1

The Working Memory Model

Learning outcomes

At the end of this chapter, you should have an understanding of the original and revised versions of the 'working memory model' (Baddeley, 1986, 2000, 2007; Baddeley & Hitch, 1974). This has been a dominant model of memory in recent decades and represents a key approach to understanding the development of memory in children with and without developmental disorders. Once you have read this chapter, you should be able to: (1) describe each of the four components of the revised working memory model; and (2) outline some of the key evidence supporting the structure of each component.

Introduction to the working memory model

The working memory model is a very influential theory of memory designed to account for how we temporarily manipulate and store information during thinking and reasoning tasks. The model helps us to understand how memory processes are used during day to day familiar activities, or during more demanding tasks that require greater effort and new thinking (perhaps

a problem-solving task that has not been encountered before). One way of understanding working memory is to consider the types of memory we need while we read, plan future activities, do the crossword/Sudoku, or follow the news headlines.

One of the important concepts to understand about working memory is that it is limited in capacity, which means that we cannot store and manipulate endless amounts of information. Therefore, the types of thinking and remembering tasks we can undertake will be constrained by working memory resources. Working memory also limits, to some degree, the types of things we can handle concurrently. Whilst there are some types of tasks that can be carried out at the same time, other types of tasks compete for the same resources within the working memory system and, therefore, interfere with each other.

Working memory is vital because it underpins abilities in many other areas such as reasoning, learning and comprehension. In the most recent description of the working memory system, Baddeley (2007) even attempts to use his model to account for consciousness!

The working memory model is used in this book as the theoretical underpinning for our discussion of memory development in typical and atypical children. There are three major reasons for choosing the working memory model for this purpose. First, the working memory model has become a major explanation for memory and thinking in recent years and has received wide support. Secondly, using one unified theoretical framework makes it much easier to compare memory development in children with typical development to those who have various types of developmental disorders (i.e. atypical development). The final reason for using the working memory model as the theoretical foundation in this book is its comprehensiveness and clear four-part structure, which accounts for many different types of remembering. The four-component structure of the working memory model provides not only theoretical sophistication, but an organisational template for every chapter in this book. Each chapter is organised around the four components of the working memory model, making it easier for readers to navigate through the research and see how development differs in typical and atypical children.

This chapter provides a description of each of the four main components of the revised working memory model and covers some of the key psychological evidence presented to support the model. However, this is not an exhaustive account of the working memory model, but rather an overview, covering the main points in enough detail so that you can understand the rest of the book. If you would like more information on the working memory model, including evidence concerning neuroimaging and neuropsychological studies, please look at the Further reading section at the end of this chapter.

Note that the next chapter (Chapter 2) provides detailed descriptions of the most common ways in which working memory has been measured in typical and atypical children/populations. Chapters 3 and 4 are devoted to the development of working memory in typically developing children. Chapters 5 to 8 go on to consider the development of working memory in children with atypical development. As already noted, every chapter adopts the same general

structure. Each area of working memory is discussed in turn with respect to the population of children under discussion.

For now, however, we return to the central issue of the current chapter, providing an introduction to the working memory model.

Key features of the working memory model – an overview

This section provides a brief overview of the key features of the 'original' working memory model (Baddeley, 1986; Baddeley & Hitch, 1974) and the 'revised' working memory model (Baddeley, 2000, 2007). In most respects, the revised working memory model simply adds to the original, but there are some changes to individual components that will be pointed out. The sections following this overview will describe each component of the model in more detail, and present some key experimental evidence to support the proposed structure of working memory.

To start to understand what working memory is, it is useful to examine a quote from Baddeley (2007), in which he describes working memory as follows:

> … a temporary storage system under attentional control that underpins our capacity for complex thought. (p. 1)

There are several important points even in this one short sentence. First of all, the system deals with temporary storage and so deals with things we are doing right now. Secondly, the system is under attentional control, indicating that, in most instances, we choose where to direct our attention. Finally, the system underpins our capacity for complex thought, making it fundamental for any type of higher order thinking or reasoning task. In this way, working memory can be viewed as the bedrock for virtually all thinking processes (often described as 'cognitive' processes) that rely on temporary memory storage. We will not go into the history of why this model was proposed as this is readily available in any of Baddeley's very readable books about working memory (see Further reading at the end of the chapter).

The original working memory model (Baddeley & Hitch, 1974) consists of three components. The most important component is a system for controlling attention, known as the 'central executive'. This is used to ensure that working memory resources are directed and used appropriately to achieve the goals that have been set. There are also two temporary storage systems. One of these is for holding speech-based information and it is known as the 'phonological loop'. The second storage system is for holding visual and spatial information and it is known as the 'visuospatial sketchpad'. These two storage mechanisms are regarded as 'slave subsystems', because they do not do anything beyond holding information in a relatively passive manner. The real 'brains' of the working memory system is the central executive. Figure 1.1 below illustrates the original working memory model.
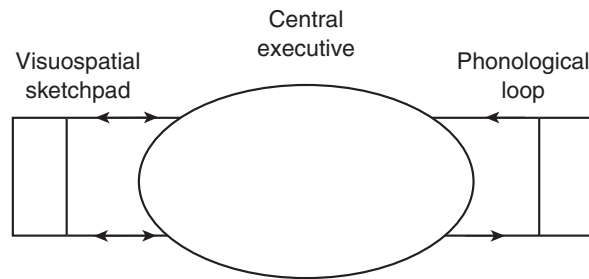
Figure 1.1   The original conceptualisation of the working memory model

Although the original working memory model was very successful in accounting for a large body of experimental research, various criticisms of the model led to some significant revisions. For example, it became clear that there was a need to account for the effects of long-term knowledge (all of the stored information that we know about the world) on working memory, something that the original model did not take into account.

Therefore, Baddeley added a fourth component to the working memory model, the 'episodic buffer' (Baddeley, 2000). This new component of working memory provides a number of important new features. First, a link to long-term memory; second, a way of integrating information from all of the other systems into a unified experience; and third, a small amount of extra storage capacity that does not depend on the perceptual nature of the input. Figure 1.2 illustrates the new version of the working memory model, which takes account of the episodic buffer.

Now we will turn to each of the four components of the revised working memory model, looking at each in more detail. We will also consider some of the more important evidence that has been used to support the proposed structure of the working memory model. The relationships between the components illustrated in Figure 1.2 will become clearer as we continue our discussion.

The phonological loop

The phonological loop component of working memory is proposed as a specialised storage system for speech-based information, and possibly purely acoustic information as well. The phonological loop is described as a 'slave' system as it is not 'clever' in any way; it does not have any capacity for controlling attention or decision-making. The phonological loop is merely a temporary store for heard information, particularly speech. It represents the storage system responsible for 'phonological short-term memory' (PSTM), the ability
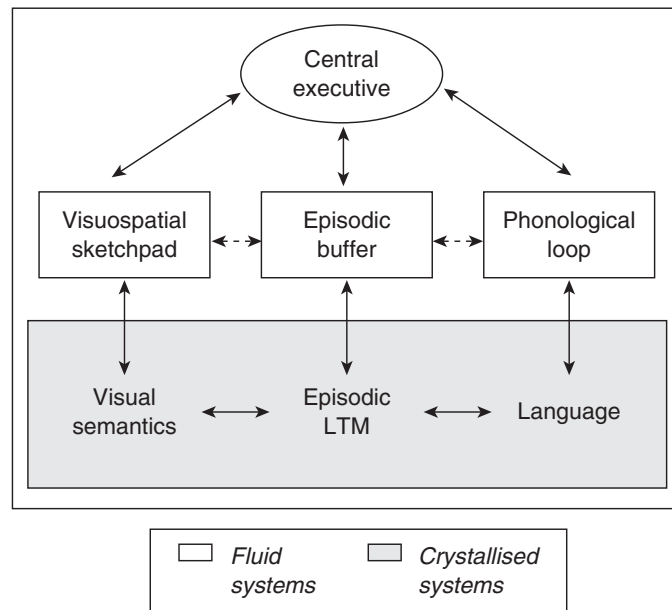
Figure 1.2   The revised model of working memory (Baddeley, 2000)

Source: Reproduced with permission from Elsevier (Baddeley, A.D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Science, 4*(11), 417–423)

of individuals to remember small amounts of heard information over short periods of time. This type of memory has been closely studied in adults and children for many years and a large part of this book will be devoted to discussing how PSTM develops in children. Please refer to Chapter 2 for details on how PSTM is measured in typical and atypical populations of children.

The phonological loop is divided into two further subcomponents, both believed to be located in the left hemisphere of the brain according to neuroimaging evidence (Jonides et al., 1998; Paulesu, Frith & Frackowiak, 1993). These two subcomponents are now described.

The phonological store

The first subcomponent of the phonological loop is the phonological store. This is the area of the system in which speech material is held for short periods of time. The phonological store is described as 'passive', because it simply holds the information; and 'time-limited', because the information fades rapidly. The information in the phonological store is often described as the 'memory trace', and the phenomenon of rapid fading is often called 'trace decay'. Trace decay reflects the fact that representations held in the phonological store are temporary, rather than completely accurate, long-lasting representations of the things we encounter. Trace decay is so rapid in the phonological store that only

around two seconds' worth of speech-based material can be held, perhaps just long enough to hold a telephone number in mind before dialing it.

