In 1927 Robert S. Woodworth noted the following in his book *Psychology: A Study of Mental Life*:

So much depends on a good memory in all walks of life... that perhaps it is no wonder that many students and business professional men become so worried about their memories and resort to "memory training courses" in the hope of improvement. (p. 332)

Today this assertion is no less valid. At the time of writing this chapter it is hard to find a conference presentation or publication in the field of psychology or special education that does not make some mention of memory, particularly "working memory," somewhere. Increasingly, researchers and practitioners in a range of fields are coming to the view that many of the behavioral phenomena we are interested in understanding, measuring, and perhaps manipulating are linked to working memory (WM) functioning in one way or another. It is for this reason, therefore, that now more than ever the detailed and accurate assessment of WM is becoming an issue with which many are concerning themselves.

In this chapter I aim to provide the reader with an overview of the assessment of WM, beginning with a look at how WM has been assessed in earlier times. In the following sections of the chapter I introduce a theoretically based battery of WM tests, the *Working Memory Test Battery for Children* (WMTB-C; Pickering & Gathercole, 2001); discuss the process by which the test was created and the uses to which it is being put; and present some research findings from children with different educational difficulties. In the
final sections of the chapter I discuss a computerized and extended version of the WMTB-C, the Automated Working Memory Assessment (AWMA) battery (Alloway, Gathercole, & Pickering, 2004), and some recent research findings from this test. The chapter closes with some thoughts on the link between WM assessment and remediation.

**ASSESSING WORKING MEMORY IN THE 20TH CENTURY**

Although philosophers have speculated about memory for more than 2 millennia, the scientific study of this aspect of cognition only began about 100 years ago, with a German scholar named Herman Ebbinghaus (Baddeley, 1997). His approach to studying memory has left a lasting legacy for anyone now interested in WM and its assessment. Ebbinghaus chose to study memory in an extremely rigorous way that avoided many of the complexities of human mental functioning. He created simple artificial materials—nonsense syllables—and investigated how such materials were learned and forgotten by a single adult participant—himself. Although a number of researchers have since protested against the lack of "ecological validity" in this experimental approach to studying memory performance (e.g., Neisser, 1978), the dominant method for measuring WM (or short-term memory [STM], as it is also referred to) today is still based on the memorization and recall of simple, relatively meaningless information, such as lists of numbers, unrelated words, or nonsense words.

The first recorded attempt to measure STM for educational purposes was carried out by a schoolmaster from London named Joseph Jacobs. Jacobs was interested in the mental capacity of his pupils and therefore devised a technique in which the child was presented with a sequence of items, such as numbers, and asked to repeat them back exactly as they had been heard. This technique is what we now call the *memory span procedure*. An important feature of this procedure is that assessment of memory performance can begin with very short sequences, which can then be increased systematically (usually by one item) until the participant cannot recall the sequences correctly. The sequence length (number of items in the list) at which the participant can recall correctly on 50% of the trials is then referred to as his or her memory span (Jacobs, 1887, cited in Baddeley, 1997).

The concept of memory span has been a very powerful one, invoking the notion of a particular mental space, or capacity, by which the participant is limited in his or her intellectual processing. This concept is far more complex than first imagined, however; capacity is often found to be different for varying types of information. Moreover, active processing of stimuli in a memory span test can increase the amount of information that can be retained at any one time. A college student studied by Ericsson and colleagues (Ericsson, Chase, & Faloon, 1980) was able to achieve a digit span of 79 items. This figure of 79 stands in stark contrast to "The magic number
seven, plus or minus one," the title of the classic paper by George Miller in 1956. In this paper Miller argued that, in adults, memory span was limited to between 6 and 8 pieces of information. He did, however, say that this magic number related to the amount of "chunks" that could be held in mind temporarily. The question of what constitutes a "chunk" is determined by a whole range of factors, including one's familiarity with the information to be remembered and the extent to which such information is actively divided into meaningful chunks. Many of the long numbers that we have to deal with in everyday life, such as telephone numbers and credit card details, are often arranged in chunks of 3 or 4 digits that form the crucial number. The recall of 79 digits was achieved using strategic approaches that involved chunking and increasing the meaningfulness of the digits (see Ericsson, Delaney, Weaver, & Mahadevan, 2004, for an account of the mechanisms involved in retaining large numbers of digits)—plus a great deal of practice.

**The Digit Span Task**

Given that it is clear that factors such as meaningfulness, chunking, and other forms of strategic activity can affect performance on memory span tests, how has this influenced the approaches that have been used to measure WM in children? The answer to this question lies with the selection of the digit span task as the most commonly used measure of short-term verbal memory over the last century. Digits lend themselves well to the assessment of STM capacity: They are acquired early in life, highly over-learned, and easily presented. Digit span tasks typically utilize the numbers 1–9, thus providing the user of the test with a small pool of memory items that can be combined and recombined in a number of different ways. Many digit span tests aim to include each digit only once in each sequence (although this is only possible with sequences of 9 items or less) and avoid the use of predictable sequences (such as 3, 2, 1). In doing so, the extent to which strategic activity such as chunking can be used during the task is minimized. Moreover, although each digit in the sequence has inherent meaning in the sense that it represents magnitude, it might be argued that the richness of meaning of individual digits is not as great as that for individual words, for example. Thus, memory span tasks that involve digits have become very popular measures of STM capacity in both adults and children.

In a typical digit span task care is taken to standardize presentation procedures; digits in the sequence are read to the participant in an even monotone, so as to discourage any likelihood of chunking the items on the basis of intonation and prosodic information. Digits are presented at a steady and even pace; in many cases this is one item per second, although some versions of the digit span procedure recommend faster rates, such as two items per second (e.g., the Recall of Digits Forward subtest of the British Ability Scales II; Elliot, 1996). The procedures for administration of the Digits Forward subtest of the Wechsler Intelligence Scale for Children III-UK (WISC
III-UK; Wechsler, 1992, p. 209) bear out what was described earlier in this chapter:

Read the digits at the rate of one per second, dropping voice inflection slightly on
the last digit in a series. After each sequence, pause to allow the child to respond.

For the British Ability Scales II, the instructions for the Recall of Digits
Forward subtest stress the lack of intonation in the voice and include refer-
ence to the faster rate of presentation (British Ability Scales II Adminis-
tration and Scoring Manual, or BAS II; Elliot, 1996, p. 302):

Read digits in an even monotone at half-second intervals. Drop your voice slightly
on the last digit . . .

Exactly what effect the difference in presentation rate may have for these
two versions of the digit span task is not immediately clear. When presen-
tation rates are set at one item per second, participants have more time
between memory items to rehearse the sequence to aid recall. However, it
is also true that the entire list takes twice as long to be presented, possibly
leading to greater decay of memory items from the temporary store that is
thought to hold them. In contrast, faster presentation rates are likely to
reduce the opportunities for between-item rehearsal, but the entire list will
be presented more quickly, which may limit the degree of memory loss as
a result of decay.

Thus, we can see that the memory span task designed more than a
century ago by Joseph Jacobs has found a central place in the assessment
of WM, both as a single test and as part of a larger assessment of overall
intellectual functioning (or intelligence quotient) as embodied by tests such
as the WISC III-UK or BAS II. In the case of the WISC and the BAS, scores
on the memory span task have been standardized for children of different
ages. This tells us something important about the performance of children
on the memory span task: It is expected that it will change with age.

Indeed, one intriguing feature of children's performance on a task such
as digit span is the extent to which span appears to increase as children get
older. A great deal of research has been dedicated to the study of this
memory span development with the aim of understanding what factors
promote increases in memory span and what consequences this might have
for the everyday functioning of children of different ages (see, for example,
Gathercole, 1999 or Cowan, 1997).

From our own data (Pickering & Gathercole, 2001) we have found that
more than 80% of children between the ages of 4:7 and 5:6 years had a
digit span of between 4 and 5 items. In contrast, a significant proportion of
children of 14:9 to 15:9 years of age obtained digit spans of 5 items (37%),
6 items (27%), and 7 items (23%). Of the older age group, 2% recorded digit
spans of 9 items, whereas none of the youngest group managed to obtain
a digit span of greater than 6 items. Why do the older children seem to have
more “space” to hold digits temporarily than the younger children? One suggestion concerns the development of subvocal rehearsal at around the age of 7 years (e.g., Gathercole & Hitch, 1993).

Those who have experience administering digit span tasks to children of different ages may have found that children appear to deal with the task in different ways depending on their age. Children of around 4–5 years of age are often found to take a relatively passive approach to the task: listening to the lists of digits without attempting to carry out any active processing of the items during presentation or prior to recall. This approach contrasts sharply with that of children of around 7 years of age and older. These children can often be seen to repeat items in the sequence to themselves during presentation, either silently (the efforts of which are often visible for the tester to see in the form of lip, head, and eye movements) or out loud. The use of rehearsal appears to increase over childhood (Flavell, Beach, & Chinsky, 1966), and the quality of rehearsal shows developmental changes too (Cowan, 1997). For example, in the period during which children are becoming aware of the usefulness of rehearsal and becoming skilled in its use, children can often be observed carrying out a rudimentary form of the strategy in which the child repeats each digit after it has been said by the tester. What children often fail to do, however, is to string the list items together and rehearse them as a sequence—a process known as cumulative rehearsal (Gathercole & Hitch, 1993).

Thus, we can see that performance on a digit span task increases significantly over childhood, and much of this increased capacity for digits appears to be dependent on the use of a cumulative rehearsal strategy after the age of about 7 years. The process of rehearsal of memory items has also been linked to speed of articulation (Cowan et al., 1998; Hulme, Thomson, Muir, & Lawrence, 1984) whereby faster articulation rates (the speed at which words can be spoken) have been found to be related to greater memory spans. This is thought to be because rate of rehearsal of items in memory is linked to speed of articulation—and speed of articulation appears to increase as children get older (Hulme et al., 1984).

The digit span task is a simple, easy-to-administer measure of the STM of an individual. It is used widely in psychological, educational, medical, and other settings to gauge the capacity of a person to hold information in mind temporarily. However, the digit span task is not without limitations, some of which are inherent in the basic structure of the task, whereas others are related to the particular design of specific versions of the task.

One obvious limitation of the digit span task is that it restricts the assessment of STM to verbal information, and in this sense the test may be more accurately described (according to the Baddeley and Hitch model of WM) as a test of phonological loop function, rather than as a measure of STM per se. In addition to this, the use of digits in the task means that the information in the phonological loop is already well established in long-term...
memory (LTM), a feature that means that immediate memory performance can be supported by the activity of LTM. This process has been termed “red-integration” (Hulme, Maughan, & Brown, 1991) and provides support for short-term recall by allowing one to compare the partially decayed memory trace in STM with possible candidates in LTM. Thus, the restricted pool of items (the digits 1–9), plus significant familiarity with these numbers, increases the potential for variables other than the basic capacity of the phonological loop to contribute to the digit span obtained.

Other factors that may affect the performance of an individual on a digit span task include the: the extent to which they are paying attention when the list of items is presented, their hearing ability, and their capacity for spoken output. Many versions of the digit span task involve both spoken presentation and recall, although the task can be presented visually and recall can be written. The transient nature of the task stimuli poses a problem for any situations in which the participant’s attention is distracted away from the stimuli. A digit sequence that was not attended to, either because the child’s attention wandered, or because of some form of external distraction (such as a door slamming nearby), will not easily be recalled. In cases like this, errors may not reflect the fact that the sequence had exceeded the child’s capacity for holding digits in memory. One way to overcome this problem is to include a relatively large number of trials at each difficulty level. By doing this, one is able to obtain a number of responses to sequences of a particular length and thus obtain a more robust indication of the child’s digit span.

**Digit Span and Beyond**

In this section of the chapter we have examined the historical basis of WM assessment by focusing on the memory span procedure, first used by Joseph Jacobs, and charting the widespread use of the digit span task as a measure of STM capacity. Although the digit span task has contributed—and continues to contribute—significantly to our understanding of the WM functioning of individuals in a wide range of settings, the limitations of the procedure outlined earlier suggest the need for a broader approach to the assessment of WM. The digit span task measures phonological loop function for a restricted pool of highly familiar material. What are the consequences for memory functioning when the pool of items is unrestricted, as in the case of words? How can we measure visuo-spatial WM functioning? Is there a way of measuring WM without the contribution of LTM? Finally, what processes can we attribute to the central executive (CE) component of Baddeley and Hitch’s WM model, and how do we go about measuring these? These questions are considered in the next section where the assessment tool known as the Working Memory Test Battery for Children (WMTB-C) is introduced.
Memory test batteries are far from being a new concept; a number of such batteries have existed for some time. These include tests such as the Rivermead Behavioural Memory Test for Children (Wilson, Ivani-Chalian, & Aldrich, 1991), The Wechsler Memory Scale III-UK (Wechsler, 1997), the Test of Memory and Learning (Reynolds & Bigler, 1994), the Wide Range Assessment of Memory and Learning (Sheslow & Adams, 1990), and the Children's Memory Scale (Cohen, 1997). Each of these tests provides the user with a range of subtests with which a child's memory performance can be measured. The Children's Memory Scale, for example, includes subtests that have been designed to measure immediate verbal memory, delayed verbal memory, general memory, immediate visual memory, and delayed visual memory in children from 5 to 16 years of age. Thus we can see that this test, like many of the others listed here, provides the user with a measure of a range of different types of memory including both LTM and STM. Clearly, some test users will be interested in such a range of memory scores, and for those users a test like this will be of great use. However, for those users particularly interested in measuring the working memory performance of a child, it might be argued that a test such as this will be of more limited use. At least two factors contribute to this view.

The first point to note is that by including subtests that measure aspects of memory other than WM, the number of subtests that are devoted to the measurement of immediate memory is necessarily limited. Second, the theoretical basis of many of the tests is not immediately clear. In other words, tests that base their structure and content on well-established, intensively researched, and well-understood models of memory functioning appear to be rare. This point is important because when we look at a child's scores on a memory battery, we want to be able to understand the cognitive structures and processes that may have contributed to performance, and what the consequences of these scores might be.

One memory battery that has based itself on a well-established and intensively researched model of WM is the WMTB-C (Pickering & Gathercole, 2001). This test was designed to measure the WM performance of children between the ages of 4:6 and 15:9 years using the WM model originally proposed by Baddeley and Hitch in 1974 (with subsequent modifications) as its theoretical basis. As other chapters in this book have described in varying degrees of detail, the Baddeley and Hitch model departed from previous conceptualizations of STM (e.g., the "modal model," Atkinson & Shiffrin, 1968) by specifying a multi-component structure and a dynamic "working" set of functions. For many years the model was proposed to consist of three major components—a central executive and two "slave systems," the phonological loop and the visuo-spatial sketchpad. In 2000 a fourth component was hypothesized to be part of the system: the episodic buffer (e.g., Baddeley, 2000). Work on this additional component had not
begun at the time that the WMTB-C was being constructed, and even now there are few tests in existence that are thought to be able to measure the functioning of this component (Baddeley, personal communication, 2005).

