities	• For activities involving sentences, reduce sentence length, reduce syntactic complexity (simple active sentence forms are the easiest), and/ or increase familiarity of the vocabulary
Child loses place in a complex task	• Use external memory aids such as number lines and useful spellings. • Ensure that the child has plenty of prior practice in the use of the aids prior to using them in more complex task settings. • Find ways of marking for the child their progress in a complex task structure


.66
Working memory (4/ 5 years)
Baseline assessments (4/5 years)
.36
.55
English attainments (6/ 7 years)