Although there are long-standing arguments over the whole notion of whether trace decay (or interference) accounts for forgetting in phonological short-term memory (PSTM), we do not have time to go into the detailed arguments here. You can read more about this issue in Chapter 3 of Baddeley (2007) referenced at the end of this chapter.

The articulatory rehearsal mechanism

The second subcomponent of the phonological loop is the articulatory rehearsal mechanism. We have already mentioned the two-second limit on the phonological store. The articulatory rehearsal mechanism is used to recite the information in the phonological store, in order to prevent this very rapid decay. The recitation of the material re-enters it into the phonological store, where it immediately starts to decay again. Baddeley describes the articulatory rehearsal mechanism as like a tape loop or a tape recorder with a two-second duration. The recitation processes can prevent the material decaying, by constantly refreshing it. The process of recitation is called 'articulatory rehearsal' or 'verbal rehearsal' and is a major strategy used to improve or enhance the capacity of PSTM.

Verbal rehearsal is usually done internally (i.e. you can't hear a person doing it) by adults, but there are interesting changes in verbal rehearsal in children throughout their development, which we will consider in Chapter 3. There are also arguments over the exact form that verbal rehearsal takes and these revolve around whether real articulation is taking place. However, most researchers would agree that verbal rehearsal involves some form of covert verbalisation (i.e. internal speech) which uses the same speech planning mechanisms that we use for real speech, even if it does not always require actual speech output.

We will consider the issue of verbal rehearsal and articulation further in Chapter 3, when we discuss the development of working memory in typically developing children. For now, Box 1.1 gives an example of how verbal rehearsal may be useful in real life, when good PSTM could prove vital.

Box 1.1   Remembering a car number plate

Witness A has just seen a hit and run driver knock down an elderly pedestrian at a controlled crossing. Knowing that providing a description of the vehicle, and better still the car number plate, is vital, Witness A attempts to remember as much as possible. The car was relatively small, royal blue in colour and had blackened windows and spoilers. Witness A thinks that she could probably remember this information using a visual image.

The number plate is more difficult. She thinks she saw it as LY06 VGC. There are a number of ways Witness A could aid her memory for the number plate. She could write the number down on a piece of paper, although in this particular instance it takes her at least a few seconds to locate a pen and paper in her handbag. So what does she do to keep the number in mind? She repeats the letters and numbers over and over again in order, using the process of verbal rehearsal, until she finds her paper and pen.

'LY06 VGC, LY06 VGC, LY06 VGC, LY06 VGC….'

Note that a Police Officer may wonder whether Witness A was accurate in her recall of the 'VGC' portion of the number plate. Why? Because these letters all rhyme. Rhyming items cause confusion in the phonological store, as we shall see later. It might be prudent in this case to check these letters in different orders (and perhaps with rhyming substitutions) against relevant databases, just in case any confusion has occurred.

Note also, that it is possible to 'chunk' various portions of the number plate together. The first two letters can be chunked together as one unit (denoting the area in the country the car was first licensed, making it easier to recall if Witness A recognises 'LY' as denoting London). The second two numbers can be chunked together as a second unit representing the date of licensing, and the third three letters can be chunked together as a unit. These final letters are visually distinct, as a space occurs in the number plate just before them, making chunking easier.

Obligatory and optional access to the phonological store

The articulatory rehearsal mechanism does not just carry out verbal rehearsal; it has a second function. This is known as 'phonological/verbal recoding' (or 'phonological/verbal coding'), a process by which information presented in a visual form (printed words, printed letters/numbers, pictures) can be converted into speech. Obviously, this can only be done if the visual information has a verbal label, e.g. a picture of a 'house' can be labelled as 'house'. Verbal/phonological coding is often advantageous, because remembering visual information can be more difficult than remembering speech (phonological) information. The benefits of remembering information in a phonological form are particularly marked for lists of separate items that must be recalled in order; and also when there is a delay between encountering information and recalling it (verbal rehearsal can be used to keep the information in mind).

Phonological/verbal coding, therefore, is carried out by the articulatory rehearsal mechanism. Items presented in a visual form are simply named or labelled, and the phonological information produced from this naming process is entered into the phonological store. Hence, the articulatory rehearsal mechanism 'converts' visual information into verbal (phonological) codes via an articulation process. Clearly, if visual items are recoded in this manner, this can change a visual remembering task into a test of PSTM.

One further point to make is that auditory information gains obligatory access to the phonological store: we do not have to do anything to create a phonological record. However, nameable visual inputs such as pictures, written letters or written words, must first be 'recoded' into a phonological form in order to gain access. Their access to the phonological store is, therefore, optional.

Figure 1.3 provides a simple schematic diagram illustrating the differences between obligatory and optional access to the phonological store. On the left, auditory inputs proceed directly into the phonological store. On the right, visual inputs must proceed via the articulatory rehearsal mechanism, before entering the phonological store. Once in the phonological store, however, all items can be recirculated between the phonological store and the articulatory rehearsal mechanism using verbal rehearsal. Verbal rehearsal operates in the same manner, regardless of how the information has entered the phonological store, i.e. via the optional route or the obligatory route. Verbal rehearsal keeps the items refreshed so long as it is continued.

Hence, the two roles carried out by the articulatory rehearsal mechanism are: (1) converting visual input into a phonological code; and (2) rehearsing the contents of the phonological store.

Summary

The phonological loop is one component of the multi-component working memory model (Baddeley & Hitch, 1974) and its structure remains largely unchanged in the revised working memory model (Baddeley, 2000, 2007). The phonological loop is a specialised storage system for holding sound-based material, particularly speech, but its contents decay rapidly (within two seconds) unless refreshed using verbal rehearsal. The phonological loop is
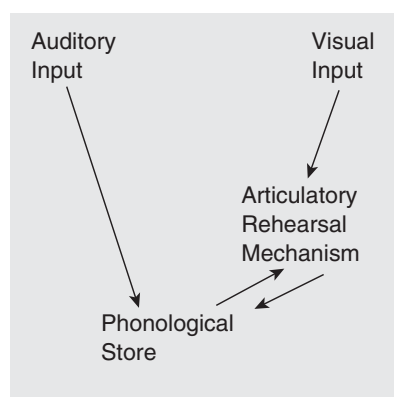
Figure 1.3   Diagram illustrating how auditory input gains direct access to the phonological store (obligatory access), whereas visual input must proceed via the articulatory rehearsal mechanism (optional access)

divided into two components, the phonological store (for storage) and the articulatory rehearsal mechanism (for verbal rehearsal and phonological coding). The basic capacity and duration of phonological short-term memory (PSTM) can be increased by using verbal rehearsal. Information we hear goes directly to the phonological store (obligatory access), whereas information that is presented in a visual form can be phonologically recoded and reach the phonological store via an optional route (optional access).

Evidence in support of the phonological loop

In the next sections, evidence in support of the main features of the phonological loop, as well as its structure (the division into a phonological store and an articulatory rehearsal mechanism), is briefly outlined. Note that this evidence concerns adults, but we will consider similar evidence in respect of children later in Chapter 3. For more detail concerning the adult evidence reviewed below see Baddeley (1986).

The phonological similarity effect

Why can we assume that the phonological loop is specialised to hold speech-based material? A classic piece of research by Conrad and Hull (1964) gave adults a test of PSTM, which involved asking them to recall short lists of letters in the correct order. Some of the lists contained letters that were all rhymes (e.g. B, G, V, P, T), whereas other lists contained letters that did not rhyme (e.g. Y, W, H, K, R).

Conrad and Hull (1964) found that rhyming lists were much more difficult to remember in the correct order than non-rhyming lists. This finding demonstrated that PSTM was affected by sound similarity, and led to the conclusion that memory for speech material utilises some kind of sound-based storage system. The logic for this conclusion is that similar sounding letters create similar sounding (and, therefore, confusable) memory traces in the storage system used to support PSTM. The phonological store of the working memory model is just such a storage mechanism, designed to hold small amounts of speech-based material. Memory traces for speech items that all sound the same have very similar features and this makes recall difficult, because the discrimination between separate items is poor.

This effect of sound confusability in PSTM is very robust and has been found many times since. For example, Baddeley (1966) found that rhyming words were also more difficult to recall in order than non-rhyming words. The effect of sound confusion is described as the 'phonological similarity effect', the 'phonemic similarity effect' or sometimes the 'acoustic similarity effect'. This is illustrated in Box 1.2.

Box 1.2   The phonological similarity effect

Read out the following list of words and then close your eyes and try to recall them in order:

ring   **bus**   **owl**   **cake**   **frog**   **clown**

Now try the same with this list:

hat   **cat**   **bat**   **sat**   **fat**   **pat**

Which list was easier to remember?

Most people find the words that are rhymes to be much more difficult, because they become confused. This is evidence that the way we store auditory information for short periods of time is based on *sound characteristics*, supporting the theoretical notion of a phonological or sound store.

Interestingly, words do not have to be exact rhymes for this effect to occur, the most important feature is that the middle vowel sound is the same (Nimmo & Roodenrys, 2004).

