CHAPTER 1

An introduction to working memory

Overview

This chapter provides an introduction to working memory, with illustrations of how it is used in everyday life. It describes the limits of working memory, the causes of loss of information from working memory, and how the components of working memory function. Differences between working memory and other kinds of memory are discussed, and the characteristics of different kinds of long-term memory are outlined.

Introduction

When asked recently to describe what working memory is, a group of teachers working with young children made the following comments.

> 'No idea. Never heard of it.'
> 'I don't know, but I have a terrible memory. I can never remember children's names, telephone numbers or other pieces of information.'
> 'Is it similar to short-term and long-term memory?'

You may be similarly uncertain about what working memory is, and what impact it has on how children function in the classroom. The purpose of this chapter is to answer some of the questions that are often asked about working memory, and to explain how it works. By

the end of this chapter, you should be familiar with what working memory is and have a reasonable understanding of its everyday uses. You will also learn how working memory differs from other kinds of memory that retain information for much longer periods of time – hours, days, years and, in some cases, decades. Working memory, in contrast, is useful only for remembering a small amount of information for a matter or seconds, or minutes at most.

What is working memory?

'Working memory' is the term used by psychologists to refer to the ability we have to hold and manipulate information in the mind over short periods of time. It provides a mental workspace or jotting pad that is used to store important information in the course of our everyday lives.

One example of an activity that uses working memory is mental arithmetic. Imagine, for example, that you are attempting to multiply together the numbers *43* and *67* in a situation where you are unable to use either a calculator or a pen and paper. To do this, you would first need to store the two numbers in working memory. The next step would be to use the multiplication rules you have already learned to calculate the products of successive pairs of numbers, adding to working memory the products as you go. Finally, you would need to add together the products held in working memory, arriving at a final solution.

This process imposes quite considerable burdens of working memory: several number combinations need to be kept in working memory for the amount of time it takes to make these calculations, and the contents of working memory have to be updated to include our number calculations as we proceed through the stages of the calculation. Without working memory, it would not be possible to carry out this kind of complex mental activity without having some means to make an external record of the numbers and the calculations.

We usually experience mental activities that place significant demands on working memory as a kind of mental juggling in which we try to keep all elements of the task – in the case of mental arith-

metic, the original numbers we are trying to multiply as well as the calculations we make as we proceed – going at the same time. Often, the juggling attempt will fail, either because the capacity of working memory is exceeded, or because we become distracted and our attention is diverted away from the task in hand. A minor distraction such as an unrelated thought springing to mind or an interruption by someone else is likely to result in complete loss of the stored information, and so in a failed calculation attempt. As no amount of effort will allow us to remember again the lost information, the only course of action is to start the calculation afresh.

Here are some more examples of everyday activities that depend on working memory.

- Following directions such as 'When you pass the church on the left, turn immediately right and then take the second left.'
- Hearing an unfamiliar word in a foreign language and attempting to repeat it several seconds later.
- Adding up and remembering the total amount spent as you select items from shelves at the supermarket and add them to your basket.
- Remembering to measure and combine the correct amounts of ingredients ('rub in 50g of margarine and 100g of flour, then add 75g of sugar'), when you have just read a recipe that is no longer in view.

Is there a limit to what working memory can hold?

Yes, the amount of information that can be held in working memory for even a short period of time is strictly limited, and if this limit is exceeded we will forget at least some of what we are trying to remember. For example, multiplying larger numbers such as 542 and 891 'in our heads' is for most of us out of the question, even though it does not require greater mathematical knowledge than calculating the product of a pair of two-digit numbers. The reason we cannot do this is simply because it would require the storage of more information than the limited capacity of working memory can hold.

It is often said that the average adult cannot hold more than six or

seven units of information in working memory. This is the upper limit, and for some kinds of information such as meaningless patterns the amount we can store in working memory is much less. You will notice that the capacity of working memory is described here in terms of units of information: so, what exactly is a unit? The answer depends whether or not the material to be remembered is not organised in a meaningful way, such as if a unit is an individual part of a larger amount of information – for example, a single digit in a sequence of digits that comprises a telephone or a PIN number compared with a single item in a shopping list. However, if the individual elements can be grouped together in a chunk, then this chunk becomes a unit. For example, it is difficult to remember nine letters that do not form a spelling pattern such as *JDIWMXLPQ,* but if we are able to group a sequence of letters of the same length into meaningful units such as *BBC-IBM-USA,* then remembering nine letters is not much of a problem. Similarly, most adults can just about remember a list of about six words such as *hat, walk, roof, duck, tree,* and *banana* that are not related to one another in meaning. If, however, the sequence of words forms a meaningful sentence such as *When the man walked down the street he saw a red fox crossing the road* which consists of more than twice as many words, it is quite easy to remember. In this case, memory for the sentence can be supported not only by working memory, but also by our memory for the meaning of the sentence. Combining these two sources of memory – working memory, and memory for meaning – boosts memory performance quite dramatically.