Thus, the WMTB-C is a battery of WM tests based on the tripartite structure of the WM model. One of the characteristics of WM, as embodied by this model, is the extent to which, although related in the sense of being a coherent system of immediate memory functioning, the activities of the three components of WM have been demonstrated to be largely separable. Data from experimental studies in which participants are asked to carry out, for example, a phonological loop task (e.g., digit recall), while simultaneously engaging in a secondary task designed to use the visuo-spatial sketchpad (e.g., spatial tapping) has shown little decrement in the primary task performance (e.g., Pickering, Gathercole, Hall, & Lloyd, 2001). This finding contrasts sharply with the results of studies in which the secondary task uses the phonological loop (e.g., articulatory suppression). Here we see significant impairments in performance (e.g., Baddeley, Lewis, & Vallar, 1984).

Other research findings support the separability of the three WM components. Research with neuropsychological patients, for example, has revealed individuals with specific impairments in one component of WM but spared performance in other components (see, for example, Henson, 2001, for a review). In addition to this, developments in the technology available for brain scanning have provided neuroanatomical evidence that activities associated with the three WM components appear to be located in different areas of the brain (e.g., Henson, Burgess, & Frith, 2000; Owen, Evans, & Petrides, 1996; Smith & Jonides, 1997).

Confirmation that the subtests selected for use in the WMTB-C fitted well with the Baddeley and Hitch model came from factor analyses that were carried out on the data collected during the standardization process for the battery. Although there were some minor, but interesting, variations in the relationships between the different subtests in the battery for children in different age groups (see Gathercole, Pickering, Ambridge, & Wearing, 2004, for a more detailed discussion of this analysis), a three-factor structure gave a good fit to the data and provided further support for both the validity of the subtests chosen and the WM model itself.

**Selection of the WMTB-C Subtests**

The selection of subtests for inclusion in the WMTB-C was based on a number of factors. The first was an understanding of the literature on the structures and processes of WM as identified by the extensive research activity that has been devoted to the study of this aspect of cognition over the last 30 years in locations all over the globe. The second was a review of what we know about the development of WM and the factors that influence such development. Research in this area has been most significant in relation to the phonological loop component of WM. Much less is known about
TABLE 9.1
Subtests Included in the Prototype Version of the WMTB-C

<table>
<thead>
<tr>
<th>Working Memory Component</th>
<th>Subtest</th>
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<tbody>
<tr>
<td>Phonological loop</td>
<td>Digit Recall</td>
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<tr>
<td></td>
<td>Word List Recall</td>
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<tr>
<td></td>
<td>Nonword List Recall</td>
</tr>
<tr>
<td></td>
<td>Word List Matching</td>
</tr>
<tr>
<td></td>
<td>Nonword List Matching</td>
</tr>
<tr>
<td></td>
<td>Children's Test of Nonword Repetition</td>
</tr>
<tr>
<td>Visuo-spatial sketchpad</td>
<td>Matrices Static</td>
</tr>
<tr>
<td></td>
<td>Matrices Dynamic</td>
</tr>
<tr>
<td></td>
<td>Mazes Static</td>
</tr>
<tr>
<td></td>
<td>Mazes Dynamic</td>
</tr>
<tr>
<td>Central executive</td>
<td>Listening Recall</td>
</tr>
<tr>
<td></td>
<td>Counting Recall</td>
</tr>
<tr>
<td></td>
<td>Backward Digit Recall</td>
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the development of the visuo-spatial sketchpad and CE components, although research in these areas is increasing.

In the early stages of the development of the test battery we added to our knowledge of children's WM by carrying out a range of experimental studies designed to fill in some of the gaps in our knowledge (e.g., Gathercole, Pickering, Hall, & Peaker, 2001; Pickering et al., 2001). The findings from such studies allowed us to design new tasks for inclusion in the battery or to better understand tasks that had already existed in the experimental literature but had not been used with children to any significant degree. On this basis we chose a number of tasks for inclusion in a prototype version of the WM battery. This battery included 12 subtests: some tests with a long-history in the STM world, such as the recall of digits; some tasks that had been adapted from experimental work with adults, such as listening recall; some new tasks that emerged from our own experimental work, such as the matrices and mazes tasks. Finally, an already-standardized test of phonological loop function, the Children's Test of Nonword Repetition (CNRep; Gathercole & Baddeley, 1996) was added.

The total set of 13 tests included in the prototype battery is shown in Table 9.1.

The prototype WM battery was administered to 87 children of 6 and 7 years of age, along with a series of standardized tests of performance in receptive language, literacy, and arithmetic. A number of interesting findings emerged from this study; these are described in detail by Gathercole and Pickering (2000a, 2000b, & 2001), along with descriptions of the subtests and their administration procedures. In summary, the battery appeared to provide an easy-to-administer and reliable way of measuring WM
performance in children of this age. Moreover, performance on the tests was found to be linked to scores on the standardized attainment tests and to performance in Key Stage 1 National Curriculum Standard Attainment Tests. Test performance also provided the ability to distinguish between children with and without Special Educational Needs (SEN) with a high degree of accuracy.

Not all subtests of the prototype battery proved equally valuable, however, and for the purposes of constructing the final version of the WMTB-C, a number of modifications were made to the test. These modifications are described in detail in Pickering and Gathercole (2001) and included the removal of some subtests from the battery (such as the Nonword List Matching task) and the modification of others (such as the Mazes task). The Nonword List Matching subtest was removed because it was found that it did not provide any additional information that could not be obtained from the sole use of the Word List Matching task. In the course of experimental work we discovered that the "lexicality effect," our superior recall of words over nonsense words, did not appear to operate in the same way when participants were required to match sequences of items rather than recall them (Gathercole et al., 2001).

The final number of subtests included in the standardization of the WMTB-C was 10. However, one of the subtests actually existed as a published psychometric test prior to the publication of the WMTB-C. The Visual Patterns Test (Della Sala, Gray, Baddeley, & Wilson, 1997) was originally designed as a neuropsychological test of visual memory in adults. However, in the course of our research we found that it could be administered easily to children as young as age 4 years. Because this test provided us with an excellent measure of visuo-spatial sketchpad functioning (the specifics of which will be discussed in the next section) we decided to include it the final version of the battery in place of the Matrices Static task, to which it is closely related. The major difference between the two tasks is that the Matrices task is computer administered and the Visual Patterns Test uses a pencil and paper format—something that can make test administration much easier for users without access to a computer.

Thus nine subtests can be found in the WMTB-C battery, and the standard scores for all of these tests, plus the Visual Patterns Test, are provided in the accompanying manual. The Visual Patterns Test can be bought separately and added to the battery, if a user so requires.

What Do Each of the WMTB-C Subtests Measure?

Having made the claim that the WMTB-C represents a theoretically based tool for measuring WM, it is important to specify what that theoretical basis is. In this section, each of the 10 WMTB-C subtests is discussed with respect to its relationship to our understanding of the structure and function of WM. The set of 10 subtests is listed in Table 9.2.
TABLE 9.2
Subtests Included in the WMTB-C

<table>
<thead>
<tr>
<th>Working Memory Component</th>
<th>Subtest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phonological loop</td>
<td>Digit Recall</td>
</tr>
<tr>
<td></td>
<td>Word List Recall</td>
</tr>
<tr>
<td></td>
<td>Nonword List Recall</td>
</tr>
<tr>
<td></td>
<td>Word List Matching</td>
</tr>
<tr>
<td>Visuo-spatial sketchpad</td>
<td>Block Recall</td>
</tr>
<tr>
<td></td>
<td>Visual Patterns Test</td>
</tr>
<tr>
<td></td>
<td>Mazes Memory</td>
</tr>
<tr>
<td>Central executive</td>
<td>Listening Recall</td>
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<td>Counting Recall</td>
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<td></td>
<td>Backward Digit Recall</td>
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</tbody>
</table>

Digit Recall

Much has already been said about the recall of digits in this chapter and elsewhere in this book. On this basis, we know that this phonological loop task requires the immediate recall of numbers and that for a response to be correct, the right numbers need to be recalled in the right order. The Digit Recall subtest measures a child's capacity for storing and outputting sequences composed of highly familiar numbers. Sequences are presented verbally (at the rate of one item per second), and the child is required to respond in spoken form. As discussed earlier, the familiarity of digits means that some support from LTM would be expected when carrying out this task. In addition, the phonological form of the numbers 1–9 is distinct: None of the digit names sounds much like the other (certainly in English anyway), and with the exception of the number 7, all of the digit names are monosyllabic. Using our knowledge of factors that have been shown to influence the operation of the phonological loop, we can see that digits are concrete (i.e., not abstract), familiar, short, phonologically distinct, selected from a closed set, and relatively easily articulated. Children of 7 years of age and older would be very likely to approach a digit recall task in an active way and to rehearse the digits to maximize their chances of recall. On this basis, we can see that performance on the Digit Recall subtest of the WMTB-C provides us with an indication of the capacity of the phonological store of WM, with additional contributions from LTM and, in older children, active rehearsal processes.

Word List Recall

The Word List Recall subtest shares some structural similarities with the Digit Recall subtest, the key difference being that the to-be-remembered information is now words rather than numbers. Examination of the
characteristics of the stimuli selected for this subtest reveals that each of the items in the sequences has a consonant–vowel–consonant (CVC) structure, contains phonemes from a restricted pool (avoiding the use of late-acquired sounds), and includes words that are likely to be within the vocabulary of even very young children. Many of the stimuli in the subtest derive from our earlier experimental work on word and nonword recall (e.g., Gathercole & Pickering, 1999). Thus, this test was designed to measure recall of memory items that form part of a much larger and notionally unrestricted pool of stimuli—in the sense that no item in this subtest occurs more than once. The stimuli are again monosyllabic, and care was taken to avoid putting phonologically similar words together in the same list.

It could be argued that words are more semantically rich than digits; many of the items in the lists may link to images, feelings, and other forms of information that are already stored in LTM and thus might be invoked during the subtest. In Chapter 1 we saw that the “Levels of Processing” framework proposed by Craik and Lockheart (1972) was very helpful in describing the phenomenon whereby information processed at a deeper and more meaningful level is more likely to be recalled.

During presentation of the Word List Recall task children may attempt to link items in the memory lists together and create mental images of them. In the case of the two-item sequence, “lip, bag,” there is scope for creating the image of a bag with a picture of some lips on it. However, children are not specifically instructed to use this strategy, nor are they instructed not to use it. Moreover, not all sequences lend themselves to the strategy as well as this example does, partly because not all of the words in the subtest are concrete and readily imageable.

Thus, the specific design of the Word List Recall subtest of the WMTB-C provides the user with a measure of the capacity of the phonological store of WM with potential additional support from other aspects of the cognitive system including long-term semantic and visual memory, visual WM, plus the active rehearsal processes available during the digit span task.

**Nonword List Recall**

As with Digit and Word List Recall, Nonword List Recall requires the immediate spoken recall of a series of verbally presented items. In this case, however, the memory items are CVC nonsense words—that is, each item in the list does not have any meaning in the English language. Care has also been taken to make sure that none of the items actually forms a homophone for a real word. The use of nonsense words in the measurement of phonological loop function has a long history stretching all the way back to the work of Ebbinghaus more than 100 years ago. One of the proposed advantages of testing phonological STM with nonsense words is that no support is available from LTM, and therefore, this type of test has been seen
as a purer measure of immediate memory capacity than those that use familiar items as their stimuli (see, for example, Gathercole et al., 2001).

This issue has subsequently proved to be much more complex than first imagined, however. As described in Chapter 1 of this volume, work by Gathercole and colleagues (e.g., Gathercole, Frankish, Pickering, & Peaker, 1999) has indicated that nonsense words can vary in their “wordlikeness”—that is, the extent to which they are perceived to resemble real words. One way that the concept of wordlikeness has been operationalized is through the use of phonotactic probabilities (Gathercole & Pickering, 1999; Gathercole et al., 1999). Pairs of phonemes cooccur to a greater or lesser extent in any given language. Research by Gathercole and colleagues found that nonsense words composed of phoneme pairs that had high phonotactic probabilities in English (e.g., bip) were significantly better recalled than those made up of pairs with low phonotactic probabilities (e.g., vook). This suggests that as well as being able to benefit from the effects of lexicality (i.e., better recall of words over nonsense words), children were able to use information stored in LTM at the sublexical level—that is, long-term knowledge about the statistical properties of our language appears to support recall of memory items that are not even known words.

On this basis, tests of phonological loop function can vary in the extent to which they draw on the contents of LTM depending on the way that the nonsense words are constructed. In the WMTB-C, nonsense words were constructed using the same restricted pool of phonemes that were used to create the words in the Word List Recall subtest. However, because we wanted to create a sufficient pool of nonsense words to allow us to include each item only once in the whole subtest, the possibility of manipulating the phonotactic probabilities of the test items was not open to us. Thus, the extent to which knowledge of the sublexical properties of the English language can help with recall of these memory items is not specifically known. A quick scan of the items that are included in the test suggests that the phonotactic probability of most of the items is neither particularly high nor particularly low. A sequence such as “gach, mup, coom, terl” appears to contain some items that appear wordlike and some that appear less wordlike. Further research will inform us of the precise phonotactic structure of the nonsense words in this task.

One particularly interesting feature of this subtest is its relationship with the Word List Recall subtest. The two tests were designed to be identical to one another except for the fact that in one case the combinations of phonemes in each memory item formed words and in the other they formed nonsense words. In all other respects the two subtests are the same. This means that a systematic comparison of the scores achieved on the two subtests is possible, allowing us to get a sense of the extent to which a child was able to draw on knowledge in LTM—be it lexical or sublexical—to support recall.
Word List Matching

The same pool of memory items was used in the construction of the Word List Matching subtest and the Word List Recall subtest. The key difference between the two subtests lies in the process by which the memory sequences are administered and the response that is required from the child. The Word List Recall subtest is an example of a serial recognition (as opposed to serial recall) task (Gathercole et al., 2001). Based on measures developed in the course of our experimental work, these tasks involve the verbal presentation of a sequence, the repetition of the sequence (either in exactly the same way as before, or with two of the list items transposed), and then a response by the child as to whether the second list was the same or different from the first list. An example from the WMTB-C is as follows:

\[
\text{cut, mob, fell, teach, pad} \quad \text{cut, fell, mob, teach, pad} \quad \text{"different"}
\]

In this example, the second sequence is different from the first because the second and third words in the sequence have been swapped with each other. In Chapter 1 Alan Baddeley discusses research evidence from studies that have used a serial recognition paradigm and suggests that such tasks provide a good measure of the phonological store of the phonological loop that appears to be free of the influence of our stored knowledge of, and facility with, language. He also suggests that performance on such tasks can be carried out without much contribution from the phonological rehearsal mechanism of the phonological loop (unlike performance on serial recall tasks). Support for this view comes from our studies of serial recognition of words and nonsense words (Gathercole et al., 2001), which revealed no significant advantage for serial recognition of word sequences over nonsense word sequences.

