SENSORY, SHORT-TERM AND WORKING MEMORY

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Preview Questions

1. How does short-term memory differ from long-term memory?
2. What are the characteristics of *sensory* memory?
3. What is *iconic* memory?
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5. What is 'cognitive lockup' and how might it be avoided?

Encoding
the function by which information is coded in a form that allows it to be stored in memory.

Storage
the function by which information is retained in memory.

Retrieval
the function by which information is recollected as needed.

Short-term memory
the store where information is temporarily held in an accessible state.

Long-term memory
the system where information is held for longer periods, and can be accessed when needed.

Recollection
the act of recalling something to mind.

Working memory
the system in which information is held and manipulated in order to perform a task.

Secondary memory
the term introduced by William James (1890) to refer to memory proper, which we now think of as long-term memory; for James it was '*the knowledge of an event, or fact,* of which meantime we have not been thinking, *with the additional consciousness that we have thought or experienced it before*'(p. 649).

Primary memory
the term introduced by William James (1890) to describe memory 'belonging to the rearward portion of the present space of time', now referred to as short-term memory.

Sensory memory
a temporary sensory register that allows input from the sensory modalities to be prolonged.

INTRODUCTION

Think of the last time you were standing on a street speaking with a friend. Try to remember the scene. What time of day was it? What was the weather like? What was your friend wearing? What did you speak about? Who and what else did you see? Now imagine you are told that a serious crime took place that day, on that street, around that time. You are asked to recall anything you saw or heard that might help with the investigation. You are asked whether you saw anything unusual. How confident would you be that you could recall a potentially significant detail?

Over the course of any one day, we encounter a vast array of sights, sounds, smells, tastes and experiences. It is important that we are able to remember the useful details without retaining every piece of information that meets the senses. In Chapter 2, we saw how the cognitive system makes sense of the complex array of information that meets the senses through perception. In this chapter and the next, we look at how memory allows us to code, hold, recover and use relevant information – that is, how we **encode**, **store** and **retrieve** information (see Figure 6.1).

The traditional view of memory makes a distinction between **short-term memory** (STM) and **long-term memory** (LTM). LTM allows you to answer questions such as: What is the capital city of Italy? What does the word 'esoteric' mean? What colour are bananas? What is your home address? Is a bat a bird? How did you celebrate your last birthday? It involves **recollection** of information. It also allows you to use memory to perform actions – to ride a bicycle, drive a car and sign your name. STM, on the other hand, allows a small amount of information to be held in mind, so that it is immediately accessible and can be used. For example, if you hear a string of digits and have to repeat them back aloud, you rely on STM to maintain that information in mind. The term **working memory** (WM) has been used in a number of different ways, but generally refers to memory that allows us to manipulate active information – to perform mental arithmetic, for example. As we will see, there is substantial overlap between the terms short-term memory and working memory, and there has been considerable debate about how they are best characterized.

The distinction between the hypothetical LTM and STM stores is long established. William James (1890), in *The Principles of Psychology*, described **secondary memory** as 'memory proper', while **primary memory** was, according to James, memory for the psychological present. This latter type of memory is the focus of the current chapter. According to the traditional view, before a piece of information enters short-term memory, its sensory aspects are stored temporarily in a very short-lived store called **sensory memory**. Sensory memory involves memory for stimuli as opposed to memory for ideas (Cowan, 2008), and there is good evidence in particular for a visual type of sensory memory, which allows a large amount of information from the eye to be held, but only for a very short period of time.

The traditional approach has viewed memory as a series of stages (Figure 6.2). Take for example your memory for the street scene described at the beginning of this chapter. The visual information that reaches the retina of the eye is processed by the brain and forms a visual percept (see Chapter 2). This is held in an initial visual memory store that forms part of sensory memory. Information is held for a short time in the sensory store. Information that needs to be acted on or

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that will be retained is transferred to the short-term memory store and if it is to be retained long term it is transferred to long-term memory. Whether you can recall a particular event from the day you met your friend on the street will depend on whether it was successfully processed and stored in long-term memory. While the process is often conceptualized as a series of feed-forward stages, there is also considerable **top-down** influence on all stages of memory.