Another factor that influences how well a particular piece of information is remembered is where it is situated within a larger sequence of material. Consider attempting to remember a list of words such as *hat, walk, roof, duck, tree, banana, car* and *sun*, in this order. Because the list contains eight words (that is, eight units because the material cannot easily be chunked), it is likely to exceed the working memory capacity of most people, resulting in errors. Interestingly, it is quite predictable where the errors are likely to occur: we are most likely to forget items from the middle of the list. Recall of the items at the very beginning of lists is relatively good because we have had more opportunity to rehearse these, and rehearsal boosts recall. This advantage to

items at the beginning of a list is known as the primacy effect. Recall is also very accurate for the final items in a sequence, and this is known as the recency effect. It occurs mainly because we do not have to hold the material in working memory for as long. Recall of the final item in a list is particularly accurate if it has been spoken rather than just read – it sometimes seems as though you can hear an echo of the most recent word that has been uttered, and this lingers on for some time. As a result, it can be useful to say something aloud rather than reading it silently if you want to recall it a brief time later.

The particular sound patterns of the words that we are trying to remember can also have an impact on the accuracy with which they are held in working memory. Sequences of words that are distinct such as *bus, clock, spoon, fish* and *mouse* are much easier to remember than a list of words that sound very similar such as *man, cat, map, mat, can* and *cap*, because we are much less likely to confuse their sounds in working memory.

How much information can be stored in working memory is also affected by background noise. The contents of working memory are best preserved in silence, and are strongly disrupted by hearing speech that is unrelated – this might consist of a conversation by other people in the same room, or may come from the television or radio. It is almost impossible to prevent this kind of material from disrupting the contents of working memory, leading to greater rates of forgetting than in quiet conditions. Constant background noise that does not involve language, such as the hum of a vacuum cleaner or the sound of a lawn mower, has little discernible effect. You may, however, be startled when a noise starts, and this could distract you from attending to the contents of working memory which may then cause accelerated loss of information.

Most of us employ strategies to prolong the period over which information is stored in working memory, even if we are not consciously aware of doing so. One common strategy is to rehearse the contents of working memory; often, this takes the form of repeatedly saying 'in our heads' the material to be remembered, until the point at which the information can be used. So, if we are told a new telephone number that we want to dial when we go to the next

room to find the phone, it is likely that we will repeat the sequence either silently, in a whisper or out loud, to keep it in mind. One factor that influences the effectiveness of rehearsal of maintaining the contents of working memory is the length of the material being rehearsed. Words that take longer to pronounce, such as *refrigerator*, *hippopotamus*, *Mississippi*, and *aluminium*, take longer to rehearse and so are less easily maintained than short words such as *bus*, *clock*, *spoon*, and *fish*.

Being aware of your memory strengths and limitations can enable you to deploy compensatory strategies very effectively. When one of the authors was discussing rehearsal recently with a group of teachers, a member of the audience described how both she and her husband had evolved a strategy of sharing their working memory resources when necessary. When they were given lengthy telephone numbers to remember, they would try to remember half of the sequence each, and so to combine their working memory capacities. They also were aware that although rehearsing their part of the sequence helped, hearing the other person rehearse aloud was very disruptive, and this led to them establishing a 'silent rehearsal only' agreement that would minimise mutual interference and distraction. By being aware of their own personal limits in this way, this couple were able to overcome their individual working memory capacities.

Although rehearsal can be extremely useful in these situations, there are other kinds of mental activities that involve working memory for which it is much less appropriate. Mental arithmetic is a good example of this. It involves retrieving our knowledge of number rules and applying this knowledge as well as storing the numbers to be operated on and any interim numbers already generated, and rehearsing the numbers has the unfortunate consequence of disturbing the mental activity of making the calculations. Rehearsal is therefore a strategy that is most effective when the current activity involves only storage, as in the case of remembering a new telephone number. When it is necessary to engage in other demanding mental activities as well as storing information in working memory, rehearsal is much less useful.