So, the Word List Matching subtest appears to be a measure of the capacity of the phonological store of WM without much contribution from language knowledge and ability. One other important feature of the task is the simple response of "same" or "different" that is required from the child. In most cases this response is obtained verbally, but if a child does experience speech output difficulties, the response can be given nonverbally by pointing to the words "same" or "different" printed on a card placed in front of the child, for example. In this way children without any spoken language can complete the task, something that cannot often be achieved with tests of phonological loop function. The Word List Matching subtest therefore provides users with a measure of phonological loop performance that is free from any limitations with spoken language that a child might be experiencing.

Block Recall

The Block Recall subtest of the WMTB-C is based on the test of visuo-spatial memory originally devised by Corsi (e.g., Milner, 1971). This task is admin-
istered using a board on which nine identical cubes (blocks) are fixed in a random arrangement. The board is placed on a table and the administrator of the test and the child sit opposite one another, with the board between them. On one side of each block a number (from 1 to 9) is printed; this is the side of the board that the administrator can see. Using these numbers, the administrator taps out a sequence on the blocks, and the child is required to repeat the sequence, touching the same blocks in the same order as they have been shown.

The Corsi blocks task has been used in experimental and neuropsychological work for some time and has provided users with a simple measure of recall of sequences of a nonverbal nature. In recent years the task has been specifically conceptualized as a measure of a spatial subcomponent of visuo-spatial WM (e.g., Logie, 1995). Findings from both experimental and neuropsychological studies of visuo-spatial WM have provided support for a fractionation of this component of the Baddeley and Hitch model, although the specific characteristics of the two suggested subcomponents are still a matter for some debate (see Pickering, 2001, for a detailed discussion of this issue). For the purposes of our analysis of the theoretical basis of the WMTB-C subtests, two important points are worth noting about the Block Recall subtest. The first is that it appears to be a measure of the capacity of some form of spatial immediate memory, and the second is that, unlike many purported measures of visuo-spatial memory, it does not lend itself well to phonological recoding. Development of good measures of visuo-spatial memory has proved particularly difficult because of the tendency to phonologically recode (i.e., name, label, describe) information to ourselves when it is presented in visual form. Children begin to do this from the age of about 8 years of age (e.g., Hitch, Halliday, Schaafstal, & Schraagen, 1988), making any test that has nameable items potentially more of a phonological memory test than a visuo-spatial one. Evidence from interference task studies suggests that tasks like Block Recall are relatively free from the effects of phonological recoding (e.g., Farmer, Berman, & Fletcher, 1986), as demonstrated when performance on these tasks is combined with something that ties up phonological loop activity, such as articulatory suppression. In this way, therefore, the Block Recall subtest provides users with a relatively "pure" measure of the more spatial aspect of visuo-spatial WM performance.

Visual Patterns Test

As mentioned earlier in the chapter, the Visual Patterns Test was designed by Della Sala and colleagues (1997) for use with adult neuropsychological patients. Both experimental and neuropsychological research with this test has indicated that it appears to measure a different aspect of visuo-spatial WM functioning from the Corsi blocks task. Using Logie's (1995) conceptualization of visuo-spatial WM as being composed of a visual and a spatial
subcomponent, the visual patterns test is suggested to measure the former, rather than the latter (see also Pickering, 2001). The task involves the recall of two-dimensional matrix patterns. Each pattern is formed by the combination of equal numbers of black and white squares in a matrix. After having seen a pattern for 3 seconds, the participant is asked to recall the location of the black squares by marking onto an empty matrix of the same size. Patterns increase in complexity as the number of black and white squares increases. This allows the user to measure visual pattern span—the number of target (black) squares that can be held in immediate memory.

It was noted earlier that the tendency to phonologically recode visually presented stimuli has been a problem in the development of "pure" measures of visuo-spatial WM. One study (Miles, Morgan, Milne, & Morris, 1996) has suggested that older children and adults may use a phonological recoding strategy when carrying out a visual patterns test. However, in our own research we found no evidence to support this view (Pickering et al., 2001). At present, therefore, although it is impossible to say that no participant uses such a strategy when carrying out this task, it appears that it is by no means universal and, perhaps more importantly, does not necessarily confer major benefits on performance. Thus, the Visual Patterns Test seems to provide us with a simple measure of the visual subcomponent of visuo-spatial WM.

Mazes Memory

The Mazes Memory subtest was developed from the Mazes (static and dynamic) task used in our earlier experimental work (Pickering et al., 2001). The test consists of two-dimensional mazes presented using a pencil-and-paper format. A route is shown through the maze in red, and the administrator of the test traces the route with their finger. Following this, the child is asked to draw the exact route that they have seen into an identical, but empty, maze.

The specific administration process for the Mazes Memory subtest combines the two presentation formats from the static and dynamic Mazes tasks from our earlier work. Children are shown information in static (visual) form—as a red line on paper—and in dynamic (spatial) form—as the sequence traced by the moving finger of the administrator. Thus, the two major forms of information thought to be processed by the two subcomponents of visuo-spatial WM are brought together in one subtest (Pickering, 2001). This was done for two reasons. One is that, although it might be possible to dissociate visual (static) and spatial (dynamic) information in carefully controlled psychological experiments, it is likely that these two types of information continually interact in the real world. Logie's model of visuo-spatial WM specifies the existence of a "visual cache" for storing visual information about shape, color, and so on and an "inner scribe" for dealing with
spatial sequential information, which may also be involved in the rehearsal of information in visuo-spatial WM. The Mazes Memory test therefore provides a measure of the whole visuo-spatial WM system.

The second reason why performance on this subtest may be interesting for WMTB-C users is that given the opportunity to use both static visual and dynamic spatial information in WM, some children may show a preference for one type of information over another or may exhibit particular problems with either visual or spatial information. On this basis, therefore, it is interesting to look at the performance of a child across all three of the visuo-spatial subtests of the WMTB-C to see whether evidence for such a dissociation in performance exists. In this way, the WMTB-C allows the user to develop a detailed description of visuo-spatial WM for each child.

**Listening Recall**

Both the Listening Recall and the Counting Recall subtests of the WMTB-C are examples of what has been referred to as “complex span” tasks (see other chapters of this book, particularly Chapters 1 and 2, for discussion of this type of task). Such tasks can be contrasted from “simple” span tasks on the basis that, whereas simple span tasks require a participant to encode and immediately recall information in immediate memory, complex span tasks require that some additional processing is carried out while information is maintained.

The Listening Recall subtest of the WMTB-C used a procedure originally developed for use with adults (Daneman & Carpenter, 1980) and adapted it to be more suitable for children. In the task the child hears a series of short sentences and is asked to decide whether the sentences make sense by responding either “true” or “false.” For example, they might hear:

- Cars have wheels.
- Rabbits have long ears.
- Bicycles eat grass.

To which the child would have responded “true” after the first and second sentence and “false” after the third. The next part of the task requires the recall of each of the final words in the sentences in the order that they were heard. Thus, the child would respond “wheels, ears, grass.”

We can see, therefore, that complex span tasks such Listening Recall measure much more than the simple storage of information and, in doing so, appear to draw heavily on the resources of the CE of WM. After the child has heard the first sentence in each trial, they must hold the final word of that sentence in mind while they listen to, and judge the veracity of, the next sentence, and so on. This subtest is particularly demanding, and even adults find trials with more than three or four sentences challenging.

Can other cognitive processes or strategic activities affect performance on this task? Possibly. It seems highly likely that children old enough to
rehearse memory items in a phonological loop task will apply this strategy to the final words of each sentence in the Listening Recall task. Similarly, the type of semantic and visual processing that was discussed with reference to the Word List Recall task might also be possible here. Preliminary findings from the application of this task to children with and without dyslexia revealed some surprising patterns of performance (Pickering & Gathercole, 2006). Children with dyslexia seemed to score particularly well on this task—a finding that might be explained by the greater tendency of individuals with dyslexia to code information in WM visually and semantically, rather than phonologically (Byrne & Shea, 1979; Rack, 1985).

Overall, therefore, we can see that the Listening Recall subtest of the WMTB-C provides users with a measure of an important aspect of CE functioning, namely the ability to store and process information simultaneously in immediate memory. Performance on this task will almost certainly depend on the ability of the CE and the phonological loop, given the verbal presentation and response requirement of the task. However, children skilled in the use of semantic and visual recoding of phonologically presented information may also benefit from the use of such strategies.

### Counting Recall

The Counting Recall subtest of the WMTB-C differs from the Listening Recall subtest in that children are asked to recall dot tallies while counting other arrays of dots (see Case, Kurland, & Goldberg, 1982). Specifically, the child is presented with a card on which there are either four, five, six, or seven dots. They are instructed to count the dots one at a time by placing their finger on the dot and counting out loud. This process is repeated until all of the dot cards are counted, at which point the child is asked to recall each of the tallies in the order in which they were encountered (e.g., "5, 4, 6, 7, 4"). In a similar way to that for the Listening Recall task, the child is holding and processing information at the same time.

The Counting Recall task is a measure of CE function, but children may also use both phonological loop and visuo-spatial sketchpad resources to carry it out. Given the verbal nature of the counting and recall process, it seems likely that phonological processes play a major role in the performance of this task, however. Thus, as with the Listening Recall task, the Counting Recall subtest of the WMTB-C provides a measure of the storage and processing function of the CE with a heavy emphasis on phonological coding. It also seems likely that a child's facility with counting will play a role in this task. Older and more able children can count faster, although the specific administration procedures for the counting part of this task are designed to preclude the use of subitizing (merely looking at an array and identifying the numbers of dots immediately) and to standardize the speed of counting for younger and older participants as much as possible.
Backward Digit Recall

A task that involves the repetition of digit sequences in reverse order is far from new; backward digit recall tasks have been included in many digit span assessments. What is interesting, however, is the way that performance on both forward and backward recall of digits has often been lumped together to form one measure of digit span (e.g., in the Wechsler intelligence tests). The cognitive processes involved in the recall of digit sequences in reverse order (e.g., 9, 5, 1, 4, 2 becomes 2, 4, 1, 5, 9) seem quite different to those involved in the recall of digits forward. Specifically, when carrying out a backward digit recall task, participants need to hold the sequence that they have just heard in mind while they reverse it ready for output. In other words, they need to carry out some form of processing of the information while storing the information in immediate memory. Here we can see that tasks involving the recall of digits in reverse order have many of the characteristics of the Listening Recall and Counting Recall tasks described earlier. For this reason, we and many others have come to view this task as a measure of CE function, rather than a simple phonological storage task.

There is no doubt that phonological coding will be very likely in the Backward Digit Recall task, given the verbal presentation and response requirement. What is interesting, however, is the range of strategic approaches that participants appear to use in carrying out this task. For example, in our studies, some children have been observed to use verbal rehearsal to maintain the presented sequence in mind while systematically attempting to recall each item in the sequence, beginning with the final item and working back. Other children can be seen to be looking upward to a virtual visual array of digits, so as to be able to read off backward from it. Some children may use a range of approaches to this task. What does seem to be clear, however, is that this task is more complex than the recall of digits in forward order and therefore much more than a simple phonological loop task.

Some Comments on the General Organization of the WMTB-C

Having described the nature of the theoretical basis of the 10 subtests of the WMTB-C, it is also worth giving some consideration to some of the overarching features of the test and the rationale for these. One of the first points to note is that the test provides a comprehensive standardized assessment of WM function and in doing so allows the user to systematically compare a child's performance across the three related, but separable, components of WM. This is done by calculating component scores for the phonological loop, visuo-spatial sketchpad, and CE from the three or four subtests that represent each of those components. By including a range of measures of each component, we are able to increase the robustness of each of these three scores. In addition, within each of the three components it is possible to make a detailed comparison of scores of each of the different
subtests, while taking into account the specific features of those subtests as described earlier (e.g., comparing recall of words and nonsense words, or visual and spatial recall). Standard scores obtained on the test can be plotted as a WMTB-C profile, giving a good visual impression of the performance of a child relative to children of his or her age, and of the strengths and weaknesses demonstrated in the three different areas of WM functioning.

Two other features of the test offer practical advantages. The first is that the child is given six opportunities to demonstrate their memory capacity at each difficulty level, of which only four of the six trials need to be correct. This allows for distractions and lapses of attention to occur during testing without having devastating consequences for the scores obtained by the child. Second, testing can be discontinued when the child fails to recall three trials correctly at a particular difficulty level, and for older and more able children, each subtest can actually begin at a point other than the first trial. These two features of the subtests mean that testing time can be significantly reduced, and moreover, children are not required to continue with a subtest once it is clear that their own level of performance has been exceeded.

**HOW HAS THE WMTB-C BEEN USED?**

Since publication in 2001, more than 300 copies of the WMTB-C have been sold worldwide. The list of those who have purchased the battery includes educational psychologists, special needs teachers, and academic researchers, among others. How do these individuals and organizations use the test? A questionnaire study of the WMTB-C asked this very question, and some of the responses are outlined below.

A number of respondents indicated that they use the WMTB-C as a diagnostic tool for the purpose of building up a pupil profile prior to referral for assessment by an Educational Psychologist. Others have used it with children as a baseline test. Some have used it with children with specific learning difficulties to find out about children's areas of strength and weakness. Some respondents have used the WMTB-C for research or teaching purposes. Many of the users of the WMTB-C told us that they found the profiles of performance across the three components useful in their work. As an academic researcher, I have used the battery extensively since 2001. One of my research interests is the study of developmental disorders such as dyslexia, developmental coordination disorder, attention deficits, autistic spectrum disorders, and other specific educational problems that manifest during childhood. Given the significant debate that surrounds these conditions in terms of their definition, diagnosis, and comorbidity, I was keen to apply a systematic assessment of WM to these populations. As indicated throughout this chapter, one of the advantages of giving a battery of WM tests to children with learning problems is that their scores can be related
back to what we already know about WM structures and functions. Thus, studies of this type may help us to understand more about the nature of both the deficits found in these populations and the areas in which they do not experience impairments. This is a very important point because much of the research on learning problems has focused on what individuals cannot do, but it has said very little about what they can do. These findings have enormous implications for understanding the learning problems themselves and for the design and delivery of learning support activities for individuals who experience them.