The word length effect

Next, we consider the evidence to support the existence of some type of verbal rehearsal mechanism that operates in 'real-time'. The evidence to support the proposed articulatory rehearsal mechanism comes from another important result, known as the 'word length effect'. This effect was described in detail by Baddeley, Thomson and Buchanan (1975) and a reference to this paper is provided at the end of the chapter under Further reading.

Baddeley et al. (1975) presented adults with a test of PSTM that required them to recall lists of five words in the correct order. Some of the lists contained short words that were all one-syllable in length, whereas other lists contained longer words of two, three, four and even five syllables. As the number of syllables increased, something interesting happened to levels of performance. Box 1.3 illustrates the 'word length effect'.

Box 1.3   Remembering lists of short words and long words

Read the following list of words once clearly to yourself out loud or inside your head, then close your eyes and see if you can recall the words in the correct order.

university   **refrigerator**   **tuberculosis**   **periodical**   **hippopotamus**

Now read this list of words, close your eyes and see if you can recall these in the correct order.

stoat   **mumps**   **school**   **zinc**   **scroll**

Although the words in both of these lists are equally familiar, most people find the longer words much more difficult to recall in order than the short words. This is known as the '*word length effect*'.

Baddeley et al. (1975) found, in a series of experiments, that recall was always better for shorter words than longer words, and called this phenomenon the 'word length effect'. They argued that word length effects occur because verbal rehearsal for long items takes longer in real time than verbal rehearsal for short items. This word length disadvantage for longer items allows more time for decay of the memory trace within the phonological store. Short items, on the other hand, can be rehearsed rapidly, so that more words are maintained within the two-second time limit of the phonological store. Remember, once information has entered the phonological store, only those items that can be verbally rehearsed (i.e. repeated over and over again in the internal 'tape loop' known as the articulatory rehearsal mechanism) will be remembered after the critical period of two seconds.

The word length effect findings are very robust and are attributed to real-time rehearsal differences. If you want to read about word length effects in more detail please refer to the papers referenced at the end of the chapter (Baddeley et al., 1975; and Baddeley, Lewis & Vallar, 1984). We will come back to evidence concerning word length effects when considering the development of working memory in typical children in Chapter 3.

The relationship between speech rate and memory span

There are further predictions that can be made, based on the proposed structure of the phonological loop and the articulatory rehearsal mechanism. In particular, the working memory model predicts a close relationship between the rate at which a person can carry out verbal rehearsal (usually measured by assessing their speech rate) and the number of items that can be recalled in tests of PSTM (often described as 'memory span'). People who use verbal rehearsal very quickly should be able to maintain more items in the phonological store than people who use verbal rehearsal more slowly.

This prediction led to the experimental approach of measuring individual people's rates of speaking (to get an approximate measure of rehearsal rate), and then measuring the capacity of their PSTM (using measures of memory span – how many words could be recalled immediately in the correct order).

This was exactly what Baddeley et al. (1975) did. Fourteen adults were asked to remember lists of words that were either of one, two, three, four, or five syllables. This created five separate measures of PSTM, each one for a different length of word. Next, participants were asked to read aloud lists of these words as quickly as they could and their reading times were measured. This gave five separate measures of reading rate, again one for each different length of word.

The final stage was to take the mean memory spans for each type of word and plot them against the mean reading rates for each type of word. Remember that the decay theory, which is part of the working memory model's account of the phonological loop, predicts that for shorter words, reading rates and memory spans should be higher, because more short words can be rehearsed verbally within the two-second time limit of the phonological store. However, as the number of syllables increases both reading rate and memory span should decline.

As you can see in Figure 1.4, there was a consistent relationship between memory span (percent correct recalled, on the vertical axis) and reading rate (on the horizontal axis). One-syllable words with the highest speech rates and memory spans are at the top of the line, and each data point consecutively below represents, respectively, two-, three-, four-, and five-syllable words. With every unit decrease in reading rate, there was a corresponding decrease in memory span, such that a straight line (linear function) could describe the relationship between the two variables over a range of words with different syllabic lengths.

In summary, these results supported the proposed structure of the phonological loop system in working memory. Baddeley et al. (1975) concluded that individuals 'are able to remember as much as they can read out in 1.8
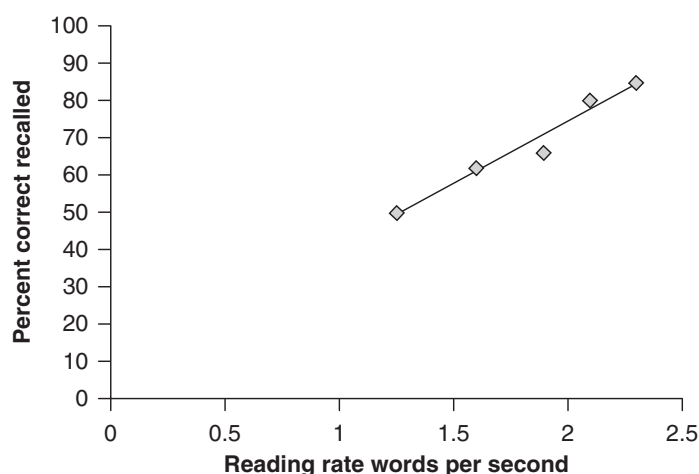
Figure 1.4 The relationship between reading rate and memory span for words of one, two, three, four and five syllables in a sample of adults

Source: adapted from Baddeley et al., 1975

seconds' (p. 583). These results have been replicated many times. For example, Schweickert and Boruff (1986) followed up Baddeley et al.'s findings by measuring memory span and reading rate for a variety of different materials, finding the same results. Similarly, articulation rates for different languages are related to memory spans in those languages (e.g. Ellis & Hennelly, 1980; Stigler, Lee & Stevenson, 1986). We will return to the relationship between articulation rate and memory span when we consider the development of memory span in typically developing children in Chapter 3.
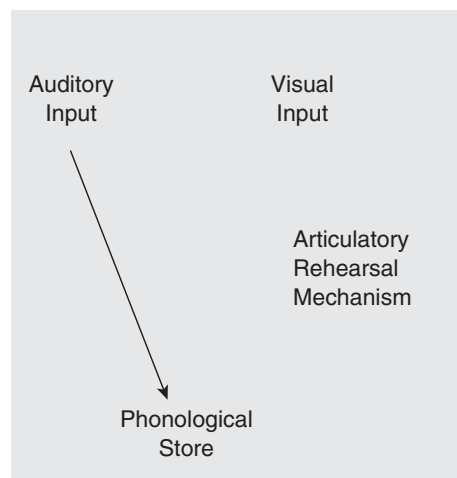
The effects of articulatory suppression

Looking back at the diagram in Figure 1.3 and comparing it with the diagram in Figure 1.5 will help to illustrate an experimental technique known as 'articulatory suppression'. Articulatory suppression is a method of 'knocking out', or blocking, the use of the articulatory rehearsal mechanism. Figure 1.5 shows the predicted effects of blocking the articulatory rehearsal mechanism, according to the working memory account of the phonological loop. These effects are as follows: (a) visual inputs should not be able to enter the phonological store (phonological coding is blocked); and (b) verbal rehearsal of the contents of the phonological store should be impossible.

Using articulatory suppression allows the predictions of the phonological loop model to be tested. How do we bring about articulatory suppression? You simply ask the participants in your experiment to repeat an irrelevant sound or word over and over again while they are carrying out the remembering task (e.g. 'blah, blah, blah', 'the, the, the', or 'one, two, three, one, two, three...' etc.). By 'filling up' the articulatory rehearsal mechanism with an irrelevant task that requires minimal attention and resources, the articulatory rehearsal mechanism becomes unavailable for either phonological coding or verbal rehearsal. In practice this means that visual inputs cannot be entered into the phonological store (they cannot be phonologically recoded) and the contents of the phonological store cannot be rehearsed. However, auditory inputs can still be registered in the phonological store, because they have direct access (see earlier section), although they cannot be rehearsed.

To test the role of articulatory suppression, researchers present participants with PSTM tasks whilst at the same time requiring them to engage in articulatory suppression. We will take one example of such research: comparing the recall of words that rhyme (i.e. are phonologically similar) and those that do not rhyme. Some lists are presented as spoken items, whereas other lists are presented as printed words. All participants use articulatory suppression, so this experiment tests between optional and obligatory access to the phonological store in relation to visual and auditory materials.

The specific research question is whether the words have been registered in the phonological store. How do we tell? If there is a phonological similarity effect, i.e. worse recall for rhyming items, this indicates that the words have been stored as sounds, despite using articulatory suppression. Phonological

Figure 1.5 Diagram illustrating what happens in the phonological store when the articulatory rehearsal mechanism is blocked by articulatory suppression

similarity effects are regarded as evidence for registration in the phonological store (see earlier section).

Looking at Figure 1.5, the predictions according the working memory model are clear. Spoken words will reach the phonological store, even when the articulatory rehearsal mechanism is blocked, because spoken items have obligatory access. Therefore, effects of phonological similarity should be expected. However, if we present lists of words in a printed form, no effects of phonological similarity should be observed, because the items cannot be phonologically recoded and entered into the phonological store via the optional route. Therefore, we do not expect a phonological similarity effect.

This is exactly the result that is found (e.g. Baddeley et al., 1984; Murray, 1968), supporting the predictions of the working memory model and the structure of the phonological loop being divided into a phonological store and an articulatory rehearsal mechanism. (Although see recent debates, for example, Baddeley & Larsen, 2007a, 2007b; Jones, Hughes & Macken, 2007.)