Other strategies that people develop across time to cope with the limits to working memory are often idiosyncratic, and play to their

individual mental strengths. For example, some people have extremely good abilities to generate mental images of information and of remembering these for quite long periods of time. Instead of writing down a shopping list, these individuals may imagine and remember a route through their local supermarket in which they stop at particular locations in the aisles at which they can retrieve each item. This uses long-term memory, so that they will be able to recollect the route several hours later when they arrive in the supermarket, rather than short-term memory. Other people have from an early age remarkable abilities to remember information such as numbers in terms of colours or other sensations that they strongly associate them with (an ability known as synaesthesia), and this for them provides a highly effective way of remembering. However, most of us cannot do this.

Sometimes we hear of individuals who have exceptional abilities to remember huge amounts of meaningless information, and may indeed have made a career on this basis. For example, cases have been reported of people who can remember sequences of more than 100 numbers in their original sequence. Do they have working memory capacities that are ten times or more greater than our own? Rather surprisingly, it appears not. What distinguishes such individuals from the rest of us is that they have developed and practised highly systematic and elaborate strategies that support their memory without relying on the rather limited working memory system. For example, one mnemonist was also an accomplished athlete, and would remember runs of numbers within the larger sequence in terms of the fastest times for races of various distances over famous routes. This is a good example of the use of chunking, described in an earlier section, as a way of decreasing working memory load and exploiting knowledge that has already been learned and organised into chunks. In situations in which their highly developed strategies are not appropriate, mnemonists typically show evidence of good but by no means exceptional working memory capacities. It is therefore clear that their undoubted memory strengths come from the strategies they have developed that exploit existing knowledge, reducing the dependence on working memory.

Does working memory capacity vary between people?

Yes, there is a personal limit to working memory, with each individual having a relatively fixed capacity that may be greater or lesser than that of others. This capacity is largely consistent over different occasions, although the other factors affecting working memory that were discussed in the section above will influence memory accuracy in particular occasions. Because of the substantial variation in working memory capacity found between individuals, it is necessary when interacting with others to bear in mind that their working memory capacities may not be the same as ours, and for this reason we may have to modify how we pass on information to them – how much information, and at what rate. As we will see later in the book, this is an important consideration for an adult working with young children, as their working memories are even more limited in capacity than those of older children and adults.

What causes information to be lost from working memory?

Because working memory capacity is limited, it can easily fail us. Typically, information in working memory is lost very quickly, within a few seconds. The contents can be lost either because our attention is distracted from it so that it fades very rapidly, or it is displaced by other information. The loss of information from working memory can to some extent be prevented by maintaining attention on it, an experience that literally feels like holding something in mind. Here are some of the situations that lead to the loss of the contents of working memory.

- *Distraction*. An unrelated thought springing to mind, an interruption by someone else, or another distraction within the environment such as a telephone ringing or a child crying is often sufficient to cause information to be lost from working memory. This is because unless we continue to attend to the contents of working memory, the stored information decays very rapidly and is soon lost

for good. It is therefore very important to minimise likely distractions if we are going to make effective use of working memory.

- *Doing something else at the same time.* Activities that require attention to be switched to another effortful activity are disruptive because they divert attention from the information being stored in working memory, leading to accelerated loss of information. These attention-demanding processes may be an intrinsic part of our ongoing activity, as in the case of using our stored mathematical knowledge when engaged in mental arithmetic. In these situations, the diversion of attention from the stored contents of working memory (the digits, and the calculations made so far) is inevitable. However, it is beneficial to switch attention from the processing (mental calculation) to the items being stored as rapidly and frequently as possible, as engaging in lengthy processing without mentally re-checking the contents of working memory will lead to rapid decay.

What happens to information when it is lost from working memory?