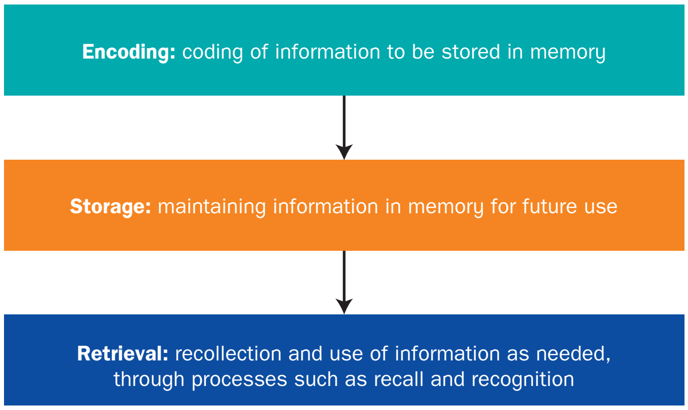

Figure 6.1 Three key processes of memory.
The three key processes involved in memory are encoding, storage and retrieval.

SENSORY MEMORY

It is a common experience for the mind to wander during a conversation (see Box 6.5). When this happens, it is often the case that, although we have not been paying attention, we can recall the last few words said and can continue the conversation without the other person noticing our lapse in attention. This ability reflects one aspect of sensory memory.

> **Top down**
> or conceptually driven processes reflect the influence of higher-order cognitive processes such as thoughts, beliefs and expectations.

Sensory memory occurs at the border of perception and memory, a boundary that is not easily identified (Roediger et al., 2017). It involves the recollection of perceptual types of how a stimulus looks, sounds, feels, tastes and so on (Cowan, 2009), and as such is assumed to be pre-categorical in nature. Sensory memory allows input from the sensory modalities (vision, hearing, etc.) to be prolonged briefly in order for us to process relevant aspects of that input. It is essentially a temporary sensory register, which has a large capacity, but fades rapidly. Models of sensory memory assume a number of modality-specific sub-stores dealing with different types of input such as visual, auditory, haptic (that is, related to the sense of touch) and olfactory (related to smell) stimuli, with close links between the sensory memory store and the corresponding sensory modality.

As yet, relatively little is known about the neurobiological basis of sensory memory. The neurotransmitter **glutamate** plays a key role in the stability of sensory memory (Beste et al., 2008) and more rapid decay of sensory memory has been shown in individuals as a function of genetic variations in glutamatergic neural transmission (Arning et al., 2014). Animal studies have also shown that drugs that facilitate glutamatergic transmission enhance memory encoding (e.g., Staubli et al., 1994).

> **Glutamate**
> an excitatory neurotransmitter that acts on both central and peripheral divisions of the nervous system and plays a key role in sensory processing.

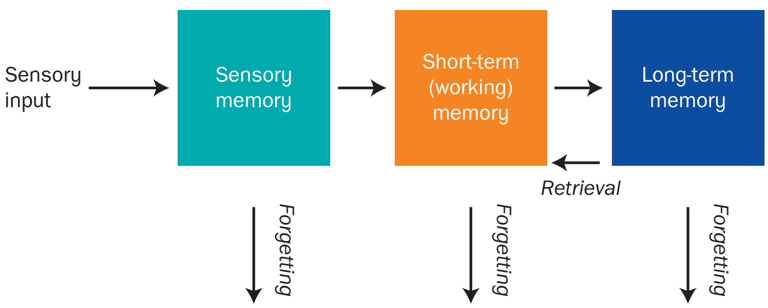

Figure 6.2 The three-stage model of memory.
The stage model of memory conceptualizes incoming sensory information as moving through a series of stores, from sensory memory to short-term and then long-term memory. See for example, Atkinson and Shiffrin (1968).