Research Findings from the WMTB-C

One possible outcome from the application of a standardized battery of WM tasks to groups with particular learning problems is that a “signature” WM profile would be found for each group. This would allow us to use WM in the assessment of children with learning problems to understand more about the type of problem they were experiencing (e.g., “the profile looks like this. . . . therefore, this child has problems of . . . type”). This is an ambitious idea and very unlikely to be borne out so simplistically in the research findings, not least because within and between various learning problems there is much overlap and much variation. Dyslexia, for example, is a hugely heterogeneous condition. Might it be possible to establish a WM profile for dyslexia in the face of all this individual variation?

The WMTB-C and Dyslexia

Several studies have been carried out in which children identified as having problems of a dyslexic nature have been administered a battery of WM tests (see Pickering, 2004 and Pickering, in press, for a more detailed description of some of this research). The first study involved the prototype version of the WMTB-C (Pickering & Gathercole, 2006). When this battery was administered to children with dyslexia, chronological age (CA) controls, and reading age (RA) controls, it was found that the scores of the dyslexic group were relatively poor on the measures of phonological loop and CE function but largely unimpaired on the tests of visuo-spatial sketchpad function. Subsequent studies using the WMTB-C have provided additional support for this finding (e.g., Pickering & Chubb, in prep), including a study carried out in Greece using a modified version of the WMTB-C suitable for administration to Greek children (Pickering & Zacharof, in prep). Inspection of the WM profiles of individual children with dyslexia indicates quite a wide range of profiles of WM performance, which may relate to a range of factors including the nature of their dyslexia (e.g., whether problems appear to be of a primarily verbal or visual nature) and the nature and extent of any remedial help that the child has already received. Nonetheless, at a group level, children with dyslexia appear to have weaknesses in phonological loop
functioning and possibly even more significant problems with CE functioning (see Chapter 2 of the this volume for a more detailed discussion of this issue). Unless phonological recoding is likely to benefit performance, visuo-spatial sketchpad functioning appears to be unimpaired in this group (although this issue needs to be examined more closely in children with visual dyslexic problems). More research is required to investigate these findings yet further.

The WMTB-C and Developmental Coordination Disorder

Developmental coordination disorder (DCD) is a problem that affects about 6% of children and is defined as a marked impairment in the development of motor coordination that significantly interferes with academic achievement or activities of daily living and is not the result of a general medical condition. Individuals with DCD (the terms DCD and dyspraxia are often used interchangeably, but there is debate about their equivalence) may exhibit marked delays in achieving motor milestones, such as walking, and may appear to be “clumsy” (see, for example, Portwood, 2000). One major problem for many involved in the assessment of developmental problems such as DCD is the extent to which the problems associated with this disorder are also found in individuals with other developmental disorders, such as dyslexia and attention disorders. One study (see Pickering, in press, for further details) allowed us to investigate the WM performance of children with DCD and dyslexia. In this study, one group of children had been identified as having dyslexia but also manifested DCD problems. A second group had been identified as having the converse pattern of problems—that is, a diagnosis of dyslexia with a cooccurrence of motor skills problems. When these children were tested with the WMTB-C it was found that children with primarily movement problems appeared to show one WMTB-C profile (with poor visuo-spatial sketchpad functioning but unimpaired phonological loop and CE functioning), whereas children with primarily dyslexic problems showed a different profile (relatively poor phonological loop and CE performance but unimpaired visuo-spatial sketchpad performance). Again, at the level of the individual child, there was some variation in memory performance, but across groups, children with motor skills and literacy skills problems seemed to experience different strengths and weaknesses in their WM performance. These findings are supported by studies by Jeffries and Everatt (Jeffries & Everatt, 2003, 2004), who found similar WM profiles to those described previously in adults with motor skills problems.

The WMTB-C and Attention Deficits

When the WMTB-C was administered to children with a diagnosis of attention deficit/hyperactivity disorder (ADHD), relatively poor performance was found across a range of subtests including Digit Recall, Word List Matching,
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Block Recall, Listening Recall, Counting Recall, and Backward Digit Recall. As Chapter 6 of this volume indicates, attention deficits appear to be linked to problems with CE functioning. This view was supported in our own research, but children also appeared to score poorly on tests other than those that measured CE function. It is interesting that 4 of the 18 children with ADHD in this study also had a diagnosis of dyslexia—a cooccurrence of learning problems that appears to be common in our schools. Problems of a dyslexic nature may go some way to accounting for the poor scores on tests of phonological loop function that were found in this study. More research clearly is needed to understand how WM functions in children with attention problems. Nonetheless, the WMTB-C may offer detailed information about the cognitive strengths and weaknesses of individual children with attention problems, either with or without other comorbid conditions.

The WMTB-C and Autistic Spectrum Disorders

A small-scale study involved administering the WMTB-C to children with autism spectrum disorders (ASD). The performance of the children on the WMTB-C was highly variable, both across subtests and across individual children. What did seem to be relatively consistent across the group of children studied, however, were poor scores on the CE subtests of the battery. CE—or executive function deficits in ASD have been proposed by a number of researchers, although there is still much debate and discussion about this issue (e.g. Russell, 1997). Again, further research clearly is needed to establish whether WM deficits are a key feature of ASD. The WMTB-C may allow those working with children with ASD to learn more about the cognitive strengths and weaknesses that these children experience and the implications that they might have for their educational progress.

Limitations of the WMTB-C

The WMTB-C was the first theoretically driven WM assessment tool for children. It provides users with a range of features that had not been available to them before. However, the test battery is not without its limitations. Indeed, it has already been pointed out that, whereas the WMTB-C is based on a tripartite model of WM, the Baddeley and Hitch model now contains four components. This issue is something that will be addressed in the coming years, as more knowledge becomes available about the new "episodic buffer" component and tests to measure its function increase in number.

A potentially more important limitation of the WMTB-C centers on the range of subtests used to measure CE function. Although these tests are based on extensive literature on the processes associated with CE functioning, they do not capture all of the different types of processing associated with the CE. More specifically, although each test measures the capacity
to store and process information simultaneously, none of the tests is able to provide specific information about the attention-based functions that have also been attributed to the CE. This may not matter so much if we are merely asking if the CE is impaired because the three CE subtests in the battery almost certainly draw on a range of CE functions, including the focusing, dividing, and switching of attention. However, because evidence is beginning to develop (see Chapters 1, 2, and 6 of this book) that CE functions can be fractionated, and moreover may be differentially affected in different individuals and populations, more precise measures of the different CE functions may be deemed to be useful in the future.

One other feature of the CE tasks included in the WMTB-C is worthy of note—that is, all three of the subtests are very strongly loaded on the phonological loop component of WM. The Listening Recall, Counting Recall, and Backward Digit Recall subtests all involve verbal responses, and the stimuli included in each subtest lend themselves very well to phonological (re)coding. One consequence of this strongly verbal CE assessment is that children who have problems with processing information in phonological form may well find these tasks difficult, not so much because they are CE tasks but because they use phonological information. The obvious solution is to include nonverbal measures of CE function; however, tasks of this sort were not available to us when the WMTB-C was developed. This has now changed, and a small number of nonverbal CE tasks have come into existence. These will be discussed further in the next section.

One final comment regarding the limitations of the WMTB-C concerns the use of the test outside the country in which it was designed and standardized. This issue is not just difficult for the WMTB-C; it has an impact on any standardized test that is used outside of its country of origin. We know from the responses to the questionnaire study that individuals outside of the United Kingdom, including those based in countries whose dominant language is not English, have bought the battery. What implications does this have for the use and interpretation of WMTB-C scores? The fact that WM has been studied internationally means that we already have some idea about how different languages affect performance on tasks designed to measure WM functioning. For example, in the case of digit recall, it has been shown that when digits are presented and recalled in Welsh, scores tend to be lower than for English (Ellis & Hennelly, 1980), but when the language being used is Chinese, digits spans tend to be higher than in English (Hoosain & Salili, 1987). These findings have been linked to the articulatory duration of numbers in the different languages. In Welsh, numbers tend to have longer vowel sounds, whereas the spoken duration of numbers in Chinese is very short. So, the language in which a child’s WM is tested may have significant consequences for the interpretation of their performance. It is interesting that some recent research in our laboratories involving the administration of the WMTB-C to children in Hong Kong found that, although the sequences in the Digit Recall task were administered in English,
some children responded in English, some in Cantonese, and some used a mixture of the two languages. The precise mechanisms by which different languages influence WM performance require further investigation. The findings of future studies may be able to tell us how language affects WM performance and may also help us to understand further the structure and function of WM as a whole.

Differences in language use are not the only factors that might need to be taken into consideration when administering a test like the WMTB-C outside of the United Kingdom. Cultural differences may mean that a child in one country may have differing experiences on which to draw when completing the various subtests. Two particular examples have been drawn to my attention, both of which relate to the experiences of children in China. The first concerns the differences in practices that are common in schools in China and the United Kingdom. In China, there is a strong emphasis on developing rote memory in children of school age, and many activities are devoted to the development of this skill. What implications does this have for children's memory development in China? Does children's WM performance benefit from such training? A second example concerns the subject matter of the Mazes Memory subtest. Anecdotal reports suggest that children in China do not usually have experience with mazes in the way that children in the United Kingdom may have. Does experience with mazes contribute to a child's ability to carry out this task efficiently? Further research is needed to answer this and other related questions. Work is in progress to tackle issues concerning the cultural and language implications for WM. WM test batteries are being developed in countries outside of the United Kingdom (e.g., Greece), and experimental investigations of WM performance in non-English children are under way. As this research develops, we should be in a better position to understand how to assess the WM of children all across the world.

**A COMPUTER-BASED WORKING MEMORY ASSESSMENT TOOL: THE AWMA**

In the previous section it was noted that the three subtests that measure CE function in the WMTB-C were very verbal in nature as a consequence of the lack of nonverbal tests available at the time that the test was developed. Since that time, however, a small number of more nonverbal CE tests have been developed, and these tests have been combined with many of the original subtests of the WMTB-C into a computer-administered version of the WMTB-C, known as *Automated Working Memory Assessment* battery (or AWMA; Alloway et al., 2004).

The AWMA contains 12 subtests. Six tests measure the ability to hold information temporarily (without any processing demands) including Digit Recall, Word List Recall, Nonword List Recall, Dot Matrix task (adapted from
the Visual Patterns Task), Mazes Memory, and Block Recall. It can be seen that, whereas the first three subtests measure phonological loop function, the second three measure visuo-spatial sketchpad function. Six further tests measure the child’s ability to hold and process information at the same time: Listening Recall; Counting Recall; Backward Digit Recall; and three newer tests, the Odd-One-Out task (adapted from Russell, Jarrold, & Henry, 1996), the Mr X. task (adapted from Hamilton, Coates, & Heffernan, 2003), and the Spatial Span task (adapted from Jarvis & Gathercole, 2003). The final three tests just listed are all conceptualized as visuo-spatial (i.e., non-phonological) CE tasks, whereas, as discussed earlier, the first three tasks in this list appear to tap mainly phonological processes (Alloway, Gathercole, & Pickering, in prep). Computerized presentation of WM tasks brings with it some procedural advantages, not least the standardization of presentation of the subtests (although experience suggests that computer presentation may also pose minor problems for some WM subtests, particularly those that involve the requirement to hear a precise pronunciation of a memory item, such as a nonword). However, perhaps the most significant contribution that the AWMA can make to the assessment of WM is the availability of nonverbal CE tasks. Such tasks allow us to develop our understanding of the specific nature of CE functioning in children, both with and without recognized learning problems.

This issue has particular relevance for our understanding of WM functioning in children with dyslexia. As outlined earlier, poor performance on both phonological loop and CE tasks has been found across a number of studies of WM in this group (see Chapter 2 of this volume and Pickering, 2004, for reviews). One problem with the assertion that CE deficits are found in dyslexia hinges on the largely verbal nature of many of the CE tests that have been used in these studies. By including tests of nonphonological CE function we are able to establish whether the pattern of results obtained so far can be explained by a general problem with the maintenance and processing of all information in phonological form or whether the deficits observed also extend to tests of nonphonological CE function. Preliminary findings from our own research suggest that children with dyslexia find verbal CE tasks more difficult than visuo-spatial CE tasks. Our next task is to establish whether performance on the visuo-spatial tasks is at age-appropriate levels. Further research is needed to clarify these initial findings and thus increase our understanding of the nature of WM in this group.

**ASSESSMENT OF WORKING MEMORY AND CONSEQUENCES FOR REMEDIATION**

A question that is often asked when information about WM assessment batteries is presented is as follows: “What do we do once the assessment has been carried out?” This is a very valid question and one that should
command the attention of educators and psychologists interested in WM. So far, however, very little has been written specifically about how to help children with problems in WM, although advances are being made in this area. The remediation of WM is discussed in two chapters of this book—in Chapter 8 in the context of WM in the classroom setting and in Chapter 10 in an account of research that has attempted to develop remedial approaches for WM problems. On this basis, a detailed discussion of WM remediation will not be presented here. Rather, this final section of the chapter will concern itself with the remedial implications that derive specifically from the use of the WM assessment batteries described earlier.

One of the envisaged strengths of the WMTB-C was the ability to sample across the whole of WM in a standardized way. Thus, users of the battery can look at a child's performance in the three WM components (phonological loop, visuo-spatial sketchpad, and CE), both in comparison to children of the same age and across different memory components. This WM profiling appears to have been found to be useful for many of the WMTB-C users that took part in the questionnaire study. Indeed, one of the strengths of a WM profile is that it allows the user to understand where the child's weaknesses lie and where they show a relative strength. Such information can be important when devising teaching and learning approaches for children, both with and without recognized learning problems.

Although we are not yet at the stage where a dedicated WM remediation program that links with the assessment batteries has been developed, we are steadily moving toward this goal (see Chapter 8 for a discussion of current research in this area). In the meantime, there are many useful sources of information that we can draw on to help children with WM problems. Some of these approaches are described in Chapters 8 and 10. In many cases, experienced teachers will have been using approaches such as these in their classrooms for many years. Teaching approaches based on “multi-sensory” techniques have been popular for a long time with those working with children with dyslexia. Similar approaches may work well with children who manifest uneven profiles on the WM batteries. For these children, WM profiles can provide important information about what type of information (phonological or visuo-spatial) is causing the most significant problems. Teaching to the strengths to overcome areas of weakness is a well-established remedial approach for many specialist teachers. This method is just one of a number of remedial approaches that may be used by those wishing to support the educational activities of children with WM problems.