Once information has been lost from working memory, it cannot be recovered. In this situation, the only option is to start again the process of entering information into working memory. Consider again the mental arithmetic problem given in the beginning of this chapter: *43 x 67*. If we had calculated *43 x 7 = 301*, and began calculating *43 x 60*, but then forgot our response to *43 x 7*, the sum would have to be re-calculated from the beginning. We are not able to retrieve the numbers that we had produced by simply trying to 'think back' on what we did, as the memory traces are no longer there. In this way, forgetting information in working memory is very different from forgetting, for example, such as where you parked your car, or whether or not you brought that important document in to work. In these cases, you can try to retrieve the information by mentally retracing your steps and stand a good chance of remembering the critical information. When you forget information in working memory, you are not able to do this. This could explain why a child may stare blankly at the teacher

when asked what he or she intends to do next. Asking them to *Try to remember what I said to you* is unlikely to help, as the crucial information will probably have been completely lost from their working memory.

How does working memory work?

Working memory is actually a system of inter-linked memory components that are located in different parts of the brain. Some of these components are specialised to store material of particular kinds; these are often referred to as short-term memory, although they are part of the larger working memory system. Verbal short-term memory stores material that can be expressed in spoken language, such as numbers, words and sentences, and is supported by structures in the side part of the left hemisphere of the brain. We know this because individuals who have experienced injury to these parts of the brain lose their abilities to remember verbal material for short periods of time, and also because the blood flow to these areas increases when a person tries to remember verbal material. The process of rehearsal described earlier in the chapter is an important part of verbal short-term memory.

Visuo-spatial short-term memory can hold images, pictures and information about locations. If we studied a picture and then had to recall the physical characteristics and locations of the objects it contained when the picture was no longer in view, we would need to rely on visuo-spatial short-term memory. This part of working memory is located in the right hemisphere, the opposite side of the brain from verbal short-term memory, and is a completely different system. Because verbal and visuo-spatial short-term memory are independent, a person who is very good at storing verbal material will not necessarily have excellent visuo-spatial storage abilities, and *vice versa*.

The final part of working memory is a more general component that controls attention and is involved in higher-level mental processes, and is often called the 'central executive'. This is a very important component because it is involved in all mental activities that involve coordinating both storage and effortful mental processing, such as mental arithmetic and many classroom activities, as described more

fully in later chapters. These activities will depend both on the central executive and either one or both of the short-term memory components (verbal and visuo-spatial), according to the nature of the activity. Mental arithmetic, for example, will involve both the central executive and verbal short-term memory. In other activities, the central executive and visuo-spatial short-term memory may work in combination. Unlike the two short-term memory components, the central executive is located in the front regions of both the left and right hemispheres of the brain.

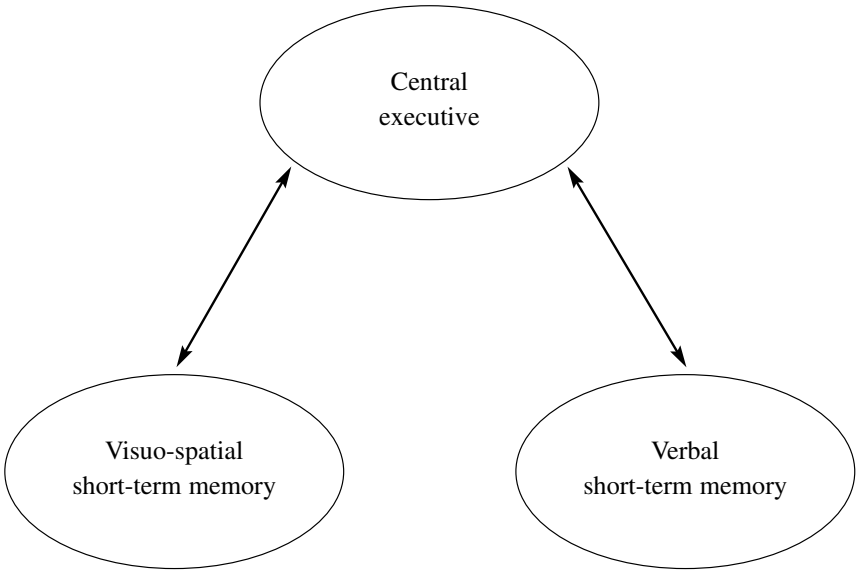

Figure 1.1 *A model summarising the main component of working memory*

The three main components of working memory are shown in Figure 1.1. Although it is simple, this diagram (which cognitive psychologists call a 'model') is based in findings from many experiments on working memory, and also from studies that have investigated the activity of the brain when people are involved in mental activities that engage working memory. A few features of this model are particularly important to note. First, each of the components has its own limited capacity. Second, there are links running in both directions between

the two short-term memory stores and the central executive. This means that the pairs of components can work directly together and exchange information as appropriate. Third, there is no corresponding path between visuo-spatial and verbal short-term memory. Because these two components store information in fundamentally different forms that are not compatible with one another, they cannot communicate directly, although they can be indirectly linked through the central executive. Finally, unlike the short-term memory stores, the central executive provides cognitive resources related to attention that can be allocated to material in any possible format. One practical consequence of this is that an individual who has low central executive capacity will typically encounter more difficulties in working memory activities that place demands on the central executive, irrespective of the particular format of information that is being handled.