The idea of a brief sensory register dates back centuries. In 1740, a German physicist, Johann Andreas Segner, attached a glowing coal to a cartwheel and rotated the wheel at various speeds. He calculated that the glowing coal was perceived as a continuous circle if the wheel rotated once in about 100 milliseconds (Cowan, 2008). As early as 1899, Wundt had proposed a type of temporary visual store, based on data from experiments examining the point at which brief flashes of light would be perceived as distinct or continuous (Sperling, 1960). Many subsequent experiments on visual memory produced anecdotal accounts suggesting that people saw far more items than they could actually report. It was Sperling's work, conducted for his doctoral thesis and published in 1960, that introduced a new methodology to this area of research, and proved what anecdotal accounts had long suggested: that people initially store a large amount of visual information but this information decays rapidly, such that only a portion of it remains available to consciousness (Sperling, 1960).

Sensory memory consists of a number of modality-specific stores: the term iconic memory refers to the brief storage of *visual* stimuli; the term echoic memory refers to *auditory* stimuli. Other stimulus types may also be stored, such as *haptic* sensory memory for touch-related stimuli. The sensory stores prolong sensory information so that we can attend to important parts of it; aspects that are not attended to fade away. There is considerable evidence for an iconic memory store in particular.

Iconic Memory

Iconic store
the sensory memory store for visual stimuli.

The **iconic store** (which was so named by Neisser, 1967) was investigated in a series of experiments by Sperling (1960). Sperling started out with a typical memory span experiment in which participants were presented with a visual array showing, for example, three rows of four letters (see Figure 6.3). This was presented for a brief duration of 50 milliseconds. In a 'whole report' condition, participants were asked to recall as many items as they could. They could typically recall about four or five items. However, verbal reports suggested that the participant had seen more items than could be reported. Sperling introduced a 'partial report' condition, in which participants were asked to recall from only part of the array. Immediately *after* presentation of the array (that is, on stimulus offset), a tone was sounded to indicate which line the participants were to report from (see Figure 6.3). A high tone signalled that they should report what they had seen within the top line of the array. A medium tone meant they should report from the middle line of the array. A low tone meant they should report from the bottom line of the array. Participants had no way of knowing in advance which line would be probed. Using the

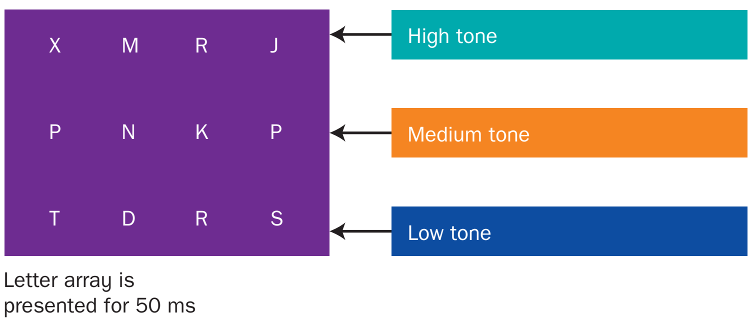

Figure 6.3 An array for testing visual sensory memory.
This figure shows the procedure used by Sperling (1960). In the partial-report condition, after a visual array is presented, a tone indicates which line participants are to report from. In the full report condition, there is no auditory cue; participants report whatever they can.

partial-report procedure, Sperling found that participants could typically recall about three items from each line; this meant that a much larger amount of information was available to participants than was suggested by the data from the whole-report condition (see Figure 6.4). This 'partial report' methodology has been used in many studies since to replicate the effect (see for example Box 6.1).

Sperling varied the size of the stimulus array that participants saw, and found that as array size increased, so did the amount of information available in the partial report condition. These results confirmed that, for a short time at least, participants can potentially register a large amount of information. In a subsequent experiment, Sperling investigated the speed of decay from the store, by manipulating the length of the delay between the offset of the stimulus array and the presentation of the tone. The results showed that the partial report advantage disappears after a delay of about half a second. Sperling's data supported the idea that there was a brief memory of a visual image, which is potentially very large in capacity but which rapidly fades away; this is iconic memory. Sperling's findings were confirmed by a number of subsequent studies; for example, Averbach and Coriell (1961) reported similar data using a version of the task that used a visual cue instead of an auditory tone.