**SUMMARY**

This chapter has examined the assessment of WM in children, beginning with an examination of the methods first used more than 100 years ago to measure immediate memory capacity. It is clear from this review that many
of the basic features of the early assessment of WM are still critical today. However, advances in our theoretical understanding and, in particular, the development of the multi-component model of memory originally proposed by Baddeley and Hitch, have allowed us to create more varied and increasingly specific tools for measuring the range of processes carried out by the WM system.

The Working Memory Test Battery for Children and the Automated Working Memory Assessment battery are two examples of detailed tools for WM assessment. Although the specific features of each test battery vary to some degree, both tests are capable of providing a user with a standardized profile of performance across different aspects of the WM system. Information of this type may assist in the identification and understanding of children with different and sometimes cooccurring developmental disorders, such as dyslexia, DCD, attention problems, and ASD. WM profiles may also help in the design and delivery of remedial help to children.

| Summary Box |

- The assessment of WM (or STM) has been of interest to educators for more than 100 years.
- Memory span for sequences of digits has remained a popular method of immediate memory assessment during this time.
- The Baddeley and Hitch (1974) WM model specified a three-component system of immediate memory functioning comprising a phonological loop, visuo-spatial sketchpad, and CE.
- The digit span task measures only the functioning of the phonological loop.
- In recent years, tests that measure the CE and visuo-spatial sketchpad have been developed; phonological loop tests other than digit span also have been developed.
- Experimental research has contributed to a much greater understanding of the factors that influence performance on a test of WM.
- A theoretically driven battery of WM tests for children, the WMTB-C, has been developed.
- When the test was administered to children with different developmental disorders, different profiles of WM performance were found.
- A computer-administered WM test battery (AWMA) combines subtests from the WMTB-C with new nonverbal measures of CE function.
- Remedial efforts with children with WM deficits may be usefully guided by the profiles obtained from tests such as the WMTB-C and AWMA.
References


9. Assessment of Working Memory in Children


Much of our childhood is spent developing complex cognitive skills that as adults we may take for granted, including language, reading, mathematics, and reasoning. These are the very skills that allow us to reap the greatest benefits from education and from life in general. Psychologists have long been interested in trying to identify general cognitive mechanisms that may underlie such complex cognitive activities. One promising candidate is working memory (WM), most generally defined as the ability to actively maintain task-relevant information during the performance of a cognitive task (Baddeley & Hitch, 1976; Shah & Miyake, 1999).

WM has evolved from the earlier concept of short-term memory. Short-term memory provides temporary on-line storage of information that decays rapidly unless rehearsed. A standard measurement of short-term memory capacity is the digit span task, in which an individual is read a string of digits and is asked to repeat them back. The longest series of digits that can be accurately repeated is that individual's digit span. However, in the real world, short-term storage of information is frequently not so static. For example, when performing mental arithmetic one must not only store the numbers, but also transform them into a new number while still
remembering the old numbers. WM measures are designed to assess an individual's ability to simultaneously store and process information. An example of a WM measure is the reading span task, in which an individual reads and judges the veracity of a series of sentences while at the same time remembering the last word from each sentence. The number of sentences for which an individual can both correctly judge the sentences and remember all of the words is that person's reading span score. Individual differences in WM measures such as reading span have been shown to predict performance on a wide variety of tasks including vocabulary acquisition (Gathercole & Baddeley, 1993), language comprehension (Daneman & Merikle, 1996), mathematics, (Bull, Johnston, & Roy, 1999), and reasoning (Kyllonen & Christal, 1990). Based on its predictive power, WM has been proposed to play an essential role in many school-based cognitive activities (Gathercole & Baddeley, 1993; Gathercole, Pickering, Knight, & Stegmann, 2004).

In the course of normal development, children show large increases in their WM capacity (Gathercole, 1999; Pickering, 2001). However, there are many children in whom the expected progression of some portion of WM appears to be either delayed or disrupted. WM deficits have been reported in a diverse array of populations ranging from children with developmental disorders with known etiologies such as Down syndrome (Hulme & Mackenzie, 1992), to those with specific learning disabilities (Swanson & Sachse-Lee, 2001a), to children who have survived chemotherapy treatments (Schatz, Kramer, Albin, & Matthay, 2000). Although these groups differ widely in the exact nature and the degree of cognitive impairment experienced, poor WM function has often been identified as playing an important role in these children's overall performance and as a target process in which to attempt remediation. Given the power of WM measures in predicting various indices of future educational achievement (Gathercole, Brown, & Pickering, 2003; Gathercole et al., 2004), even small increases in the efficacy of WM skills may significantly improve these children's performance in the classroom and in their daily lives.

In this chapter, we provide a broad overview of the different approaches taken in rehabilitating cognitive functioning that either target WM function directly or have been shown to improve WM function. We then examine the types of WM deficits identified in different populations of children who are learning impaired and the extent to which different forms of remediation have been attempted in each. Finally, we conclude with a summary of the general principles for remediation that can be drawn from the current evidence and suggest future directions for research.

THEORETICAL APPROACHES TO WORKING MEMORY REMEDIATION

The standard model of WM proposed by Baddeley and Hitch (1976) is a three-part system consisting of a central executive (CE) and two peripheral
systems: the phonological loop and the visuo-spatial sketchpad. The phonological loop and visuo-spatial sketchpad are temporary storage systems responsible for maintaining verbal and visuo-spatial information, respectively. Each can be divided into two basic subcomponents: a limited capacity store, which holds only a few items and decays rapidly without being refreshed by the second subcomponent, a rehearsal process (Baddeley, 1986). The CE has been broadly defined as the supervisory system that oversees and regulates the cognitive processes involved in WM performance (Baddeley, 1986). So-called “executive” processes thought to reflect the functioning of the CE include various forms of attentional control such as focusing attention, switching attention, and dividing attention as well as the ability to inhibit unwanted thoughts or actions and the ability to stay focused on a particular goal (Baddeley, 2002; Duncan, 1995; Miyake et al., 2000).

Therefore, within the Baddeley model, deficits in WM function have multiple possible origins, including differences in the size of the phonological or visuo-spatial stores, the efficiency of the rehearsal processes, or the integrity of higher-level processes of the CE. As a result, a continuum of WM measures exists, with very simple storage tasks at one end and complex problem-solving tasks at the other. Tasks along this continuum differ in the amount and type of CE processes required. An example of a task low in executive demand would be a simple span task in which an individual must remember a series of letters, movements, or sounds and repeat them back. An example of a task that requires one aspect of CE functioning, the inhibition of prepotent responses, is the Stroop task. The Stroop task requires participants to view color words written in different colors of ink and inhibit the well-practiced response of reading the words, instead of naming the color of the ink (Stroop, 1935). Finally, an example of a task that involves multiple executive processes would be a problem-solving task such as the Tower of London/Hanoi, which consists of a puzzle in which a person must move a series of disks across a series of pegs. Such problem-solving tasks require storage of information in memory along with focusing attention, inhibitory processing, and maintaining and updating goals and subgoals.

Although most WM theorists usually agree on the existence of peripheral systems that process relatively domain-specific information (e.g., visual as opposed to verbal information), as well as centralized control mechanisms that may be more domain general, there are differences amongst theoretical approaches as to the source of individual variations in WM performance. For example, a number of researchers have proposed that capacity differences in the amount of “WM resources” or “controlled attention capacity” possessed by individuals predict individual differences in performance on a variety of WM measures, independent of the specific processing domain (Just & Carpenter, 1992; Kane & Engle, 2002; Daily, Lovett, & Reder, 2001). Although these theories of WM acknowledge that acquired knowledge and experience may have an impact on performance of individual tasks, they suggest a large proportion of the individual variability on many novel, intelligence-demanding tasks relevant for schooling may be accounted for by
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this general factor (Engle, Tuholski, Laughlin, & Conway, 1999). Therefore any intervention that could increase this capacity should have general effects on WM and tasks thought to require it.

However, other theories such as long-term WM (Ericsson and Kintsch, 1995) and connectionist approaches (MacDonald and Christiansen, 2002; O'Reilly, Braver, & Cohen, 1999) emphasize the role of domain-specific knowledge and the importance of strategies in the performance of complex cognitive tasks that rely on WM. Individual differences in performance on WM tasks may not solely result from differences in capacity limitations; they also may result from differences in long-term memory and processing strategies gained through experience. These theories assume performance on tasks that demand WM can be improved but that this improvement is highly strategic and specific to the task practiced. For example, through training, one individual expanded his digit span to 79 continuous items by devising strategies to quickly remember numbers. This well exceeds the capacity limits of the phonological store (Ericsson, Chase, & Faloon, 1980). However, this extra capacity was not seen when the same individual was asked to remember a series of letters, in which he did no better than an average span. A more common example is experienced restaurant servers who may excel at remembering customer orders without writing them down but then may perform no better than anyone else on another WM demanding task, even if it is another verbal one (Ericsson & Polson, 1988).

There then exist multiple possible reasons why WM may be impaired and multiple routes by which intervention may be attempted. Damage may be localized to one of the peripheral systems, or it may have a more general effect through a failure of the CE. Within a system, possible underlying problems include reduced processing capacity, poor knowledge representations in long-term memory, failures to use efficient and appropriate strategies, or any combination with one deficit possibly causing or exacerbating another. For example, children with poor attentional capacity may have more difficulty self-initiating a rehearsal strategy that would improve their performance. Although training these children to use rehearsal strategies may improve WM performance, it may not be as effective as treating the underlying cause of the deficit. Therefore the success of a remediation attempt may depend on correctly targeting the locus or loci of impairment in a particular population of children.

Remediation of Peripheral Impairments

Specific impairments of peripheral systems have been hypothesized in a number of different developmental learning disorders ranging from severe intellectual disabilities to very specific learning difficulties without any other obvious intellectual impairment, such as dyslexia. The selective nature of many of these conditions has been used as evidence in support of the separability of the different peripheral systems such as the phonological loop
and the visuo-spatial sketchpad (Wang & Bellugi, 1994). In light of these patterns of impairment, a number of remedial approaches for children with developmental disorders have focused on the improvement of storage and processing in one or other of the peripheral WM components.

Of the two peripheral systems, the phonological loop has received the greatest amount of research both as a locus of deficit and as a target for remediation. Phonological WM is hypothesized to consist of two components: a phonological store, which holds only a few items and decays rapidly without being refreshed by the second component, a subvocal rehearsal process (Baddeley, 1986). This rehearsal process is also responsible for translating visual or written materials into phonologically based representations through a process known as phonological recoding (Gathercole & Baddeley, 1993; Palmer, 2000b). The visuo-spatial sketchpad has received comparatively less attention in terms of being specifically damaged and even fewer attempts at remediation. However, it is thought to be similar to the phonological loop in that there is also a store and rehearsal processes (Logie, 1995).

### Strengthening Storage Representations

One proposed source of deficits specific to either the phonological or visuo-spatial storage systems is poor long-term memory representations or the inability to retrieve long-term representations. In the context of phonological representations, where this issue has been most extensively studied, listeners must code acoustic information into phonological codes that rely on the quality of information in long-term memory. Thus, crisp, highly distinguishable memory representations lead to greater WM capacity (Cowan, 1996). Conversely, poor and indistinct memory representations result in reduced WM capacity.

Auditory temporal processing deficits are frequently proposed as an underlying source of poor phonological representations (Tallal, 2003; Veale, 1999). Auditory temporal processing skills involve the ability to process rapidly presented stimuli. To develop distinct neural representations of phonemes in any language, the listener must first be able to distinguish between auditory input that is rapidly changing, often in less than 40 milliseconds (Tallal, 2003). Children who process speech sounds too slowly to identify and distinctly represent different phonemes (such as children with specific language impairment and dyslexia) also have impairments in phonological WM and other language skills (Montgomery, 2003). Thus, one approach to remediation has been to train children to process acoustic changes in speech more rapidly (Merzenich et al., 1996; Tallal et al., 1996; Veale, 1999). Although there has been little investigation as to whether improving the speed of auditory processing in children leads to improved performance on WM tasks per se (but see Deutsch, Miller, Merzenich, & Tallal, 1999), we include it nonetheless as a possible method for remediation.
tion in children with poor phonological WM, in light of the theoretical links between temporal processing, phonological representations, and WM (Downie, Jakobson, Frisk, & Ushycky, 2002). The fact that temporal training has also been shown to affect language processing and reading comprehension tasks that are problematic for children with poor WM is also promising (Tallal, 2003; Veale, 1999).

Phonological awareness is the conscious knowledge of the phonological structure of language and describes an individual's ability to recognize and manipulate the various components of words such as syllables and phonemes. Thus, phonological awareness has been identified as a construct highly related to phonological WM, with a number of studies demonstrating a correlation between phonological awareness and phonological WM (Gillam & van Kleeck, 1996; Leather & Henry, 1994; Oakhill & Kyle, 2000). One explanation is that phonological awareness tasks usually require active maintenance of information in WM to compare and process phonological information. Gillam & van Kleeck (1996) argue that because phonological awareness tasks are demanding of phonological WM, training on phonological awareness may lead to improvements in WM. Another possibility is that better phonological awareness is a result of high-quality phonological representations in long-term memory that allow for easier storage and processing in WM. Phonological awareness training generally consists of repeated practice on a series of phonological awareness tasks such as judging the initial sound in a word, categorizing a particular sound, blending two phonemes together, and deleting a phoneme from a word. Such training has been shown to improve performance on a large number of related phonological awareness tasks (Downie et al., 2002; Torgesen & Davis, 1996) and on reading ability (Maridaki-Kassotaki, 2002; Wright & Jacobs, 2003).

Rehearsal

Deficits in WM may also arise from failures to use appropriate rehearsal strategies. Before the age of 7 years, children do not appear to use rehearsal consistently, and it is the development of rehearsal and other strategies that is thought to be at least partly responsible for increased WM span (Gathercole, 1999). Evidence that some children fail to develop rehearsal, or have poor organizational strategies, has led some to attempt to remediate WM by explicitly teaching children to rehearse or to use other strategies such as chunking words or digits into larger units, which are easier to remember. The training of even simple rote rehearsal strategies has been shown to improve WM performance in adults with low memory spans (McNamara & Scott, 2001; Turley-Ames & Whitfield, 2003). However, there is also evidence that, for these individuals, the teaching of more complex strategies may be less effective given the greater difficulty in mastering them (Turley-Ames & Whitfield, 2003). It may be that differences in strat-
egy use may be more centrally based, with some individuals simply being more strategic overall, regardless of the processing domain (McNamara & Scott, 2001). However, rehearsal training has frequently been undertaken in the service of improving WM in the context of specific impairments in a peripheral system.