Similar logic is used to account for the data when articulatory suppression is used in combination with the word length effect. Looking at Figure 1.5, it is clear that blocking the articulatory rehearsal mechanism should block all forms of rehearsal, regardless of how the items are presented. Without rehearsal, we would not expect word length effects.

Baddeley et al. (1984) found results to support this prediction. They showed that word length effects disappeared when articulatory suppression was used, regardless of whether the presentation of memory items was auditory (heard items) or visual (printed items). This was because the articulatory

rehearsal mechanism was blocked and unable to carry out any form of verbal rehearsal, regardless of how the items had been presented. Articulatory suppression simply prevented all verbal rehearsal from occurring. However, although the method of input was irrelevant, as predicted by the phonological loop model, it is important to note that articulatory suppression needed to continue throughout the presentation and recall of a list to totally eliminate verbal rehearsal (Baddeley et al., 1984).

In this book we will be using the framework of the working memory model to try to understand memory development in typical and atypical populations. One of the key strengths of the phonological loop model is the explicit link between how material is encoded and stored on the one hand and how strategies for enhancing that encoding and storage (such as verbal rehearsal or phonological coding) can be used on the other.

There is a great deal of research on PSTM in typical children, as this area of memory development has received detailed attention. We will consider this research in Chapter 3. We have also touched upon the strategy of verbal rehearsal and will consider this and other verbal strategies in Chapters 3 and 4, as these strategies are central to understanding the development of PSTM. Where adequate research exists in atypical children, these issues will also be covered in Chapters 5 to 8.

Finally, it is useful to consider more broadly what the phonological loop may be for. In other words, what biological function has it evolved to serve? Baddeley (2007) argues that the purpose of the phonological loop is for learning language. There is quite a lot of convincing evidence for this and the best place to read about this in some detail is in a paper by Baddeley, Gathercole and Papagno (1998), which is listed in the references at the end of the book.

Summary

The 'phonological loop' component of the working memory model was designed to accommodate a great deal of experimental evidence concerning phonological short-term memory (PSTM) in the most parsimonious manner possible. In order to do this, Baddeley and Hitch (1974) proposed a two-part phonological loop system, comprising a phonological store (to hold speech input temporarily) and an articulatory rehearsal mechanism (to refresh this information as necessary). A range of experiments exploring the properties of the phonological loop has supported this structure, which remains largely unchanged from the original working memory model.

We will now move on to considering the next 'slave' storage system in the working memory model, the visuospatial sketchpad.

The visuospatial sketchpad

The visuospatial sketchpad is the other 'slave' storage system proposed in the working memory model. This component is responsible for holding visual and spatial information for short periods of time, so that it can be used during

thinking, remembering and processing tasks (Logie, 1995). Therefore, this is the component of working memory responsible for supporting visuospatial short-term memory (VSSTM). Please refer to Chapter 2 for details on how VSSTM is measured in typical and atypical populations of children.

One of the first questions to ask about the visuospatial sketchpad is whether it is completely distinct from the other slave storage system we have just discussed, the phonological loop. In fact, a range of experimental evidence has indicated that VSSTM is very much distinct from phonological short-term memory (PSTM), such that we really do need two separate short-term stores for each of these types of information (e.g. Baddeley, 1986; Logie, 1995).

Like the phonological loop, the visuospatial sketchpad has been described as a 'slave' storage mechanism (Baddeley, 1986). Again, this means that the system is not in any way 'clever'; it is not responsible for the overall control, allocation or switching of attention. It is simply a repository for holding information temporarily.

The visuospatial sketchpad is believed to be located in the right hemisphere of the brain (the hemisphere that is most often specialised for dealing with visual and spatial information), as opposed to the phonological store, which we saw earlier is believed to be located in the left hemisphere of the brain (the hemisphere that is most often specialised for language).

One distinction that is helpful in understanding the visuospatial sketchpad is that between remembering 'what', i.e. the visual features of an object such as form and colour, and remembering 'where' i.e. where in space an object was located. Broadly speaking, these two types of remembering can be referred to as visual versus spatial short-term memory. Although the visuospatial sketchpad deals with both types of information, visual and spatial, several authors have argued that there are likely to be separate mechanisms within the sketchpad to deal with each of them (e.g. Vicari, Bellucci & Carlesimo, 2006). There is also some evidence for a third subsystem that stores sequences of actions in a kinaesthetic code (e.g. Smyth & Pendleton, 1989). Figure 1.6 illustrates the three types of information it is proposed that the visuospatial sketchpad can store, coordinate and manipulate.

Like the phonological loop, storage in the visuospatial sketchpad of working memory is subject to very rapid trace decay. The details of exactly how rapidly this occurs are far less clear than they are in the proposed phonological loop model. However, it is assumed that some form of rehearsal (i.e. keeping information in mind by refreshing or repeating it before it fades) does take place.

Although there are few interpretations of the nature of rehearsal in the visuospatial sketchpad, one exception is the model of Logie (1995). He proposed a passive 'visual cache' that is responsible for the storage of visual information like form and colour, and may be closely linked with activity in the visual perceptual system. Logie (1995) describes a second component, the 'inner scribe', as a more active system designed to hold information about movement sequences and also to carry out rehearsal, which will refresh the contents of the visuospatial sketchpad and reduce time-related decay. The inner scribe may also be responsible for image manipulation and is regarded as being more directly involved in the spatial component of the system.

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Figure 1.6   The visuospatial sketchpad is hypothesised to deal with three
types of information

Overall, the details of the visuospatial sketchpad are not so carefully
worked out as those of the phonological loop. In his more recent writing,
Baddeley (2007) has somewhat extended the role for the visuospatial sketch-
pad, describing it in the following terms:

> The sketchpad is a subsystem that has evolved to provide a way of
> integrating visuospatial information from multiple sources, visual,
> tactile and kinaesthetic, as well as from both episodic and semantic
> long-term memory. (p. 101)

This somewhat more complex system requires further research to distin-
guish it clearly from other components of the working memory model.
Baddeley (2007) points out that there is a surprising lack of research
on VSSTM, probably because memory researchers have focused on ver-
bal materials that are somewhat more tractable in terms of experimental
manipulation.

We will now look at some evidence for splitting the visuospatial sketchpad
into at least two separate subcomponents that deal with information about
visual appearance (colour, shape, pattern) and memory for spatial location
(locations or movements between locations). This evidence concerns adults,
but we will review evidence relevant to typical children in Chapter 4.

Separate visual and spatial components?

One way of examining whether there are separate components dealing
with visual/spatial information is to examine neuropsychological patients
with particular cognitive difficulties arising from brain damage. For exam-
ple, Della Sala, Gray, Baddeley, Allamano, and Wilson (1999), among others,
have found evidence that some patients show specific difficulties with visual
information, whereas other patients show specific difficulties with spatial
information. A second way of looking at the potential separation between
visual and spatial components in the visuospatial sketchpad is to consider
how these components might develop in children. This will be considered in
Chapter 4.

A third way of assessing whether there are separate visual and spatial com-
ponents in the visuospatial sketchpad, is to ask people to remember visual or
spatial information and then try to interfere with their recall. This experimental
procedure involves asking people to remember either visual or spatial informa-
tion, but with the additional handicap of an interference condition in each case.

The interference is carefully designed to be either visual or spatial in nature, so that four experimental conditions are created as follows (see Box 1.4).

Box 1.4   Four relevant conditions in an 'interference' study of visuospatial working memory

1   a visual memory task with visual interference
2   a visual memory task with spatial interference
3   a spatial memory task with spatial interference
4   a spatial memory task with visual interference

---

The predictions are as follows. If there are separate mechanisms for visual and spatial short-term memory, visual interference should affect only visual memory and spatial interference should affect only spatial memory. This prediction is based on the assumption that if there are separate storage areas for visual and spatial information, they will be able to deal with interference of the opposite type of material, but not of the same type of material. Two visual inputs or two spatial inputs (the memory material and the interference), on the other hand, will compete for the same storage capacity and interfere with performance.

This method aims to provide evidence for a 'behavioural double dissociation' between visual and spatial memory. Several studies using this method have been reported in the literature (e.g. Della Sala et al., 1999; Logie & Marchetti, 1991), but we will look at just one to illustrate.

Darling, Della Sala and Logie (2007) employed the four conditions described above by asking adults to look at a display of 30 small boxes on a contrasting background. All were empty except one, which contained the letter 'p', in any one of over 400 different fonts. Some participants were asked to concentrate on the location of this letter (i.e. which box did the letter appear in), which aimed to assess memory for spatial location. By contrast, other participants were asked to concentrate on the appearance of the letter 'p' (i.e. focus on the font), which aimed to assess memory for visual appearance. Figure 1.7 illustrates a similar display, albeit using only 14 boxes instead of 30.