Iconic memory allows visual input to be prolonged, which means that our visual experience is not an exact reflection of reality. For example, it allows us to see a series of still images as moving picture sequences in motion pictures and in animation. A motion picture presents images at a rate of 24 frames per second, but in order to ensure that we perceive a flicker-free, smooth moving picture, each frame is presented two or three times. The human visual system is sensitive enough to detect flicker at 24 frames per second (24 Hz) but by presenting the image twice and increasing the rate to 48 frames per second (48 Hz), the flicker will not be detected (Galifret, 2006). Other animals have greater sensitivity to flicker. Birds of prey fly at great speeds to intercept their quarry and can redirect their trajectory in order to do so – a task requiring keen visual perception. A bird of prey has sensitivity to flicker detection in excess of 100 Hz (Winkler, 2005) and bees' sensitivity may be as high as 300 Hz

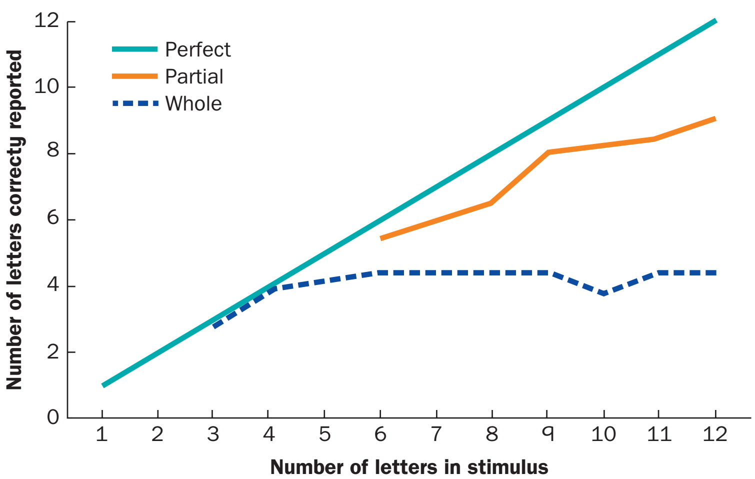

Figure 6.4 Results from the partial and whole report testing.
This figure shows the results from Sperling's (1960) first experiment. The number of letters that can be reported is limited in the whole report condition, while the partial report condition shows that a much larger amount of information is potentially available. The straight line shows the hypothetical perfect performance for comparison.

Source: Adapted from *Sperling (1960)*.

(Lea & Dittrich, 2000). Such sensitivity produces greater control over responses to visual stimuli at speed. Humans achieve such speeds only when driving a car, an activity for which the evolution of the visual system has left us underprepared.

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The prolonging of visual sensory input is also evident in the way people perceive a lightning bolt as continuous although it consists of a number of separate strokes, which can be separated by as much as 40–50 milliseconds (Uman, 1986). Similarly, we are unaware of the flicker of fluorescent lights (which flicker at a rate of about 100 Hz). Flicker perception in humans, while less sensitive than that of some animals, is among the faster processes conducted by the visual system (see Chapter 2).

Evaluation

Some researchers questioned whether Sperling's data might reflect use of a guessing strategy in the partial report condition (e.g., Holding, 1970). Converging evidence soon emerged that supported Sperling's notion of a temporary visual register. Haber and Standing (1969) used a task in which participants saw a series of successive circles, which were presented for 10 milliseconds each and separated by brief intervals. They varied the duration of the interval and asked participants to report if the preceding circle had disappeared before the subsequent one was presented. They found that at intervals of less than a quarter of a second, participants reported no gap between presentation of the circles, whereas at longer intervals participants saw the first circle disappear before the second one appeared. These findings support Sperling's account and lend further support to the idea of stimulus persistence lasting about half a second. Research is beginning to uncover the neuronal basis for visual sensory and working memory, and to examine the role top-down processes play in the modulation of activity in the visual cortex (e.g., see van Kerkoerle et al., 2017).