**Centrally Based Processing and Remediation Approaches**

A second approach to the remediation of WM difficulties in children has focused on possible impairments in the functioning of the CE. Three basic approaches have been proposed to remediate CE deficits in WM: the direct training of planning and metacognitive strategies, process specific training, and the use of pharmacologic agents intended to increase attentional capacity.

One method proposed to improve cognitive performance in children believed to have more global attentional or CE problems has been to teach them various planning strategies and better metacognitive awareness of their own performance (Marlowe, 2000; Ylvisaker & DeBonis, 2000). Although these interventions are not thought to have a direct effect on WM capacity (Mateer, Kerns, & Eso, 1996), they may allow children who are impaired to better manage the diminished attentional resources they do possess. In addition, such training has the potential to improve the efficacy of other remediation attempts when used in tandem. Training may include helping students to be more aware of which situations require executive processes and the teaching of strategies such as the verbal mediation of performance, in which children are taught a sequence of orienting questions that allow them to identify the current goal and to benefit more from feedback (Sohlberg, Mateer, & Stuss, 1993). Although there is little evidence on how effective these approaches are for direct measures of WM performance such as the reading span, there is some work showing improvement on various educational measures such as reading comprehension and arithmetic performance, which are thought to rely on WM (Singer & Bashir, 1999).

A second approach to remediation is process-specific training, in which the repeated practice of a particular cognitive process is hypothesized to lead to an improvement and reorganization of that process. This approach was originally developed for the rehabilitation of cognitive deficits in adults with brain injury and was thought to be especially useful for the rehabilitation of attentional abilities (Sohlberg & Mateer, 1987). Attention process training (APT) is a process-specific approach in which individuals receive repeated practice on tasks in five areas of attention: focusing, selecting, sustaining, switching, and dividing attention (Sohlberg & Mateer, 1987). A number of studies have reported improvements in attention or executive function in adults who have been brain injured (Park, Proulx, & Towers, 1999; Sohlberg & Mateer, 1987; Sohlberg et al., 2000) and in adults with
schizophrenia (Lopez-Luengo & Vazquez, 2003). However, many of these studies have been criticized for the small sample size and limited generality of the improvements reported (Park & Ingles, 2001). Although APT was originally developed for adults, there is a growing interest in adapting this procedure for use in children.

A third approach to the remediation of the CE has been to try to improve the underlying efficiency of the neural systems involved by targeting the neurotransmitter systems on which they are thought to depend. Drugs that act on the catecholamine system have been shown to affect WM performance both in animals (Solanto, 2002) and humans (Mehta et al., 2000). Several studies have demonstrated improvements in the visuo-spatial WM performance of adults with the administration of methylphenidate (Ritalin) and other agents that increase dopaminergic and cholinergic function (Elliott et al., 1997; Furey, Peiterini, & Haxby, 2000; Kempton et al., 1999; Mehta et al., 2000). Therefore, for children in whom WM difficulty may have a clear neurochemical basis, pharmacological approaches to remediation may hold a great deal of promise.

REMEDICATION APPROACHES IN DIFFERENT WORKING MEMORY IMPAIRED POPULATIONS

In the next section of the chapter we shall examine the types of remediation approaches taken in different populations of children with WM impairment. WM impairments are reported in a number of different developmental disorders and conditions. However, the exact nature of the deficit in a particular disorder is frequently a source of great debate. Naturally, understanding the source of a deficit would seem to lead to better interventions. However, it may be that the type of interventions that are successful will also be informative about the type of deficit present in a given population of children.

Children Who Are Intellectually Disabled

In the United States, individuals are classified as having intellectual disability (ID) if their IQ (intelligence quotient) is measured as being below 70. This includes individuals for whom the source of their disability is known, such as those individuals with Down syndrome, and those for whom there is no clear etiology. A number of studies have found that children with ID appear to be disproportionately impaired in measures of verbal WM, whereas their performance on visuo-spatial WM measures is relatively spared (Jarrold, Baddeley, & Hewes, 1999; Rosenquist, Conners, & Roskos-Ewoldsen, 2003; Wang & Bellugi, 1994). One hypothesis for this pattern of impaired and spared abilities is that children with ID fail to develop verbal rehearsal. A frequently cited piece of evidence indicating a lack of rehearsal in these children is a reduced or absent word-length effect compared to age-
matched, or vocabulary-matched, controls (Hulme & Mackenzie, 1992). The word-length effect is the finding that immediate recall is usually better for words that take less time to pronounce than longer words, even when the number of syllables is held constant (e.g., “bishop” is recalled better than “harpoon”) (Baddeley, Thomson, & Buchanan, 1975). A failure to find the word-length effect has been reported both in children with Down syndrome (Hulme & Mackenzie, 1992; Jarrold, Baddeley, & Hewes, 2000) and with individuals whose ID is of unknown origin (Rosenquist et al., 2003). Given the evidence for a specific deficit in rehearsal, a number of studies have examined the possibility of improving verbal WM performance in these children by training them explicitly in the use of rehearsal (Broadley, MacDonald, & Buckley, 1994; Comblain, 1994; Hulme & Mackenzie, 1992; Laws, MacDonald, & Buckley, 1996) and other organizational strategies, such as chunking (Broadley et al., 1994). Such remediation programs have been shown to significantly improve WM performance (Conners, Rosenquist, & Taylor, 2001), although the gains have been criticized for being fairly small in magnitude, with only a half to one memory item improvement (Jarrold et al., 2000). There is also some question as to how long these improvements are maintained once the training is completed, with some studies reporting sustained benefits weeks and months later (Bowler, 1991; Broadley et al., 1994), whereas others found these benefits to diminish with time (Comblain, 1994, Laws et al., 1996).

Although rehearsal training does appear to be helpful, at least in the short term, there is growing evidence that a lack of rehearsal alone does not explain the WM deficits reported. Jarrold, Baddeley, & Hewes (2000) found that children with Down syndrome had poorer verbal WM scores even when compared with matched children with learning disabilities. In this study, neither group was observed to be using a rehearsal strategy, but the children with Down syndrome still showed significantly greater impairment. Similar findings were reported by Vicari, Marotta, & Carlesimo (2004) using a control group matched for mental age. They concluded that lack of rehearsal was not a sufficient explanation for the differences between the two groups (neither of which used rehearsal) and that other possibilities, such as reduced capacity in the phonological store or a more general impairment of the CE, must be examined. Indeed, a study of the structure of WM in individuals with ID identified a general WM factor composed of performance on CE measures and dissociable from a separate phonological factor (Numminen et al., 2000). This general factor was related to performance on an intelligence test and various academic measures such as reading, writing, and mathematic performance. The phonological factor, however, was related to reading, writing, and sentence comprehension, but not with intelligence or measures of everyday cognitive performance. The authors interpreted these results as indicative of a separate CE deficit in ID that appears to be relatively independent of impairments in the phonological loop (Numminen et al., 2000). Unfortunately, to date there have been no attempts to apply
more general capacity-based remediation methods to the proposed CE deficits in ID.

**Specific Language Impairment**

Specific language impairment (SLI) is a term used to describe children who exhibit a delayed development of language, both in comprehension and production, without other obvious intellectual impairments (Bishop, 2004). Related to their specific language impairments, these children have also been found to be impaired on various WM tasks, especially those thought to measure the effectiveness of the phonological loop (Dollaghan & Campbell, 1998; Gathercole & Baddeley, 1990; Montgomery, 1995).

It has been hypothesized that the phonological loop plays an important role in language acquisition because it allows auditory input to be transformed into a phonological representation and then held temporarily for analysis and transferred to long-term memory (Gathercole, Baddeley, & Papagno, 1998). Phonological WM capacity in children has been shown to predict their ability both to acquire (Gathercole, Hitch, Service, & Martin, 1997; Gathercole, Service, Hitch, Adams, & Martin, 1999) and produce language (Adams & Gathercole, 1995). Thus, one specific hypothesis about the role of WM in the language deficits seen in children with SLI is that they have some impairment in the functioning of the phonological loop. Explanations of the role of phonological problems in children with SLI have focused on the capacity of the short-term phonological store rather than the rehearsal process because deficits in the use of rehearsal do not appear to be present in children with SLI (Gathercole & Baddeley, 1990; Montgomery, 1995). This view of SLI leads to a number of possible interventions, which include giving children practice with encoding and maintaining phonological representations and encouraging the use of strategies that use long-term memory, or other components of WM, to compensate for the reduced storage (Gathercole, 1993; Montgomery, 2003). For example, Gill and colleagues (Gill, Klecan-Aker, Roberts, & Fredenburg, 2003) found significant and lasting improvements in the ability to follow instructions in children who were taught a rehearsal strategy that involved visualizing the different instructions.

It has also been suggested that the phonological store may be impaired in SLI because the phonological representations to be stored in memory suffer from a lack of distinctiveness and are therefore difficult to distinguish from one another (Elbro, 1996). One reason that these representations may be incomplete is the presence of a deficit in phonological awareness, the conscious knowledge of phonological structure (Gillam & van Kleeck, 1996). Therefore, training of phonological awareness is another form of remediation frequently used in children with SLI. However, although such training has been shown to lead to improvements on tests of phonological awareness, only one study has found any evidence of transferable improvement
to a measure of phonological WM. In this study, Gillam & van Kleeck (1996) reported improvements after a course of phonological awareness training in children's performance on nonword repetition tasks that are frequently used to measure the performance of the phonological loop. They hypothesized that the training was beneficial for two reasons. First, the intervention improved the children's ability to translate a phonological representation into WM, and second, the phonemic awareness tasks themselves were WM demanding and thus the phonological intervention provided direct practice on WM.

A related hypothesis concerning the quality of phonological representations is that poor representations in children with SLI may result from a deficit in processing and producing brief sequential events in sensory domains such as vision and audition (Tallal, 1998). According to this model of SLI, slow auditory processing speed may lead to the inability to encode phonemic information rapidly and accurately. Tallal and colleagues (Tallal et al., 1996) have developed a computer-based intervention called "Fast ForWord" for children hypothesized to have slowed auditory processing; it consists of a number of video games, primarily designed to improve processing speed and accuracy. In a typical task, children are presented with artificially slowed speech, allowing them to detect relevant information and distinguish between phonemes in the context of a computer game. As children get better at performing the task, the duration of the presentation of the sounds is reduced. "Fast ForWord" has been highly successful in improving the performance of children with SLI on a wide variety of language comprehension and reading measures (Tallal, 2003). Furthermore, in the one preliminary study that we are aware of, children's performance in WM was improved after participation in the training program (Deutsch et al., 1999).

It should be noted that it is not clear which aspects of the "Fast ForWord" program lead to children's improvements and, specifically, whether increasing auditory processing speed benefited children on WM tasks. In addition to tasks designed specifically to support temporal processing of auditory information, "Fast ForWord" also includes language comprehension tasks that involve listening to phrases of increasing syntactic complexity and short-term storage tasks that involve remembering phonemes for brief periods of time. Thus, any improvements in WM seen after training using "Fast ForWord" may directly result from practice on the comprehension and storage tasks, rather than improved auditory processing.

A final view of SLI is that WM deficits may be the result of more centrally based processing limitations (Ellis Weismer, 1996; Montgomery, 2002), as evidenced by studies demonstrating disproportionate impairment on tasks with high executive processing demands (Ellis Weismer, 1996; Montgomery, 2003). If the WM deficits in children with SLI are the result of a more general executive deficit, then remediation approaches that have been effective in improving the function of the CE may also be helpful for
SLI. However, to date there have been no attempts at remediating central attentional processing capacity in these children.

**Reading Disability**

Reading disabilities have long been associated with WM impairments (Cain, Oakhill, & Bryant, 2004; Chiappe, Siegal, & Hasher, 2002; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003; Swanson & Howell, 2001, and Chapters 2 and 3 of this book). This is true both in individuals identified as dyslexic (in whom poor reading performance is not accompanied by any other intellectual difficulties) and in “garden variety” poor readers (in whom intellectual performance is poor overall). Although there have been many attempts at improving the reading performance of these children, only a few studies have examined the possible role of WM in the remediation of reading disability by including WM tasks as either part of the training or as an outcome measure. Those that have fall into two basic categories: remediation targeting the properties of the phonological loop and the remediation of deficits in more general attentional processing.

Children with reading disorders are most commonly hypothesized to have problems specifically in the phonological loop component of WM because they evidence impaired performance on tasks such as digit or letter span (Cain et al., 2004; Smith-Spark et al., 2003; Swanson & Howell, 2001). Therefore attempts at remediation in these children have frequently focused on improving the function of the phonological loop in ways similar to the intervention programs seen in children with specific language disorders, such as improving auditory temporal processing, phonological awareness, and repeated practice on phonological WM tasks.

Deficits in both auditory temporal processing and phonological awareness have been reported in children with reading impairments (Cacace & McFarland, 2000; Carroll & Snowling, 2004; Cormier & Dea, 1997; Goswami & Bryant; 1990); training in auditory temporal processing as typified by the “Fast ForWord” program and training targeting phonological awareness alone have both been shown to be effective in improving reading performance in children with dyslexia (Lovett et al., 1994; O'Shaughnessy & Swanson, 2000, Temple et al., 2003). In addition, there is evidence that patterns and activity levels of brain areas hypothesized to play a role in WM processing are affected by such training manipulations, with improved frontal and temporoparietal activity seen in children with dyslexia after auditory temporal process training (Temple et al., 2003) and changed activity seen in the left occipitotemporal areas of children with dyslexia after training on phonological awareness (Shaywitz et al., 2004). However, the little research that has directly examined the effect of phonological awareness training on WM performance is equivocal. O'Shaughnessy & Swanson (2000) reported significant improvements in the verbal WM of children with
reading disabilities after lengthy training on phonological awareness using two measures of verbal WM (recall of similar sounding words and reading span). However, a second study reported no improvement on a verbal WM task as measured by reading span after a similar course of phonological awareness training (Gonzalez, Espinel, & Rosquete, 2002).

Only one study has investigated the extent to which training directly on a phonological WM task will lead to improvements in reading performance. Maridaki-Kassotaki (2002) gave schoolchildren a course of training on phonological WM using repeated practice on nonword repetition. Training was administered 15 minutes a day, 4 days a week, for the duration of a school year (7 months). Both a training and control group were tested pre- and post-training on nonword repetition and on a measure of reading comprehension. There were no group differences before the training intervention. However, post-training, the training group showed significantly better performance on both nonword repetition and reading comprehension. Although these results are preliminary, they do suggest that children who are reading impaired may benefit from interventions that provide direct practice on verbal WM tasks. However, the extent to which this is true for tasks other than nonword repetition is unclear.