Working memory as a whole consists of the combination of these three components, and any particular activity might engage some or all of them. There is a large research literature devoted to investigating in detail how each of these components work in both children and adults. For the purposes of this book, it is mostly sufficient to distinguish between two main terms – working memory and short-term memory.

How is short-term memory different from working memory?

From reading the previous section, you may already understand that the two short-term memory components (verbal and visuo-spatial short-term memory) form part but not the whole of the larger working memory system. Psychologists use the term 'short-term memory' to refer to those situations in which the individual simply has to store some material without either manipulating it mentally in some way, or doing something else at the same time. Remembering a telephone number is a good example of an activity that depends on short-term memory – in this case, verbal short-term memory. Working memory is an umbrella term for the larger system of which short-term memory is a part, and activities that tax the central executive (possibly in combination with the short-term memory stores) are often described as

working memory tasks. In practice, these tend to be more complex activities than short-term memory tasks, involving not only the storage of information, but also either its mental transformation or being engaged in some other effortful mental process. The distinction between the meaning of the terms 'short-term memory' and 'working memory' is important to understand because they play different roles in learning new skills, particularly during childhood. More information on the precise links between short-term memory, working memory and learning is provided in Chapter 3.

One source of confusion arises because the phrase 'short-term memory' has now entered everyday language, and is widely used to mean something rather different to the psychologists' definition. Informally, short-term memory is used to refer to the relatively recent past, such as something that happened earlier in the same day or possibly the previous day. In fact, the contents of working memory (or the short-term memory stores that it encompasses) could not extend over this lengthy period, and indeed usually last for no more than seconds. The type of memory to which this everyday use of short-term memory refers is what psychologists call 'episodic memory', and is classified as a long-term rather than short-term memory system because the information it retains can survive lengthy delays and distraction. Episodic memory is a very important aspect of memory that underpins our recollection of events or episodes that occurred relatively recently. In the following section, information about this and other kinds of long-term memory is provided.

How is working memory different from long-term memory?

The term 'long-term memory' is reserved for memory of experiences that occurred at a point in time prior to the immediate past or near present, and also for knowledge that has been acquired over long periods of time. There are several different kinds of long-term memory, each with its own unique psychological properties. The characteristics of the four main kinds of long-term memory are briefly described below, and are summarised in Table 1.1.

Episodic memory

This part of long-term memory stores memories for specific events in the relatively recent past – events that occurred either minutes, hours and days ago. Episodic memory is used to remember the mundane details of life, such as what you had for breakfast this morning, where you parked the car when you arrived at work and, possibly, what clothes you were wearing yesterday. Although episodic memory can retain many details of events, it is certainly not a perfect record of our experiences that resembles a video recording or an audio tape. Rather, episodic memory stores our mental interpretation of our experiences, and tends to be best at retaining the most important or notable features of events. These memories fade rapidly unless they are later retrieved, rehearsed or discussed and, in practice, we are unlikely to remember any of the details of relatively routine aspects of our lives after a small number of days. So, it is unlikely that we will remember what we wore to work a week ago, although it is relatively easy to recall what we wore yesterday. We may, however, remember for a much longer period a surprise encounter with an old friend, or the time that we unexpectedly received some shocking news. This is in part because such non-routine events are often reflected upon and discussed subsequently, which can both prolong their retention in episodic memory and also lead to the event being stored in a more permanent system – autobiographical memory, that is described next.

Autobiographical memory

Some information about our lives is retained in an even longer lasting memory system known as 'autobiographical memory'. Autobiographical memory stores two main kinds of information. One is the set of our personal facts including our name, information about family and friends, and the nature of our major lifetime periods such as what schools we attended, what jobs we have had, what houses we lived in. Autobiographical memory also retains memory of significant and sometimes emotionally charged experiences from our life. Some of

these memories are quite predictable, such as the first day at school or nursery, birth of siblings, wedding days, and birth of children. Other personal memories are much more idiosyncratic, and we may not know why we remember this event in particular. Typically, the earliest distinct memory that can be remembered dates back to about three or four years of age.