Box 6.1 When Things Go Wrong: Synaesthesia and sensory memory

Sometimes when things 'go wrong', a pattern of advantages can be seen as well as disadvantages in some domains. Luria (1968) described the case known in literature as S., which has become the seminal case of extraordinary memory ability or '**hyperthymesia**'. However, S.'s ability came at a cost, with cognitive deficits in abstract thinking and categorization. Such extraordinary memory can be mentally burdensome; one individual studied, named A.J., described her memory intrusions as 'non-stop, uncontrollable, and automatic' (Parker et al., 2006). At least some of A.J.'s and S.'s abilities derived from their tendency to form multimodal associations in memory, a condition known as **synaesthesia**.

Hyperthymesia
'hypermemory' or highly superior autobiographical memory (HSAM), evident in some individuals.

Synaesthesia
an uncommon condition where stimulation of one perceptual modality results in experiencing a percept in a typically unrelated modality (e.g., tasting a sound).

Synaesthete
a person with synaesthesia.

Synaesthesia is a rare neurological phenomenon in which a triggering stimulus (referred to as the inducer) gives rise to an atypical, additional experience (referred to as a concurrent). In most varieties, it is considered to be a benign, and sometimes beneficial, condition affecting somewhere between 1 and 4 per cent of the population to some degree (Simner et al., 2006). Synaesthesia is sometimes categorized as a 'blending' of the senses, but this does not reflect the variety of experiences that can fall within the condition. Many different inducer–concurrent pairings can occur, and they can fall within or across sensory modalities or cognitive streams (see Auvray & Deroy, 2015; Lunke & Meier, 2018). The **synaesthete** may reliably associate a sound with a taste, or a shape with a colour; for example, hearing a doorbell may give rise to an experience of tasting custard, or seeing a number 3 shape may evoke the colour yellow. This latter variety, one of the most common forms of synaesthesia, is known as

grapheme–colour synaesthesia, and in such cases seeing a letter or number evokes a colour. This happens spontaneously and involuntarily; the synaesthete has no control over the concurrent experience. Importantly, the relationship between the inducer and the concurrent is consistent; a given letter reliably evokes the same colour on each occasion. Neuroimaging studies confirm spontaneous activation of the brain areas associated with both the inducer and concurrent experiences (Paulesu et al., 1995).

Grapheme–colour synaesthesia one of the more common types of synaesthesia in which a written letter or number is spontaneously associated with a colour.

Synaesthesia has been associated with a number of advantages in long-term memory (see Rothen et al., 2012) and creativity (Ward et al., 2008), linked to the richer memory traces laid down by activation of multiple sensory experiences. However, it has recently been shown that this advantage extends to sensory memory, which may well be the basis for the long-term memory advantage. Gosavi and Hubbard (2019)replicated Sperling's (1960) partial report paradigm (described above) using letters and non-alphanumeric symbols (such as # and &) as stimuli. Participants were grapheme–colour synaesthetes and a group of non-synaesthetic age- and sex-matched controls. The letters would be expected to evoke colours in the synaesthesia group, while the non-alphanumeric symbols would not, allowing a comparison to be made between the groups.

Participants were presented with an array of either 3 × 3 or 4 × 3 black letters or symbols on a white background. After a short delay of either 0, 150, 300, 500 or 1000 ms, they then heard a low, medium or high-pitched tone. As in Sperling's study, a low tone signalled that participants should report the bottom row, a medium tone indicated that they should report from the middle row, and a high tone that they should report from the top row. Participants could not tell which row would be probed until they heard the tone. They then had 2000 ms to recall as many letters or symbols as they could from the appropriate row.

As found in Sperling's study, longer delays were associated with decreasing performance overall. The results showed an advantage for the synaesthete group, who demonstrated a larger iconic memory capacity compared to the controls across both the 3 × 3 and 4 × 3 array sizes. This was evident only when the stimuli were letters; when the stimuli were non-alphanumeric symbols the advantage disappeared. The synaesthete advantage for the letter arrays was more prominent for the large 4 × 3 arrays. Gosavi and Hubbard (2019) concluded that the memory advantages of synaesthesia extend to the earliest stages of memory, and they suggested that the advantages that are evident in the later stages of memory may in fact arise from these earlier advantages in sensory memory.