Following the presentation of the original display participants received 'interference' for either five or 15 seconds. This took the form of another display of distracting visual information (flickering black-and-white randomly placed dots) or the requirement to do a distracting spatial task (pressing keys on a 3 x 3 key pad in a figure of eight pattern). A final set of participants had 'no interference' as a control condition. The flickering dots were argued to interfere selectively with visual short-term memory; the spatial task was
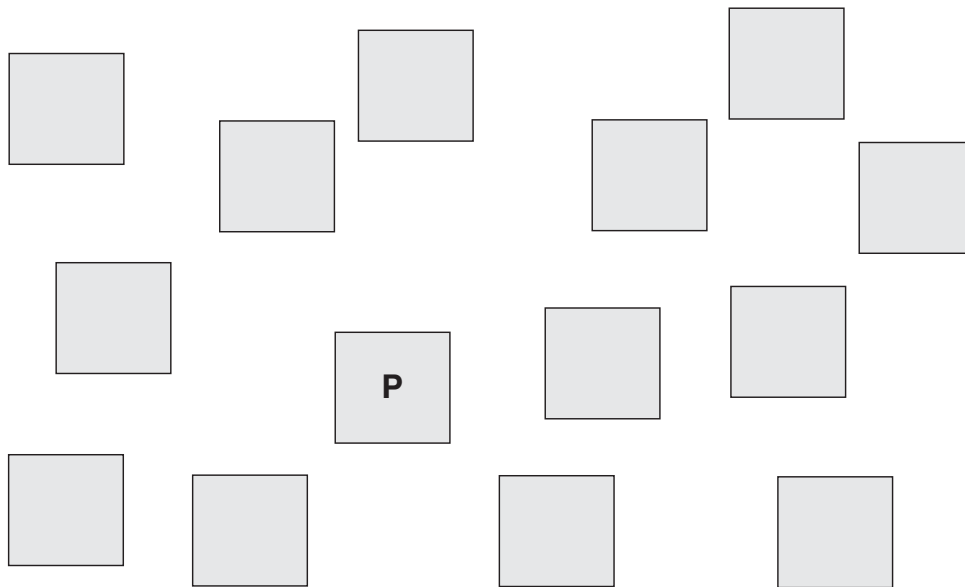
Figure 1.7   Illustration of type of display used by Darling et al. (2007) in their study of location and appearance memory (note that this does not correspond to the actual experimental materials)

argued to interfere selectively with spatial short-term memory. Finally, a 'memory' display containing the 30 squares was presented again, with the letter 'p' in one of the boxes. Participants had to judge whether the letter 'p' was in the same location in the 'location memory' task, or of the same appearance in the 'appearance memory' condition. The features of spatial location and appearance were varied systematically on each trial.

The authors looked at how quickly participants responded: i.e. how fast could they remember location or appearance information? Results were in line with predictions: spatial interference had a stronger negative impact on memory for spatial location; whereas visual interference had a stronger negative impact on memory for the appearance. Figure 1.8 illustrates reaction times after five seconds of 'interference'. Note that long reaction times imply the task was more difficult.

These findings support the proposal that visual and spatial aspects of VSSTM are reliant on separate mechanisms that do not selectively interfere with each other.

One potential criticism of these general findings is that spatial tasks are often sequentially presented (for example remembering a series of spatial locations), whereas visual tasks are often simultaneously presented (for example, looking at one visual image). Some have argued that the apparent separation between visual and spatial short-term memory may simply reflect differences between sequential and simultaneous presentation (Pickering, Gathercole, Hall & Lloyd, 2001).
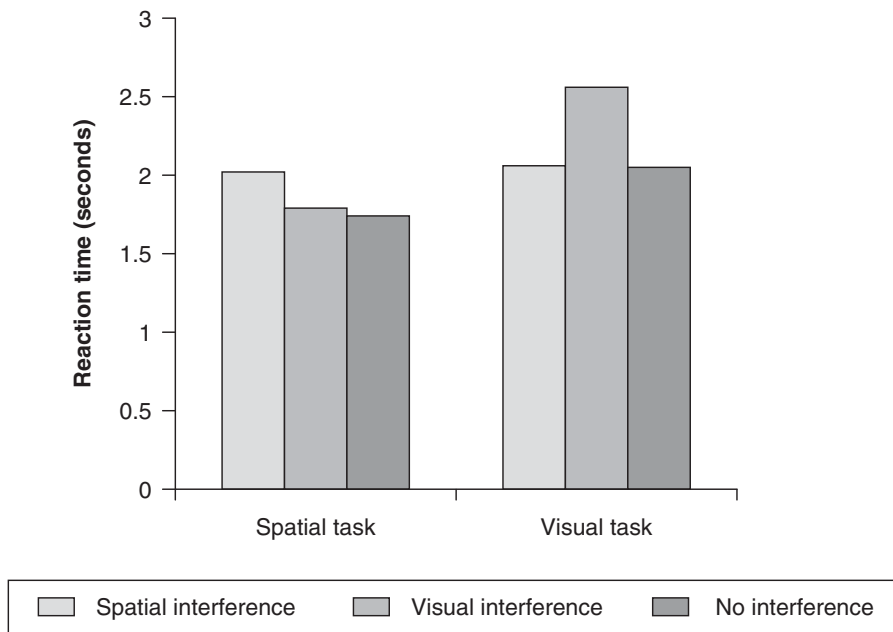
Figure 1.8   Mean adjusted reaction times to illustrate the relative effects of visual interference, spatial interference or no interference on a visual short-term memory task and a spatial short-term memory task

Source: data adapted from Darling et al., 2007

However, some evidence supports the view that the visual/spatial distinction is more important than the sequential/simultaneous distinction. Darling, Della Sala and Logie (2009) used a similar method to the one described above and found that it made no difference whether the visual and spatial information was presented simultaneously or sequentially. In either case, spatial interference had a greater detrimental effect on recalling spatial information and visual interference had a greater effect on recalling visual information. This supported the original distinction between visual and spatial mechanisms.

However, others have argued a 'middle way': that there are distinctions between visual and spatial mechanisms, yet spatial information is further subdivided into sequential spatial information and static spatial information (Mammarella, Pazzaglia & Cornoldi, 2008). This issue has not yet been resolved, but further research on the proposed visuospatial sketchpad of the working memory model will offer more insights in the future.

Increasingly, links are being made between research into visual memory, visual attention and visual working memory, which will no doubt increase the level of theorising in this area. However, the treatment of visuospatial working memory development in children is not always so sophisticated, and usually does no more than compare memory for visual materials with memory

for spatial materials. Accordingly, the research that we discuss in later chapters will generally focus on this somewhat more simplistic level of analysis.

Summary

The visuospatial sketchpad is a specialised 'slave' storage system for holding visual and spatial (and perhaps kinaesthetic) information for short periods of time; hence, it supports visuospatial short-term memory (VSSTM). Information in this store decays rapidly unless rehearsed. Compared to the phonological loop, there is less experimental evidence to flesh out the details of the visuospatial sketchpad, but this is changing rapidly. For example, measures of dynamic (moving) versus static (still) visuospatial recall are now believed to reflect the operation of different submechanisms within the visuospatial sketchpad.

We will now move on to considering the intellectual powerhouse of the working memory model, the central executive.

The central executive

The central executive is the component of working memory that has overall attentional control of the working memory system. It was originally described as: (1) having some capacity for storage; (2) having the possibility of interfacing with long-term memory; and (3) allocating resources between the components of working memory by focusing, dividing and switching attention.

The current view of the central executive has changed somewhat. First, the central executive is now not regarded as having any capacity for storage, rather, it is only responsible for the control and allocation of attention (Baddeley, 2000, 2007). Secondly, the link between the various working memory components and long-term memory is now via a new component known as the 'episodic buffer', which will be discussed more fully in the next section.

Therefore, the core role of the central executive in the revised working memory model is in allocating attention within the working memory system, and this is done via focusing, dividing and switching attention. Baddeley (2007) argues that there may be separate subcomponents for focusing and dividing attention, but he considers the evidence for a separate component for the switching of attention to be limited at present.

When the model of working memory was first presented (Baddeley & Hitch, 1974) little detail was given about the central executive. Baddeley (1986) fleshed out the central executive by adopting the model put forward by Norman and Shallice (1986) of a supervisory attentional system (SAS). The SAS was responsible for intervening to direct behaviour when new thought and planning was required. In other words, this attentional system came into play when it was not possible to rely on well-learned patterns of responding. New ideas, new strategies and new plans to deal with new situations required a more demanding degree of attentional control, and this was provided by the SAS (Shallice, 1990).

Therefore, the central executive provides the higher levels of executive control that are required for carrying out novel tasks requiring new behaviour or new approaches. Box 1.5 provides an example to illustrate how central executive resources may be used in novel situations.

Box 1.5   Using executive resources when things go wrong

Think about driving to work using a well-known route on a day when nothing unusual happens. This probably does not require much in the way of central executive resources to focus, divide or switch attention. The route is familiar, driving is a routine process and nothing untoward occurs during the journey.

However, imagine that, on a particular day, the usual route is blocked because of a burst water pipe. In this circumstance, the central executive must intervene to *inhibit* the well-learned behaviour (i.e. following the familiar route) and work out a new plan that achieves the same goal of reaching the desired destination.

Central executive resources may also be required to change the plan if other upsets occur such as traffic jams, to monitor progress, to check that the goal is being reached, and focus attention on negotiating an unfamiliar route.

Note that satellite navigation systems remove much of the central executive burden from such tasks, which probably accounts for their popularity!