Semantic memory

The stored knowledge that we have acquired about the world through our personal experiences is held in semantic memory. One important part of semantic memory is our mental lexicon of language, which stores information about words such as their meaning, their pronunciation and their spelling. Semantic memory links together the words in our mental lexicon, so that we know how different concepts are related to one another. For example, we know that a dog is a mammal and that mammals are animals, and that Paris is the capital of France. We also know that although bread and butter are distinct concepts, they have a close association. Semantic memory also retains detailed knowledge of the visual characteristics of concrete objects, and of other familiar entities such as the faces of people that we can recognise. When we encounter an event that corresponds to an item stored in semantic memory – such as when we read the word *dog* – it also activates to some extent related concepts such as *cat*, *lead*, and *kennel*. In this way, it is easier to recognise something – whether a word or a physical object – that is related to something else we have experienced very recently. In this way, our recent experiences interact with knowledge about the world that is stored permanently in semantic memory. A feature of semantic memory that distinguishes it from episodic memory is that we are unable to recall the time when we learnt the facts that are stored in it, probably because we have repeatedly encountered the fact so many times: we simply 'know' them. In contrast, episodic memories are located very specifically in a particular place and time, and so we describe ourselves as remembering rather than knowing them.

Procedural memory

Actions or skills that we have learnt through practice and now have become automatic form part of a very basic long-term memory system known as procedural memory. A hallmark of procedural memory is that although we know that we can do something, we cannot describe easily the precise ways in which we can do it. Good examples of such skills are walking, whistling, riding a bicycle or driving a car. Procedural memory is one of the most basic forms of memory, and is probably not exclusive to the human species. This kind of memory is also very stable, tends to persist over many decades, and is fairly resistant to disruption by disease or old age.

Working memory and long-term memory can work together

There are many kinds of remembering that do not rely on working memory. Without working memory, we can get on a bike and cycle it successfully, understand the meaning of a printed sentence and say it out loud, recall an event from our childhood, and remember who we went out to dinner with last night and what we ate. In each case, these feats of memory involve long-term rather than working memory. However, this does not mean that these kinds of memory are irrelevant to situations in which we are trying to remember information for a brief period of time. Although working memory is distinct from long-term memory, material that is stored in long-term memory can boost our immediate memory performance by decreasing reliance on the very limited capacity of working memory. We are therefore more likely to remember a string or list of words that are meaningful to us such the name of our favourite foods or of ingredients in a highly familiar recipe than a random combination of words that we have not previously encountered. The memory benefit does not arise because our working memory capacity has changed in any way, but instead because we can use other sources of memory information that can be used to bolster the fragile working memory system. As we will see in later chapters, using long-term memory to supplement working

memory is an excellent strategy for increasing our chances of meeting the memory demands of many activities.

Table 1.1 Characteristics of different kinds of memories

Kind of memory	Duration	Type of information	Example
Short-term	Seconds	Verbal or non-verbal	Briefly remembering an unfamiliar phone number
Working	Seconds	Any kind	Following lengthy directions of how to reach a location
Episodic	Hours to days	Details of particular experiences	Remembering what you had for breakfast this morning
Autobiographical	Lifetime	Basic facts and conceptual knowledge	Remembering your wedding day
Semantic	Lifetime, with regular exposure	Knowledge, including personal facts	Knowing that Paris is the capital of France
Procedural	Lifetime once skill is established	Any kind of skill that can be used automatically	Knowing how to drive a car

POINTS TO REMEMBER

- Working memory is used to hold information in mind and manipulate it for brief periods of time in activities such as mental arithmetic.
- Working memory is limited in capacity. The capacity varies between individuals and is affected by characteristics of the material that is being stored.
- Information is lost from working memory when we are distracted, or attempt to overload its limited capacity.
- Working memory is a system of linked components, consisting of short-term memory stores for verbal (language) and visual or spatial information, and a coordinating component that controls attention that is called the central executive.
- Short-term memory involves storage, whereas working memory is involved more generally when a task involves storing and mentally manipulating information.
- There are four main kinds of long-term memory: episodic memory, autobiographical memory, semantic memory and procedural memory.