This sensory memory advantage of synaesthetes may depend on attentional processes. Rothen et al. (2018) used a different type of partial-report task to explore the point at which the synaesthete advantage emerged. In their task, eight black letters were arranged on a circle around a fixation point on a grey background. The letters disappeared, and following a variable delay of 0, 50, 100, 250, 500 or 1000 ms, a red asterisk appeared to signal the position of the letter the participants was required to report. Black asterisks replaced the non-target letter positions. (This use of colour cues may well be problematic.) After participants gave their response they also rated the subjective clarity of the target letter, on a scale ranging from 'no experience of the letter at all/guessing' to 'clear experience of the letter'.

Participants were grapheme–colour synaesthetes, and age- and sex-matched controls. The experiment manipulated three additional factors: the length of the inter-stimulus delay, the target letter and the target position. Again, as in Sperling's study, longer delays were associated with decreasing performance. The results showed that while sensory memory was not generally enhanced in the synaesthetes compared to the controls, the synaesthetes showed a performance advantage when subjective clarity of the target was high.

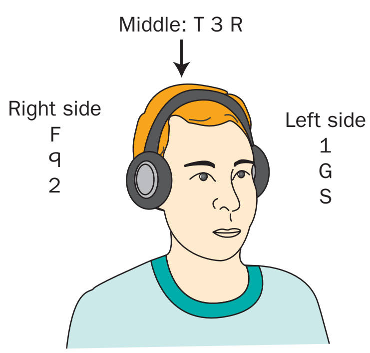
This suggests that the effect is not pre-attentive but depends on participants' awareness of the inducer stimulus. However, an additional factor also emerged in the study that complicates matters. The results showed that the level of synaesthetic consistency was an important predictor of sensory memory performance. The group of synaesthetes showed a range of synaesthetic ability; some showed a high level of consistency in the experience; others less so. A general memory performance advantage would have emerged for the synaesthetes relative to the controls had the study included only the highly consistent synaesthetes. This points to the importance of strict inclusion criteria for studies involving synaesthetic participants, as the extent of synaesthetic experience may vary considerably, affecting the results of studies on memory. Furthermore, it has been shown that the memory advantage differs by *type* of synaesthesia (e.g., Lunke & Meier, 2018), giving another important variable to consider and underlining the diversity of experience within the synaesthetic population.

Echoic Memory

Echoic memory
sensory memory specific to auditory stimuli.

Echoic memory is the auditory equivalent of iconic memory; it is sensory memory for heard information. Sperling's partial-report technique was applied to auditory stimuli initially by Moray et al. (1965), and their procedure was extended by Darwin et al. (1972). Darwin et al.'s experimental set-up is illustrated in Figure 6.5.

The Darwin et al. study involved presenting auditory stimuli independently to each ear, or to both ears, using stereo headphones, such that the sounds would be heard from three spatial positions: from the left or right, or from the 'middle' (i.e., in stereo). Nine letters and nine digits were used to form sequences; three items were presented to the left channel, three to the right, and three were presented simultaneously in stereo. They were presented such that the first item of each group was heard simultaneously;



Participant wears stereo headphones

1. Present nine stimuli: left 1 G S
   middle T 3 R
   right F 9 2
2. Following last letters variable delay interval, 0–4,000 milliseconds.
3. Signal bar presented on a screen. Bar is left of, in front of or to right of participant.
4. Participant attempts to report stimuli signalled by bar.

Figure 6.5 The procedure used by Darwin et al. (1972).
The illustration shows the procedure used by Darwin et al. (1972). The participant hears letters and numbers presented simultaneously to one or other ear, or to both, via the headphones. A visual cue signals which location to report from.

Source: Adapted from Loftus & Loftus (1976).

similarly, the second items were presented simultaneously, and then the third. In the example shown in Figure 6.5, participants would hear 1, T and F, simultaneously, then G, 3, 9 and finally S, R, 2.