Baddeley (1986) described the SAS as a 'potential framework' for the central executive because the job it does is very similar to his conceptualisation of the role of the central executive. Executive processes are likely to be strongly dependent upon frontal lobe functioning (Kane & Engle, 2002). For example, there is a large body of evidence from patients with frontal lobe damage showing that they often have difficulties with inhibiting well-learned patterns of behaviour and arriving at new ways of solving problems. They become trapped in repetitive cycles of well-learned behaviour (known as 'perseveration') and lack the flexibility to change their behaviour when novel situations arise. Baddeley refers to these general difficulties as the 'dysexecutive syndrome' (e.g. Baddeley & Della Sala, 1996), although those who work in neuropsychological settings might use the term the 'frontal syndrome'.

Therefore, it is increasingly helpful to view the central executive of working memory as a broad attentional control space. This type of system is likely to resemble very closely what many authors mean when they refer to 'executive functions'. If we take a current definition of executive functions, 'processes that control and regulate thought and action' (Friedman, Miyake, Corley, Young, DeFries & Hewitt, 2006: 172), it becomes clear that the concepts of 'central executive' on the one hand, and 'executive functions' on the other, are very similar.

It is beyond the scope of this book to provide a theoretical synthesis and comparison of these two concepts. However, the striking point is the similarity between them both in practical and theoretical terms. Therefore, in order to provide a full and comprehensive account of 'central executive' processing in typical and atypical children, we will consider research on 'executive functioning' rather broadly. In every section on the central executive throughout this book, the research will be discussed in two separate subsections: one dealing with 'executive-loaded working memory' (ELWM); and one dealing with 'other aspects of executive functioning'.

Summary

The central executive component of working memory is responsible for focusing, dividing and switching attention. It provides the overall regulation and control of the working memory system and coordinates activity between all of the components. Defining the types of activities undertaken by the central executive has led us to conclude that the broader concept of 'executive functioning' is very similar to the working memory model's proposals regarding what a central executive might do. Therefore, research evidence concerning both central executive-loaded working memory and executive functioning more generally will be considered in this book.

We will now go on to explore the different areas of skill that can be regarded as requiring 'central executive' resources. In order to do this, it makes most sense to draw on the more general literature pertaining to 'executive functioning'.

Different types of executive functioning

Research in the area of executive functioning has grown rapidly in recent years, both in the adult and developmental literatures. One of the key issues to emerge is the belief that executive functions represent not just a single type of skill, but a number of related skills (e.g. Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000). Therefore, within the broad domain of executive functioning there are, nevertheless, separate abilities that can be distinguished.

A recent twin study has provided support for this viewpoint. Friedman, Miyake, Young, DeFries, Corley and Hewitt (2008) showed that executive functions draw on a common factor that is highly heritable, arguing that this is why different measures of executive functioning are related to each other. These authors also suggested that executive functioning is not simply another ability that can substitute for 'intelligence'. They have provided evidence that executive functions are not uniquely related to measures of intelligence, despite the fact that they are, nevertheless, responsible for much of what we might describe as 'intelligent' behaviour (Friedman et al., 2006).

One of the sub-skills in the executive functioning 'family' of abilities has been identified as 'working memory', but the meaning of this term is rather specific. For example, Swanson (2006) defines working memory as:

a processing resource of limited capacity, involved in the preservation of information while simultaneously processing the same or other information. (p. 61)

There are several other skills believed to belong to the executive functioning family of abilities, and these will all be described in the next section, together with further details about executive-loaded working memory (ELWM). However, an important point to reiterate before we do this relates to what brings together and unifies all executive functioning skills. This is that executive skills, regardless of their exact type, are used to deal with tasks that are novel; tasks that require new solutions outside routine behaviour. As we have already pointed out, this is what the central executive is designed to do, so the concepts of 'executive functioning' and 'central executive' are at the very least highly overlapping, although there are uncertainties about exactly how these concepts interrelate.

In the literature on executive functioning, some authors (e.g. Pennington & Ozonoff, 1996) have suggested that executive functioning can be divided into five or six discrete sub-skills. This division is often referred to as the 'fractionation' of executive functioning. Box 1.6 describes the main areas of executive functioning identified in the literature.

Box 1.6   Different sub-areas of executive functioning

1   *Planning/problem-solving*: this type of skill refers to the preparation of future actions to achieve goals and the generation of solutions for difficulties.

2   *Set shifting/switching*: this refers to the ability to change responses/strategies when necessary, or after feedback indicates that the original plan is not working.

3   *Fluency*: this refers to the ability to quickly and efficiently search for and generate new information (sometimes called generativity).

4   *Inhibition*: often it is as important to *stop* doing certain irrelevant actions that get in the way of achieving goals as it is to execute relevant actions.

5   *Working memory*: in the executive functioning literature, this refers to the ability to keep in mind goals, current performance and future actions.

6   *Self-monitoring:* the ability to check on progress towards goals.

Other authors have suggested that there is good evidence for three sub-skills of executive functioning: inhibition, working memory and set shifting. There is a reasonable amount of evidence in children and adults for the existence of these factors (Anderson, 2002; Fisk & Sharp, 2004; Garon, Bryson & Smith, 2008; Huizinga, Dolan & van der Molen, 2006; Lehto, Juujärvi, Kooistra &

Lulkkinen, 2003; Miyake et al., 2000; van der Sluis, de Jong & van der Leij, 2007). However, not all of the evidence is entirely consistent, particularly for children, and this issue will be returned to in Chapter 4. Another point to emphasise is that several of the aforementioned studies did not look for more than three factors, so this figure may be arbitrary.

Another key point that has emerged from the literature is that, whilst we can divide executive functioning into a number of distinct sub-skills, these skills are still loosely related to each other. Again, the evidence is not entirely consistent, but there is reasonable consensus that the sub-skills of executive functioning measure broadly the same types of abilities in relation to the control and regulation of behaviour during complex, novel tasks (Miyake et al., 2000). This evidence will be considered in more detail in Chapter 4.

In this book, we will look at a wide range of tasks that have been used to assess executive skills to keep our discussion as inclusive as possible. These areas include executive-loaded working memory, inhibition, set shifting, planning, fluency, dual-task performance and random generation. Some of these tasks have traditionally been used to study executive skills within the working memory domain, whereas others have been regarded as measuring executive functioning more broadly. This comprehensive approach has been taken to try to gain a greater understanding of executive control in typical and atypical development. However, please bear in mind that there are still uncertainties with respect to the relationships between the central executive and executive functioning in its widest sense. There is also the issue of exactly how these systems might be limited in terms of capacity, although it is clear that such capacity limitations do exist (e.g. Swanson, 2006).

In the next sections brief overviews will be given of each sub-skill of executive functioning discussed in this book. Please refer to Chapter 2 for details on how they can be measured in typical and atypical populations of children.

Executive-loaded working memory

This aspect of executive functioning captures our ability to manipulate and store information at the same time. A good way of understanding executive-loaded working memory (ELWM) is to think about situations in which you must process some information (perhaps adding two numbers together) and then store the results of that processing while you move on to something else (perhaps performing another mathematical calculation). Sometime later, you are asked to remember the results of your various processing tasks. This is a bit like memory 'plus' in that you must keep in mind ever increasing amounts of information, whilst carrying out other tasks. Mental arithmetic is a good example of a task that requires ELWM resources.

We will look at exactly how ELWM is measured in the next chapter. However, it is worth briefly describing the historical background for one of the more important working memory tasks in the literature known as 'reading span'. In a now classic study, Daneman and Carpenter (1980) asked participants to read a sentence, make a judgement about the sentence, and then recall the final word from the sentence. This, of course, is trivial with only one sentence, but becomes increasingly difficult as the number of sentences is increased. Daneman and Carpenter (1980) noted that performance on this reading span task was more strongly related to reading aptitude than performance on simple word span tasks.

There followed, in subsequent years, an enormous degree of interest in this task, which saw it being developed in many different ways. Tasks of this nature are often described as 'complex span' tasks and all have the same basic requirements, although they can be designed to incorporate different skills or domains of processing. There is a remembering component, as well as a processing component. These two requirements, storage plus processing (at the same time), place a load on executive resources. In terms of the working memory model, one of the slave subsystems may be used to store interim information, i.e. the phonological loop in a verbal ELWM task (for evidence that the phonological loop is implicated in verbal ELWM tasks, see Lobley, Baddeley & Gathercole, 2005) or the visuospatial sketchpad in a visuospatial ELWM task. However, it is also necessary for this information to be continually updated, and for real-time processing to be carried out on new information being presented.

Hence, complex span tasks require a combination of updating, processing and overall monitoring, which all necessitate input from the central executive. This is why complex span measures are regarded as assessing ELWM, and, more broadly, executive functioning.

However, a set of related tasks, collectively known as 'updating' measures, are also described by many authors as assessing ELWM resources. The Debates and Issues box below considers whether there is evidence that updating and complex memory tasks are closely related or not.

Debates and Issues 1.1   Complex memory and updating tasks – do they measure the same underlying construct?

St Clair-Thompson and Gathercole (2006) assessed whether measures of complex memory span and updating were, in fact, assessing closely related constructs. This is an important issue, because if they are, we are justified in thinking about both of these types of tasks as measures of executive-loaded working memory (ELWM). Much of

the literature is rather vague on this issue, making assumptions that many different types of tasks assess 'working memory'.