Other researchers have focused on the possibility of deficits in the CE component of WM and have hypothesized that at least in some children who are reading disabled, more general attentional capacity limitations underlie deficits in reading performance (Palmer, 2000a; Swanson, 1999). For example, dyslexic readers have been shown to be impaired on a number of executive tasks including the Wisconsin Card Sorting Task (WCST), a measure of inhibitory processing and switching (Palmer, 2000a); reading span (Cain et al., 2004; Chiappe et al., 2002; Swanson & Sachse-Lee, 2001b; Swanson & Howell, 2001); and letter updating (Smith-Spark et al., 2003). Therefore remediation approaches targeting CE processing constitute another means by which performance may be improved in children who are reading disabled.

Deficits in the ability to inhibit have been hypothesized as one source of executive impairment in reading disability (Chiappe et al., 2002; Palmer, 2000a), with some researchers proposing that reading problems in dyslexia may be the result of impaired spatial attention processing ultimately derived from an inhibitory deficit (Facoetti, Lorusso, Paganoni, Umilta, & Mascetti, 2003). For example, Facoetti et al. (2003) found that children with dyslexia failed to demonstrate normal inhibitory processing in a covert visual attention task. They then used an intervention called “visual hemisphere specific function” (VHSS; developed by Bakker, 1992), in which they stimulated either the right or left hemisphere (depending on the type of dyslexia) with words presented in the left or right visual field for 32 training sessions across 4 months. Participants in the intervention performed better on spatial attention tasks at post-test compared to a control group, who received a
traditional intervention for dyslexia, such as phonological awareness training or individual reading tutoring. Furthermore, they were also better on measures of reading accuracy and reading speed.

A final possibility is that WM difficulties in at least some children with reading disorders may result in part from a lack of vocabulary knowledge. In general, children with reading disorders tend to have less knowledge about print, story structure, and vocabulary (Cain et al., 2004; Hecht, Burgess, Torgesen, Wagner, & Rachotte, 2000). In addition, McDougall & Donohoe (2002) found that children with reading difficulties performed equally as well as children without reading difficulties on span tasks that used high-frequency words, but they performed worse than children without reading difficulties on span tasks that used low-frequency words. This result is in line with results from studies of long-term WM that show a relationship between how much information can be actively maintained and the organization and quantity of long-term knowledge (Ericsson & Kintsch, 1995). Results such as these suggest another possible approach to remediation may be to expand these children's knowledge bases.

Attention Deficit/Hyperactivity Disorder

Attention deficit/hyperactivity disorder (ADHD) is a developmental disorder characterized by inattention, overactivity, and impulsive behavior (see also Chapter 6 of this volume). It is believed to be fairly common, with estimates as high as 3–5% of all children affected (American Psychiatric Association, 1994). Whereas a number of WM and executive function deficits have been reported in children with ADHD, the primary impairment has widely been hypothesized to be a failure of inhibitory processing (Barkley, 1997; Schachar, Tannock, & Logan, 1993), which is then believed to lead to poor performance on WM and executive function tasks. Deficits have been reported for both verbal and visuo-spatial measures of WM (Karatekin & Asarnow, 1998; Mariani & Barkley, 1997; McInnes, Humphries, Hogg-Johnson, & Tannock, 2003, but see Pennington & Ozonoff, 1996; Shue & Douglas, 1992) and a wide array of executive tasks including WCST (Pineda et al., 1998; Reeve & Schandler, 2001; Seidman et al., 1997), verbal fluency (generating as many items that meet some criterion, such as starting with the letter R or belonging to the category flower, in a short time frame; Pineda et al., 1998), the Stroop Task (Reeve & Schandler, 2001; Seidman et al., 1997), switching between tasks (Cepeda, Cepeda, & Kramer, 2000), and Tower of London (Cornoldi, Barbieri, Gaiani, & Zocchi, 1999).

Naturally, clinical interventions often focus on the remediation of the behavioral problems seen in children with ADHD. However, there is evidence that the WM problems seen in these children may also be responsive to treatment. Three major approaches have been proposed in the remediation of WM and executive function impairments in ADHD. These
are process-specific training, instruction in metacognitive strategies, and medication.

In process-specific training, a damaged cognitive process is rehabilitated by repeated practice on tasks that exercise the damaged processes. One example is the APT described earlier, which was developed originally to help rehabilitate adults with brain injuries with attentional and executive function deficits (Sohlberg & Mateer, 1987). However, several preliminary studies have begun to examine the potential of modified forms of APT in children with ADHD. In Kerns, Eso, & Thomson (1999), children with ADHD aged 5–10 years were given training on both visual and auditory versions of sustained, selective, alternating, and divided attention tasks for two 30-minute sessions a week for 8 weeks. Each task used materials that had been modified from earlier APT work so that they would be more interesting and appropriate for children. The performance of the trained children was compared to a control group pre- and post-training on 6 tasks thought to reflect attentional and executive abilities. Although not all the measures used showed evidence of transfer, the authors did report training-related improvements on a measure of sustained auditory attention, a measure of sustained visual attention, and a variant of the Stroop task commonly thought to require inhibition and selective attention. However, they did acknowledge that the small sample size (7 children) and the lack of follow-up testing limited the conclusions that could be drawn.

A second study investigating the effectiveness of APT in ADHD used a combination of metacognitive and process-specific methods. Semrud-Clikeman et al. (1999) trained a group of children with ADHD on two tasks taken from the APT program (Sohlberg & Mateer, 1987)—a visual attention task in which children had to find a target in an array of distracters and an auditory task in which they counted targets presented in an auditory stream of stimuli such as certain letters of words beginning with a specific sound. They were also given specific guidance and practice on the use of effective strategies and goal setting in the performance of the training tasks. The training intervention consisted of two 1-hour training sessions a week, for a total of 18 weeks. At the end of the training period, the children who had been trained showed significantly more improvement on both an unpracticed selective visual attention measure and an unpracticed auditory divided attention measure, in comparison to a control group of children with ADHD who had not received the training. Although this study found clear improvements, the extent to which the training benefits would generalize was uncertain and the contribution of each form of remediation (process specific and learning of strategies) to the gains seen was unclear. Additionally some of the children were taking medication at the time of training, and others were not. Unfortunately, as noted by the authors, there were not enough children taking traditional stimulant medications to be able to compare the efficacy of this form of training in children both undergoing and not undergoing pharmacological therapy (Semrud-Clikeman et al., 1999).
A third study by Klingberg, Forssberg, & Westerberg (2002) combined basic principles from both process-specific training and sensory discrimination training in training WM in children with ADHD. In this program, children were given repeated practice on a computerized version of a visuo-spatial WM task, Backward Digit Span, Letter Span, and a go/no-go reaction time task (in which participants must inhibit a frequent response given a “no-go” signal). The difficulty for each individual subject was adaptable on a trial-by-trial basis, with each child receiving 20 minutes of training a day, 4–6 days a week, for 5 weeks. A control group of children received a lesser version of the same training tasks in which the difficulty was not adjusted, but it was for less than 10 minutes a day. Group differences in pre- and post-training improvement between training and control groups were reported on an untrained visuo-spatial WM task; Raven’s Progressive Matrices, a common measure of fluid intelligence; and the Stroop task (Klingberg et al., 2002). In a later neuroimaging study, Olesen, Westerberg, & Klingberg (2004) found increases in prefrontal and parietal areas associated with WM after a similar course of WM training in normal young adults.

Another form of remediation proposed to have possible effects on WM and executive performance in children with ADHD is the teaching of organizational strategies such as self-monitoring, verbal mediation, and various higher level problem-solving strategies (Marlowe, 2000; Wasserstein & Lynn, 2001). No studies have directly examined the extent to which such a program alone would remediate WM. However, such training has been proposed as an important addition to process-specific training and other forms of remediation (Sohlberg & Mateer, 2001) as seen in Semrud-Clikeman et al. (1999).

A third possibility in the remediation of WM and executive deficits may lie in the stimulant medications traditionally used to reduce hyperactivity in ADHD because there is growing evidence that they may also improve certain aspects of WM function. Methylphenidate is the most commonly prescribed stimulant medication used to treat ADHD and has been shown to increase dopamine levels in normal subjects (Solanto, 2002; Volkow, Fowler, Wang, Ding, & Gatley, 2001). Behaviorally, treatment with methylphenidate appears to reduce problems in children with ADHD (Whalen et al., 1987), and it has also been reported to improve performance on a number of school-related activities (Douglas, Barr, O’Neill, & Britton, 1986). A number of studies have reported improvements with the use of methylphenidate on both WM and executive tasks. Two studies comparing children treated with methylphenidate to unmedicated children and normal controls found no difference between the medicated and control groups’ performance on spatial WM and executive function tasks, whereas unmedicated children were impaired on both (Barnett et al., 2001; Kempton et al., 1999). Other studies have directly compared the performance of children with ADHD, both taking and not taking medication, and found better performance while medicated on measures of verbal WM (Tarnock, Ickowicz,
& Schachar, 1995), visuo-spatial WM (Bedard, Martinussen, Ickowicz, & Tannock, 2004), focused and sustained attention (Konrad, Gunther, Hanisch, & Herpertz-Dahlmann, 2004), and task switching (Kramer, Cepeda, & Cepeda, 2001).

Another pharmacological agent that has shown promise in improving WM function is modafinil. This drug is different from methylphenidate and related compounds in that it is not thought to affect dopaminergic systems; instead, it affects an individual's level of arousal. Therefore it is often used in the treatment of narcolepsy. However, two studies have reported improvements of clinical features of ADHD with modafinil use in children (Rugino & Copley, 2001) and adults with ADHD (Taylor & Russo, 2000). Although the direct action of modafinil on cognitive dysfunction in ADHD has not been directly tested, it has been shown to improve cognitive performance in animals (Beracochea et al., 2001) and in humans, with enhanced performance on tasks requiring WM and inhibitory processing (Turner et al., 2003).

As we have seen, there are several approaches targeting the CE that appear to hold promise in the remediation of the WM and CE deficits seen in ADHD. However, one factor that has not been considered in the remediation attempts to date is the large comorbidity of ADHD with other learning impairments and conditions such as reading disability (Dykman & Ackerman, 1991) and anxiety disorders (Tannock et al., 1995). The extent to which the efficacy of these different programs of remediation is changed in these subpopulations of children with ADHD is a topic for further research.

**Childhood Schizophrenia**

Schizophrenia is another relatively common disorder in which WM impairment has been hypothesized to constitute a core deficit. Poor WM performance, in both the verbal and spatial domains, has been reported in children with schizophrenia (Asarnow et al., 1994; Karatekin & Asarnow, 1998) and adults (Barch & Csernansky, 2002; Goldman-Rakic, 1994; Huguelet, Zanello, & Nicastro, 2000; Silver, Feldman, Bilker, & Gur, 2003). Individuals diagnosed with schizophrenia also perform poorly on a variety of executive function measures including the WCST (Goldman-Rakic & Selemon, 1997), verbal fluency (Bokat & Goldberg, 2003), and the Tower of London (Andreasen et al., 1992; Morris, Rushe, Woodruffe, & Murray, 1995). Although the remediation of WM has yet to be attempted in children with schizophrenia, there are a growing number of studies in which the amelioration of WM deficits has been undertaken in adults, using cognitive training techniques or new pharmacological treatments.

Two cognitive training programs that have shown promise in the remediation of WM deficits in schizophrenia are the frontal/executive program (FEP) developed by Delahunty and Morice (1996) and neurocognitive
enhancement therapy (NET) developed by Bell et al. (2001). In the first program, FEP, patients with schizophrenia are given targeted training on a series of paper and pencil tasks in three different domains of executive function: cognitive flexibility, WM, and planning (Delahunty & Morice, 1996). Training in each of these domains emphasizes errorless learning, immediate feedback, and explicit instruction in various strategies for each domain. Wykes et al. (Wykes, Reeder, Corner, Williams, & Everitt, 1999) trained schizophrenic individuals using this program for approximately 40 days, with three to five 1-hour sessions of training per week. They measured a variety of cognitive and social measures, both before and after the training, and compared the amount of improvement seen to a control group of patients who received a more traditional occupational therapy. They found improvements in performance in a planning task, digit span, and WCST for both therapies, with a significantly larger advantage for the group receiving the FEP. In addition, there is early evidence that this training may have demonstrable effects on areas of the brain shown to be involved in WM processing. In a preliminary study, Wykes et al. (2002) reported increased frontal activation during the performance of an untrained WM task after an extended course of FEP training in several patients with schizophrenia. However, although increased activation was seen in areas associated with WM processing, it was not correlated with any improved performance on the task.

A second approach to the remediation of WM deficits in schizophrenia has been more process specific in nature because patients are given repeated practice with an increasing level of difficulty on various tasks but are not explicitly taught any particular strategy for improvement. This approach has been termed neurocognitive enhancement therapy (or NET; Bell et al., 2001). Two studies have compared the cognitive benefits of a course of work therapy to a course of work therapy augmented with a course of NET training, in which patients were given lengthy training (up to 5 hours a week for 26 weeks) on 4 computer-based programs, 2 visual tracking tasks requiring sustained attention, practice at a computerized versions of digit and word spans, and a planning task similar to the Tower of London (Bell et al., 2001; Bell, Bryson, & Wexler, 2003). In the first study, the group that received neurocognitive training in addition to work therapy showed greater levels of improvement on both an executive measure (WCST) and a common measure of WM (Backward Digit Span) (Bell et al., 2001). This was replicated in a later study, with the same benefit found for the training group on the Backward Digit Span (Bell et al., 2003), and training benefits enduring for at least 6 months after training had concluded (Fiszdon, Bryson, Wexler, & Bell, 2004). There is evidence that this form of remediation also has the potential to affect patterns of brain activity measurably. In a study in which verbal WM was targeted for training, 8 patients with schizophrenia were scanned while performing an auditory serial position memory task both before and after 10 weeks of intensive training on auditory verbal
serial position memory tasks (Wexler, Anderson, Fulbright, & Gore, 2000). Although not all of the patients showed significant improvements with training, those who did showed increased task-related activity in the left inferior frontal cortex, shown to be active in normal control participants in performance of the task. One patient who received an additional 5 weeks of training was shown to have a normalization of brain activity after training, so that his pattern of activation was virtually the same as that of the controls.

Although the efficacy and the generalizability of cognitive remediation in schizophrenia is debated (Krabbendam & Aleman, 2003; Pilling et al., 2002), there is growing evidence that, in the treatment of WM and executive problems, it can have some positive impact. However, the degree to which WM can be remediated, and improvements generalized to real-life activities, is still unknown. In addition, the effect of these programs on children with schizophrenia, which is thought to be more severe in nature than adults, is still not yet known.