Following Sperling's procedure, the auditory stimuli were presented and, after a delay that varied from 0 to 4 seconds, a cue indicated from which set the participants were to report. In this case, a visual cue (e.g., a signal bar appearing on screen) was presented to the left, middle or right, and the participants reported what they had heard from the corresponding location. Consistent with Sperling's findings on iconic memory, Darwin and colleagues found that performance in the partial-report condition suggested a large initial memory of auditory information, which decayed rapidly. At zero delay participants could report about five of the nine items. After a delay of 4 seconds, performance had dropped to 4.25 items on average, the same number as would be expected in a whole-report condition. This suggested that there was a sensory store for auditory information that was similar in some ways to iconic memory; this became know as the echoic store (another term coined by Neisser, 1967). The echoic store provides an acoustic register, allowing auditorily presented information to be prolonged so that some aspects of the input can be retained for processing.

The auditory partial report data are broadly consistent with findings using the **shadowing** technique, in which participants must 'shadow' or repeat back a message presented to one ear or the other. For example, Glucksberg and Cowan (1970) had participants shadow a passage of prose that was presented in one ear while another prose passage was presented to the other, 'unattended' ear. Participants were to ignore the second passage, but were warned that digits would occur in that text from time to time, and that when a light flashed, they were to report the last digit heard in the unattended message. The duration between the presentation of the digit and the light cue was manipulated. Performance on the task deteriorated at about 4 seconds. Similarly, Treisman (1964) found that if participants shadowed a message while a second unattended message was presented, they only recognized that the two messages were the same if they occurred within about 2 seconds of each other. More recent research has confirmed that echoic memory provides a brief register of auditory input, and is highly sensitive both to decay and to interference (for example, see Kinukawa et al., 2019).

Shadowing
a technique that involves repeating back an auditorily presented message.

Evaluation

From Darwin et al.'s data, the span of echoic memory seemed to be less than that of the iconic store and its duration longer, but this may reflect a limitation of the procedure used. While Sperling could present the visual stimuli all at once without affecting the spatial relationships between the stimuli, in an auditory version of the task, all the sounds could not be presented simultaneously; three sets of temporally distinct sounds were presented. This produces some clear differences between their two procedures and may have led to an over-estimation of the duration of storage in the echoic register. Efron (1970a, 1970b, 1970c) had participants adjust the onset of a light to coincide with the offset of an auditory tone. The duration of the tone was varied and it was found that, for very short tones (e.g., 60 milliseconds), participants adjusted the light to come on 150 milliseconds after the onset of the tone. In other words, short tones were prolonged in echoic memory so that they were perceived by participants as lasting longer than they actually were. This supports the idea of a modality-specific store that prolongs auditory stimuli, and provides an estimation of echoic persistence that is more accurate and more consistent with other estimates (e.g., Massaro, 1975, estimated 250 milliseconds).

What can be done with the information stored in sensory memory? Another of Sperling's experiments used an array that contained both letters and digits, and introduced a second partial report condition, in addition to the whole and partial report conditions described above. In the new partial report condition, participants were instructed to report only the letters or only the digits within the array; a tone cued which type they were to report (letters or digits). In this partial report condition, no advantage over the whole report condition was evident. Participants could report only about four to five items. This gives us a clue as to the nature of the representation of the stimuli in the iconic store; it appears that participants have access to a visual stimulus but cannot yet categorize it or access its meaning. As Cowan (2008, p. 25) put it, 'we can think of sensory memory as the memory for the knowledge-free, sensation-based characteristics of stimuli that resemble what a newborn would perceive'. Sperling's letter/digit experiment demonstrated that information held in the sensory register is not yet in a form that the cognitive system can effectively utilize and manipulate. For this, further processing and transfer to short-term memory is needed.

Masking
reduced perception of a visual stimulus when another stimulus is presented in spatial or temporal proximity to it.

Stimulus onset asynchrony
the time between the onset of a stimulus and the presentation of a mask.