Around 60 11-year-old children were given four complex memory tasks (listening, backwards digit, odd one out and spatial span) and two updating tasks (letter memory, keep track task). They were also assessed on two measures of inhibition (refer to Chapter 2 for further details on these tasks).

St Clair-Thompson and Gathercole (2006) used 'principal components analysis' to see which of these eight tasks would cluster together. Tasks that clustered together on the same 'component' were likely to be measuring similar abilities.

In fact, the complex span and updating tasks all loaded together on the same component (i.e. clustered together), giving reassuring evidence that these two types of measures were assessing the same underlying construct of ELWM.

Set shifting/switching

There are several names for this ability in the literature and they include switching, mental flexibility and set shifting. These terms all describe the following skill: how readily can a person switch from one strategy or behaviour to another, when they receive feedback that their original strategy has not been successful in achieving their goals? In other words, the executive skill of switching captures the ability to adapt behaviour to changing task situations, and to do so quickly and flexibly (Davidson, Amso, Anderson & Diamond, 2006).

In order to switch strategies, a person must be able to monitor how successful they are being in achieving their goals. This monitoring function is assumed to be carried out by the central executive. Once feedback is received that the current strategy is not successful, a new strategy must be generated. Finally, the current strategy must be inhibited and the new strategy adopted. Therefore, mental flexibility is required in order to switch from one strategy to another, in a timely manner, in response to feedback. The central executive carries out this switching; in fact, one of its three key features is the 'switching' of attention.

Many patients with frontal lobe damage find this type task very difficult, preferring to carry on with their original strategy. This inflexibility is often described in the literature as 'perseveration'.

Planning/problem-solving

Planning and problem-solving refer to the ability to generate solutions to overcome difficulties in achieving goals, and to plan how these solutions might be carried out. Planning and problem-solving are at the heart of successful goal-directed behaviour, particularly when achieving goals is not straightforward, or there is no well-known method of proceeding. In some

instances, it might be necessary to do one thing before another in order to reach a target goal; in these circumstances, planning ahead is clearly an advantage.

As we stressed earlier, executive skills are not essential for routine tasks, for which we have established ways of proceeding. The central executive is required for generating potential solutions for more unusual or novel tasks. As we will see in the next chapter, measures of executive functioning must contain an element of novelty. The central executive is required for planning and problem-solving precisely because there are no automatic methods of dealing with novel situations.

Inhibition

Inhibition refers to the ability to ignore information or strategies that are not relevant to the current task goals. Davidson et al. (2006) describe mature levels of inhibition in the following terms; they allow a person:

> to act on the basis of choice rather than impulse, exercising self-control (or self-regulation) by resisting inappropriate behaviours and responding appropriately. (p. 2037)

For inhibition to require executive resources, most authors believe that the irrelevant information/strategies must be very salient. In other words, the person may be drawn strongly to particular information (which may be automatically processed) or towards strategies that represent the typical way of responding. For example, you may be familiar with the yes/no game. A person asks you a series of questions and you must answer them without using the words 'yes' or 'no'. This is a good example of executive inhibition, because the central executive must intervene constantly to inhibit the powerful tendency to respond with 'yes' or 'no'. It requires continual monitoring of every response and intervention to change behaviour where relevant. Interventions of this kind are believed to be controlled and executed by the central executive.

Fluency

Fluency describes the ability to generate new instances of a particular class of information. For example, generating as many different types of 'animals' as possible, as many different uses for a 'brick' as possible, or drawing as many different 'sketches' as possible within a certain time period (often one minute). Executive control is required in tasks such as these to facilitate search processes through long-term memory, to use strategies for accessing the relevant information, and to monitor the output to avoid repetition. A degree of inhibition may also be required in order to inhibit responses that have already been given.

These comments illustrate clearly that many of the sub-skills of executive functioning we have just described are not entirely distinct from each other.

Although these five areas are often regarded as separate executive skills, there is, nevertheless, overlap between them. In fact, it is acknowledged that executive skills have some areas of overlap and other areas of distinctiveness. Therefore, we would expect to find relationships between different sub-skills of executive functioning, yet we should also expect that each sub-skill broadly measures a somewhat distinct ability (Miyake et al., 2000).

In this book, we will make an assumption that it is possible to measure different areas of executive functioning using tasks that are largely measures of the skill in question (further details in Chapter 2). However, it must be stressed that few measures of executive functioning are totally pure, although many authors have attempted to draw distinctions between 'pure' measures, which are less likely to require a range of skills, and 'complex' measures, which are acknowledged to draw on more than one type of executive resource (e.g. Miyake et al., 2000).

Dual task performance

Dual tasks are relatively rare in the literature on child development but are sometimes used. This is an approach that has developed out of the working memory literature and was designed to test theoretical predictions of the working memory model. Dual task performance involves asking a participant to do two things at once, and looking at the 'cost' to performance of combining the two tests together. For example, a participant may be asked to hold a list of digits in mind by reciting it over and over again, whilst at the same time judging whether two words rhyme.

The role of the central executive in dual task performance is to coordinate performance on both tasks and allocate appropriate amounts of attention when and where required. Often, the instructions for dual task performance require participants to focus more on successfully carrying out one task (primary task) than the other (secondary task), and executive control can be used to allocate more attention to the 'primary' task. On the whole, the participant must decide to focus attention on one task at the expense of the other or switch attention between tasks. These higher-level decision processes relevant to the overall conduct of the task are believed to be carried out by the central executive.

Random generation

This task was also developed as a theoretically effective way of assessing the types of skills believed to be carried out by the central executive. The participant is asked to generate sequences of numbers or letters, but they are instructed to ensure that the sequences are in a random order. In other words they must avoid non-random sequences such as '123', '999', 'MSN' or 'SOS'. This task is often used as a central executive-loaded secondary task, as it would be expected to interfere with the attentional control of complex tasks where executive input is necessary. Again, it is rarely used in the developmental literature on executive functioning.

Final comments

One difficulty with the concept of the 'central executive' is that many of the tasks developed to assess executive processes reflect them rather than directly measure them (see next chapter for examples). We can infer that central executive resources are required in order to carry out the task, but one cannot measuring central executive processing on its own with no other working memory (or other cognitive) components involved. This is almost inevitable, because the central executive allocates attention between all of the relevant components of the working memory system, and complex tasks are almost bound to involve more than one component of working memory.

This is why it is often useful to describe executive tasks as 'central executive-loaded' or 'executive-loaded'. The reading span task described earlier offers a particularly clear example of how the various components of working memory interact. The storage of the final words from each sentence and the processes involved in reading the sentence will most likely involve the phonological loop and possibly the visuospatial sketchpad (e.g. Baddeley & Logie, 1999), but this will be in combination with the central executive, which is responsible for the allocation of attention to the processing and storage components of these tasks.

A second difficulty with the concept of a central executive is that in Baddeley's most recent work he describes complex working memory span tasks as reflecting the episodic buffer and its interface with the central executive. This is a somewhat new way of looking at these tasks and will require further study and theorising to flesh out the full implications. Whether the episodic buffer is involved in other executive-loaded tasks is currently unclear, but it would seem a reasonable guess to expect that it would be heavily involved in tasks such as fluency, where searching lexical long-term memory is explicitly required, and in random generation, to help identify non-random series of numbers and letters.

Summary

The central executive is the key component of the multi-component working memory model (Baddeley, 2000, 2007; Baddeley & Hitch, 1974). It controls the allocation of resources within the working memory system by focusing, dividing and switching attention as necessary. The central executive has no storage capacity; the other components of the model store information. Although this component of working memory was historically little understood (e.g. Baddeley, 1986), the wider literature on executive functioning is adding to our understanding of the types of functions that may be carried out by the central executive. There is a growing consensus that executive skills are 'fractionated' into several areas that are nevertheless linked together. In this book a broad perspective on executive functioning will be taken in order to provide a more comprehensive overview of the area.

The episodic buffer

The episodic buffer is the most recent addition to the working memory model and represents the greatest change to the original model (Baddeley, 2000). The episodic buffer is an entirely new component, described as a 'multimodal' temporary store. This means that it does not just store information in one modality (e.g. auditory or visual or spatial or kinaesthetic), but deals with information from many different modalities. This makes it unlike the phonological loop or the visuospatial sketchpad, which are both specialised to hold particular types of information and nothing else.

The other main characteristic of the episodic buffer is that it 'binds' together information from different sources within the working memory system. For example, information about a scene may comprise visual information, speech sounds and movement. It is the episodic buffer that is hypothesised to join this information together into a coherent memory episode. Binding may be relatively automatic for visuospatial information and coherent language inputs such as prose, but more active, resource-demanding binding requiring additional executive resources cannot be ruled out (Baddeley, 2007).

The capacity of the episodic buffer is not clearly specified, but is believed to be limited and to reflect the number of chunks or episodes of information that can be maintained simultaneously. Presumably, the more the information can be bound together in a coherent fashion, the greater the capacity of the episodic buffer. The idea of a chunk is not precise, but probably reflects a single unit of information. See Box 1.7 for an example of chunking.

The notion of a capacity limitation in terms of chunks may be similar to the conceptualisation put forward by Cowan (2005) in his alternative model of working memory. He argues convincingly that adults are able to cope with only three to five chunks of information in our 'focus' of attention, regardless of how these chunks are measured.