Another approach that holds promise for the remediation of cognitive deficits, and WM dysfunction in particular, lies in new drug therapies being developed to treat schizophrenia. Although early descriptions of schizophrenia emphasized the importance of the cognitive dysfunction seen in patients (Andreasen, 1999), traditional drug treatments such as haloperidol have focused on relieving the positive symptoms of schizophrenia, such as hallucinations. These early treatments were not effective in treating the cognitive deficits of the disease and may have, in fact, worsened WM performance (Castner, Williams, & Goldman-Rakic, 2000). However, there is growing evidence that some of the newer drug therapies, the so-called "atypical" neuroleptics, may improve WM performance by increasing dopaminergic activity in the prefrontal systems identified as being important for WM performance (Gemperle, McAllister & Olpe, 2003; Hertel et al., 1996). Abnormal activity in these same areas has been found repeatedly in neuroimaging studies of schizophrenia and WM (Barch & Csernansky, 2002; Callicot et al., 2003; Manoach et al., 2000). One drug, risperidone, has been shown to improve WM performance (Green et al., 1997; Harvey, Green, McGurk, & Meltzer, 2003) as well as increase activation in several brain areas associated with WM, including the right prefrontal cortex (Honey et al., 1999). Three other "atypical" drugs that have shown some promise in treating WM deficits are clozapine (Meltzer & McGurk, 1999), olanzapine (Harvey et al., 2003), and iloperidone (Gemperle et al., 2003). In addition to direct improvements in WM and executive performance, another possible benefit to these drug treatments is that they may enhance the effectiveness of other forms of remediation, such as cognitive training (Wykes et al., 1999).

Cognitive remediation of WM deficits is an important goal in the treatment of schizophrenia, especially in light of the evidence that it is the resolution of these deficits rather than more dramatic symptoms (such as hallucinations) that best predict a patient's long-term social outcome (Green et al., 2000). Another possible area of investigation is in the remediation of
deficits in children who are genetically at greater risk of developing schizophrenia because they have been shown to have poorer WM function (Davalos, Compagnon, Heinlein, & Ross, 2004; Erlenmeyer-Kimling et al., 2000), and the extent of the deficit has been shown to be predictive of the likelihood of their later developing the disorder (Erlenmeyer-Kimling et al., 2000). Therefore, it is possible that early intervention and improvement of cognitive function may have some effect on whether and how severely the disease manifests itself. Although this proposition is highly speculative, given the devastating effects of schizophrenia, it is worth future investigation.

**Autism**

Autism is another developmental condition in which executive function has been hypothesized as playing an important role (Pennington & Ozonoff, 1996) and for which the remediation of the CE has been proposed as a treatment strategy (Ozonoff, 1998). However, the exact nature of the WM and executive deficits seen in autism is not entirely clear and is currently the topic of some debate. Several studies have reported finding WM deficits in children with autism (Bennetto, Pennington, & Rogers, 1996; Luna et al., 2002; Minshew & Goldstein, 2001; Pennington & Ozonoff, 1996), whereas others have not (Russell, Jarrold & Henry, 1996). A similar situation exists for different measures of executive function, with some studies reporting impaired performance (Ozonoff, 1998), and others not (Griffith, Pennington, Wehner, & Rogers, 1999). One explanation for these inconsistent findings is that children with autism have impaired development and use of organizational strategies and that their performance suffers in situations where planning and strategy are important for optimal performance (Minshew & Goldstein, 2001).

Minshew & Goldstein (2001) studied WM span in individuals with autism using letter sequences, word sequences, and a sequence of directions. The subjects with autism were not significantly impaired on the letter sequences but were significantly worse for both word and direction sequences, with performance decreasing as opportunity to benefit from strategy use increased. The authors interpreted this as support for the hypothesis that as the complexity of the material increases and lends itself more to strategies, the more impaired individuals with autism are. A related proposition is that individuals with autism have poor or nonexistent inner speech, which would curtail any attempts to verbally mediate an organizational approach to the material, and that performance deficits will be the greatest on tasks in which there are arbitrary rules that must be followed, such as in planning tasks like WCST and the Tower of London/Hanoi (Russell et al., 1996). This theory may also help to explain the findings of Griffith et al. (1999), who reported finding no differences between autistic and age- and ability-matched children on eight separate measures of executive function. The
children in this study were tested between the ages of 4 and 5 years, before reliable rehearsal and strategy use appears to develop in children (Gathercole, 1999). If poor performance on executive tasks in children with autism results in part from a failure to use organizational strategies, differences may not become apparent until children are older.

Although little has been attempted in the specific remediation of WM and executive function deficits, some of the same approaches used in other impaired populations have been proposed for children with autism. These have included stimulant medications such as methylphenidate, metacognitive training to increase organizational skills and strategies, and process-specific training in areas such as cognitive flexibility (Ozonoff, 1998). Currently there are no published studies evaluating the effectiveness of each of these approaches in children with autism. However, in addition to the possible rehabilitative benefits of such interventions being tested, there is also the possibility that the success or failure of different remediation attempts may be informative about the underlying deficits in autism. One prediction is that if the main deficit is the organization and utilization of strategies, then the direct instruction in the development and use of metacognitive strategies may be most effective.

Traumatic Brain Injury

WM and executive function deficits are frequently reported outcomes of traumatic brain injury in both adults and children (Levin et al., 1988; Levin et al., 2004; Roncadin, Guger, Archibald, Barnes, & Dennis, 2004; Slomine et al., 2002; Thompson et al., 1994). Although traumatic brain injuries can result from several different causes, such as infections, vascular accidents, and tumors, the most common cause is closed head injury, to which the frontal lobes appear to be especially vulnerable (Levin et al., 1997). The remediation of WM deficits has thus focused on the executive processes theorized as relying on frontal integrity. In a similar manner to that for developmental disorders in which the nature of WM impairments is hypothesized as lying in the CE, three forms of intervention have been presented as methods by which the attentional functions of the CE in individuals who have been brain injured can be improved. These are process-specific training, metacognitive approaches, and the use of stimulant medications.

Several studies have attempted to assess the extent to which patients who have been brain injured can benefit from process-specific training and the degree to which the improvements seen will generalize to new tasks. Interventions using programs such as APT (Sohlberg et al., 2000) and other forms of repeated practice on executive tasks, such as random number generation (which requires participants to generate a list of random, unrelated digits and inhibit well-learned sequences and recent responses), dual task performance, and n-back (which requires participants to remember and
update a sequence of digits or letters and judge whether a particular item is the same as one presented a certain number of items previously) (Cicerone, 2002), have shown some limited promise in adult patients. However, a recent meta-analysis of the effectiveness of different attentional rehabilitation programs for patients with brain injuries found little evidence of generalized benefits from direct retraining efforts such as APT (Park & Ingles, 2001). A similar situation exists in the research on APT in children with brain damage, with preliminary results suggesting possible improvements with training (Mateer, Kerns, & Eso, 1996). Further controlled research is necessary to thoroughly assess the benefits of this approach in children.

Metacognitive deficits have also been reported in children with severe traumatic brain injuries (Dennis, Barnes, Donnelly, Wilkinson, & Humphreys, 1996; Hanten, Bartha, & Levin, 2000; Hanten, Levin, & Song, 1999). In adults with brain damage, the ability to improve with practice has been linked to their ability to develop and use strategies (Dirette, Hinojosa, & Carnevale, 1999). Therefore metacognitive training may be of benefit to children who are brain injured and may allow them to benefit more from other forms of training. A program attempting to rehabilitate memory and attention in children with brain injuries used a combination of process-specific and metacognitive training (van't Hooft, Andersson, Sejersen, Bartfai, & von Wendt, 2003). The Amsterdam Memory and Attention Training program has been formulated as a multi-pronged approach in which children are given both process-specific training on various attentional and memory tasks and metacognitive training focusing on the learning of specific performance strategies. In addition, children also receive social and therapeutic counseling. Pilot data obtained from three children with traumatic brain injuries who completed this program of training found weak evidence for improvements on selective attention as measured by the Stroop task and WM as measured by digit span (van't Hooft et al., 2003). However, considerably more research is necessary to establish the effectiveness of this program and the extent to which any improvements will generalize to other tasks.

The attentional deficits frequently seen in patients who are brain injured have led to investigations of the efficacy of stimulant medications such as methylphenidate in remediating these impairments. However, both the pediatric and the adult literatures are mixed, with some studies reporting improvement in attention and memory function after treatment with methylphenidate in children with brain injuries (Hornyak, Nelson, & Hurvitz, 1997; Mahalick et al., 1998) and in adults with brain injuries (Kaelin, Cifu, & Matthies, 1996; Plenger et al., 1996), and other studies with no such reports (Speech, Rao, Osmon, & Sperry, 1993; Williams, Ris, Ayyangar, Scheff, & Berch, 1998). A review of methylphenidate use in treating brain injuries concluded that, although there is evidence to support the effective-
ness of the drug on behavioral problems such as impulsivity, the support for cognitive improvements is weak (Jin & Schachar, 2004).

Unlike adults, children may appear to have recovered from a brain injury only to manifest deficits months or even years later (Mateer & Williams, 1991; Thompson et al., 1994). This phenomenon by which children appear to grow into a deficit is likely to be a result of the increased WM and executive function demands of school and other activities as children age. Therefore, it is possible that successful remediation given shortly after the injury may help prevent or alleviate these later impairments. Although the possibility of such benefits is only speculative at this time, given the cognitive difficulties faced by these children, it is worth further investigation.

Chemotherapy and Cranial Radiation Treatments

Children treated with chemotherapy and cranial radiation therapy manifest a pattern of WM and executive impairments similar to children with traumatic brain injuries, including the delayed onset of deficits, which may not appear until 2 or 3 years after a child begins treatment (Butler, Kerr, & Marchand, 1999; Copeland et al., 1988; Mulhern & Palmer, 2003; Schatz et al., 2000). This unintended side effect to these life-saving measures is thought to arise from radiation damage to white matter and other subcortical areas such as the basal ganglia (Mulhern et al., 1999).

In light of the deficits suffered by these children, an ambitious rehabilitation program has been developed to treat them. Butler & Copeland (2002) have developed the cognitive remediation program in which children receive a combination of APT (Sohlberg & Mateer, 1987), explicit instruction in metacognitive strategies and cognitive-behavioral therapy in which children learn and practice strategies to resist distraction, and mnemonic strategies such as chunking. Training consists of 50 hours of treatment, with children receiving treatment 2 hours a week for 6 months. A pilot study of the effectiveness of this study found significant improvements on measures of WM (digit span and sentence memory) and sustained attention (the continuous performance test) for a group of young cancer survivors who completed the training, compared to a control group who did not receive treatment (Butler & Copeland, 2002). However, a fourth measure, a test of arithmetic achievement, did not show differential improvement. Although the lack of transfer to an academic measure correlated with WM performance was disappointing, the authors conceded that the data are preliminary and that more research is necessary before the true efficacy of the program can be evaluated. Therefore, they are conducting a large multi-site study to evaluate this program of cognitive remediation (Butler & Copeland, 2002). This is the most comprehensive and ambitious exploration of the possibilities of cognitive remediation to date.
CONCLUSION

In this chapter, we have documented an increasing interest in the remediation of WM impairments in children. Multiple forms of remediation have been attempted, with the type of intervention dependent on the hypothesized source of the deficit in a particular population of children. Taken as a whole, these studies suggest that at least some form of WM improvement is possible, although the specific mechanisms responsible for any changes have not been precisely identified. Thus, the extent to which different theoretical approaches to remediation are most appropriate in a given population of children is uncertain because there has so far been no systematic approach to research on cognitive remediation. There do, however, appear to be a few general principles that can be distilled and used in future attempts at remediation.

The first general principle is the importance of variability in training. Although not always desirable when trying to determine the possible causes of improvement in any given situation, it has been well established in the skill-acquisition literature that variability in training promotes greater transfer than training on a single task (Schmidt & Bjork, 1992). This also appears to be true when training is applied toward remediation, with the more successful programs reported here (such as Klingberg et al., 2002, Semrud-Clikeman et al., 1999, and Tallal et al., 1996) combining different tasks and types of training interventions. Two additional general principles for successful training are the length of training and the adaptability of difficulty. Most remediation programs reported here consisted of at least 1 hour of training a week for weeks or months. In addition, most programs had some form of difficulty adaptation. Klingberg, Forssberg, & Westerberg (2002) demonstrated the importance of difficulty manipulations and length of training by including a control group that received training on the same tasks for far less time and without trial-by-trial adaptations of difficulty and who then did not show improvement. A final general observation is that there is a growing use of neuroimaging techniques such as functional magnetic resonance imaging to demonstrate and measure the effects of training interventions on neural activity. However, until there is a clearer understanding and set of expectancies for how compensatory processing is accomplished in the brain, these results should be interpreted with caution.

It should be noted that the previous discussion of children with WM deficits is naturally limited by the extent to which attempts at remediating WM have so far been made. There are a number of additional populations of children who may also benefit from WM interventions including children with low birthweight (Harvey, O'Callaghan, & Mohay, 1999), phenylketonuria (Welsh, Pennington, Ozonoff, Rouse, & McCabe, 1990), fetal alcohol syndrome (Connor, Sampson, Bookstein, Barr, & Streissguth, 2000), arithmetic disability (Bull & Johnston, 1997), and epilepsy (Kadis, Stollstorff,
Elliott, Lach, & Smith, 2004). The inclusion of these different populations in future research will help to broaden our understanding of what types of WM remediation are possible and the mechanisms by which they can occur.

### Summary Box

- Deficits in WM, the cognitive system involved in the active maintenance of task-relevant information, have been reported as a consequence of a diverse array of childhood disorders.
- WM ability may not be entirely fixed, and numerous interventions have shown promise in improving performance on different kinds of WM tasks.
- A number of approaches have been used to improve WM; these approaches include ones that focus on the ability to maintain specific kinds of information such as phonological or visuo-spatial information and those that focus on executive/attentional control skills.
- Children with intellectual disabilities such as Down syndrome have benefited from training in rehearsal strategies.
- Successful remediation of WM problems in children with language and reading impairments has often focused on teaching compensatory strategies, improving phonological awareness, and improving auditory processing speed.
- Children with ADHD suffer from impairments in executive functioning, and research suggests that such processes may be improved by process-specific training (repeated practice on impaired skills) and stimulant medications.
- Although remediation of children with schizophrenia has not been attempted, process-specific training and medications have improved executive functions in adult with schizophrenia; such approaches may be beneficial for childhood schizophrenia.
- Process-specific training and metacognitive strategy training have also been successfully used to treat WM deficits in children with traumatic brain injury and brain injury from chemotherapy and cranial radiation.
- Although our review of the literature suggests the potential for remediation of WM, much more research is necessary to establish the extent to which WM can be improved and what types of remediation are most effective for different populations.
References


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10. Sources of Working Memory Deficits in Children and Possibilities for Remediation


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