Box 1.7 Chunking

A single numeral could reflect one chunk of information. For example, 5.

However, in many cases, several numerals grouped together in a meaningful manner can also reflect one chunk. For example, 911, or the area code for a local telephone number.

Whenever discrete pieces of information (whatever they are) can be *grouped together* into a meaningful 'bundle', this is called chunking. Cowan (2005) argues that human memory never really exceeds four chunks of information.

For example, the following digits can be chunked together to make the series more memorable. Can you make these 14 digits fit into *four* chunks?

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

Baddeley (2007) describes the episodic buffer as:

> ...a temporary storage system that is able to combine information from the loop, the sketchpad, long-term memory, or indeed from perceptual input, into a coherent episode. (p. 148)

Thus, the episodic buffer integrates information from a variety of sources into a meaningful unit or 'episode'. However, it also acts as a link between the central executive and long-term memory so that we can access and utilise our stored knowledge during ongoing memory and processing tasks. This explicit link to long-term memory is one of the key theoretical advances associated with the episodic buffer, as this was missing from the original working memory model.

In the episodic buffer, information is represented in a single 'multidimensional' code. This makes it a flexible interface for integrating information deriving from different sources and in different formats. Central executive resources may be required to control attention while retrieving long-term memory knowledge and/or binding together information from slave storage systems when these processes are effortful and attention-demanding (Allen, Baddeley & Hitch, 2006). Conversely, some binding and long-term memory activation may be relatively automatic.

More dramatically, the episodic buffer is potentially what gives us our experience of consciousness. To experience consciousness we must be able to keep track of our current experience, but also be able to reflect on this experience in real-time. Baddeley (2007) points out that the 'keeping track' and the 'reflecting' could be regarded as storage and processing respectively, something that the working memory system as a whole is specialised to do. Figure 1.2 (earlier in this chapter) shows how the episodic buffer is integrated into the working memory system and how various long-term memory storage systems (visual semantics, episodic long-term memory, language) are linked together and to other components of working memory.

What does the episodic buffer offer? Baddeley (2007) notes that the episodic buffer can act as a 'backup store' to supplement the phonological loop or the visuospatial sketchpad, as well as providing a link to long-term memory. For example, the recall of sentences and paragraphs is considerably better than would be expected on the basis of how many unrelated words can be recalled. We might be able to recall only five or six unrelated words at a time, whereas most adults could recall many more words if they were part of a sentence. Performance might be even better in terms of numbers of words recalled if we were asked to remember an entire paragraph. The episodic buffer, therefore, does two things: (1) it provides extra storage capacity; and (2) it accesses long-term knowledge about language, grammar and the structure of sentences to bolster phonological short-term memory in the phonological loop.

Several research studies support the notion of an episodic buffer, which provides such access to long-term memory knowledge. To take one example, Hulme, Maughan and Brown (1991) found that remembering lists of non-words was much more difficult than remembering lists of familiar words.

They went on to show that if participants learnt the 'meanings' of nonwords (in this case, Italian words), memory for them improved. These results illustrated the role of 'semantic' information, i.e. knowledge of the meanings of the words, on short-term recall. The mechanism through which this information can improve recall is hypothesised to be the episodic buffer (see Chapter 3 for further discussion of this, and related, research).

The episodic buffer also deals with a number of other problems that arose from confining short-term memory storage to just the phonological store and the visuospatial sketchpad (see Baddeley, 2000). For example, why did articulatory suppression not reduce memory for lists of words as much as would be expected, given that it 'knocks out' access to the phonological store and prevents verbal rehearsal? How is it that we can integrate visual and verbal information into a coherent whole, without even thinking about it? The answers to these questions can be provided by the inclusion of an episodic buffer in the working memory model. It provides extra storage capacity; and binds together information from different slave storage systems.

The full set of roles performed by the episodic buffer can, therefore, be summarised as follows in Box 1.8.

Box 1.8   Summary of the roles performed by the episodic buffer

1   Allows long-term memory knowledge to be utilised in the working memory system
2   Offers an extra storage mechanism to back up other storage areas
3   Blends together or 'binds' information from different sources/modalities into a coherent memory experience

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The interrelationships between all of the components of working memory continue to be refined and specialised. The debate summarised in the box below illustrates that there may be other roles carried out by the episodic buffer, as yet to be determined by future research.

Debates and Issues 1.2   Item and order information

According to the working memory model, remembering *item* information (which items were in a list) and *order* information (which order these items were in) is carried out

(Continued)

by the slave systems of working memory (the phonological loop and visuospatial sketchpad). This means that memory for serial order is *modality specific*; in other words, there are separate mechanisms for remembering the order of verbal information (the phonological loop) and visuospatial information (the visuospatial sketchpad).

However, this is an area of considerable debate, and the working memory view has recently been challenged by Depoorter and Vandierendonck (2009). These authors found evidence that *verbal* serial order memory tasks interfered with *visuospatial* serial order memory tasks and vice versa. This is not predicted by the working memory model, as these two tasks should be carried out by separate slave systems, so should not interfere with each other. Depoorter and Vandierendonck (2009) suggested that memory for serial order is not *modality specific* as previously thought, but carried out by a modality *independent* system.

Interestingly, Depoorter and Vandierendonck (2009) argued that the episodic buffer may be 'the ideal medium to maintain a modality-independent order code'. Therefore, research continues to reveal new ways in which the episodic buffer may contribute to the working memory system.

Summary

The episodic buffer is the newest component of the multi-component working memory model, having been added relatively recently (Baddeley, 2000, 2007). It binds together information from different sources and integrates new material with information we already know (in long-term memory) so that our experiences and memories are unified and coherent. The episodic buffer has a small storage capacity, which does not depend upon the type of input (i.e. it is not visual, spatial or phonological in nature, but 'multi-modal').

Overall summary

The working memory model was developed to account for how we temporarily manipulate and store information during thinking and reasoning tasks in everyday life. It consists of four components: the *phonological loop*, specialised for holding speech material for short periods of time; the *visuospatial sketchpad*, specialised for holding visual, spatial and, possibly, kinaesthetic information for short periods of time; the *central executive*, responsible for the overall control of the working memory system via focusing, dividing and switching attention in a flexible manner; and the *episodic buffer*, responsible for binding or integrating information from the other components together into a coherent whole. This final component also helps us to make sense of conscious experience by allowing long-term knowledge to be used in tandem with current experience.

The working memory model has had an enormous impact on the field of cognitive psychology over the past four decades and has shaped a great deal of research on memory development in children with typical and atypical development. This chapter has given an overview of the main features of the model, to help provide a foundation for understanding the remainder of this book. It is important to emphasise that this is not the only model of memory, but because it has been so influential across the UK, North America and Europe, we are using it as a unified basis for understanding memory development in both typical and atypical populations of children.

Before we move on to considering the development of working memory in children with typical and atypical development, Chapter 2 first describes how all of the components of the working memory system are measured. In this book, there is a strong focus on methodology in the treatment of experimental evidence. A sound understanding of the tasks that are used to assess working memory in children is the foundation for understanding experimental methods. One of the goals of this book is to encourage a critical and evaluative approach to research evidence, vital for understanding the field as a whole, drawing reliable conclusions and writing good essays.

Further reading

Working memory model

Baddeley, A.D. (1986). *Working memory*. Oxford: Oxford University Press. Still very useful on the original model of working memory.

Baddeley, A.D. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences, 4*, 417–423. An excellent outline of the original working memory model and introduces the new episodic buffer component.

Baddeley, A. (2007). *Working memory, thought, and action*. Oxford: Oxford University Press. The most recent book on the working memory model, but fairly demanding.

Experimental papers on the phonological loop

Baddeley, A.D., Gathercole, S.E. & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*, 158–173. What is the phonological loop for?

Baddeley, A.D., Lewis, V. & Vallar, G. (1984). Exploring the articulatory loop. *Quarterly Journal of Experimental Psychology, 36A*, 233–252. Another classic experimental paper.

Baddeley, A.D., Thomson, N. & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behaviour, 14*, 575–589. Experiments on the word length effect. A classic paper.

Experimental papers on the visuospatial sketchpad

Darling, S., Della Sala, S. & Logie, R.H. (2007). Behavioural evidence for separating components within visuo-spatial working memory. *Cognitive Processes, 8*, 175–181. A clear introduction and a great experimental technique to separate visual and spatial working memory.

Papers relevant to executive functioning more generally

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A. & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex 'frontal lobe' tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100. Already a classic paper on executive functioning, but fairly demanding.

Pennington, B.F. & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry, 37*(1), 51–87. A more accessible outline of executive functioning in the context of four developmental disorders.

Papers relevant to the episodic buffer

Allen, R.J., Baddeley, A.D. & Hitch, G.J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General, 135*, 298–313. Suggests that binding visual features is relatively automatic.

Hulme, C., Maughan, S. & Brown, G.D.A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language, 30*, 685–701. Demonstrates the impact of long-term memory on short-term memory processes.

Potential exam questions

1   Critically discuss each of the four components of Baddeley's revised working memory model, using experimental evidence where relevant to support your arguments.

2   Compare and contrast the original and revised working memory models. What significant advantages does the revised model offer?