Sensory memory is fragile and can easily be disrupted before stimuli can be transferred into short-term memory (STM). Backward **masking** procedures involve the presentation of a 'masking' stimulus immediately after the target stimulus; for example, a briefly presented visual stimulus (e.g., a letter) might be followed by a row of hash marks (####). The participant is subsequently required to identify the letter in a recognition test. Recognition increases as the duration between the presentation of the target stimulus and the masking stimulus (the **stimulus onset asynchrony**, or SOA) increases, to about 250 milliseconds. Data from backward masking also support a shorter duration to echoic memory than the partial report data outlined above (see Cowan, 2008, for an overview).

Cowan (e.g., 1984, 1988) suggested that there are two stages to sensory memory in each of the modalities (see also Massaro, 1976). The first phase is a short, pre-perceptual phase lasting about 250 milliseconds, while the second is longer, lasting several seconds, and involving more substantial processing and access to memory. The modality-specific differences in the partial-report data outlined above came about because Sperling's visual array data involve the first of these sensory phases, while Darwin's auditory data involve the second (see Cowan, 2008).

Haptic and Tactile Memory

It is likely that there are also sensory memory stores serving other modalities. Support for a haptic (related to touch) sensory store was provided in a study by Bliss et al. (1966), who used a tactile version of Sperling's partial report procedure. Their participants were trained to associate a letter of the alphabet with three sections on each of four fingers of one hand. Participants then placed their hand in a device that administered a puff of air to some of these regions, and had to report which regions had been stimulated by giving the associated letter. In the partial report condition, a visual stimulus cued whether participants were to report stimulation presented to the upper, middle or lower sections of the fingers. A small advantage for the partial-report condition was found, as long as the visual cue appeared within 800 milliseconds of termination of the tactile stimulation.

Similarly, Gallace et al. (2008) used the partial report procedure to investigate whether information regarding the number of tactile stimuli presented across the body (rather than just to the fingers as in the Bliss et al. study). Across a series of experiments, they found a partial report advantage similar to that seen in iconic memory, with participants able to report, on average, five items, compared to three items in the whole report condition. Their data suggest that a maximum of five items can be stored in tactile sensory memory. The data also show that the capacity of tactile sensory memory is far smaller than that of its visual counterpart, iconic memory, and that it decays rapidly. These data support a temporary register for tactile input and are consistent with data demonstrating **change blindness** (see Chapter 4) in the tactile modality (e.g., Gallace et al., 2006; Gallace et al., 2006; Gallace & Spence, 2014).

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Change blindness
the phenomenon where substantial differences between two nearly identical scenes are not noticed when presented sequentially.

While sensory memory provides a temporary register that is rich in sensory detail, such memory is short-lived and cannot be manipulated. In order for effective processing to occur, information must be held in short-term memory. It is to this aspect of memory that we now turn.

SHORT-TERM MEMORY

Short-term memory (STM) holds information in consciousness; it provides temporary storage for active information. STM has a limited capacity, and information can be lost from it relatively easily. If someone gives you their telephone number, but you forget it as you try to enter it on your phone, you will be aware of the capacity limitations affecting STM. STM allows us to complete the many daily tasks that involve active use of information, from understanding a conversation or a passage of text, to calculating a tip in a restaurant, to imagining an alternate route home when you find your usual route blocked. This last example illustrates that STM is not limited to verbal information; similarly, if you are asked how many windows there are on the front of your house, the visual image you create to address this question is also inspected in STM. Much of the information that we process in STM is not retained, and is quickly purged from STM, allowing our attention to move on to the next task. This is important for the efficiency of STM. As Bjork (1972) noted: ‘We overhear conversations, we see things in newspapers and store windows, we add up numbers, we dial telephone numbers, we pay attention to advertisements, and so on – nearly all of which we have no use for beyond the point at which we attend to them’ (p. 218).

William James’s (1890) description of short-term memory as primary memory equated it with the psychological present, the information that is available in consciousness. Hebb (1949) also made the distinction between short-term and long-term memory, and a number of models in the 1950s and 1960s supported the distinction between stores of different types (e.g., Broadbent, 1958; Neisser, 1967; Waugh & Norman, 1965). Atkinson and Shiffrin (1968) introduced a model of memory that became known as the *modal model* (‘modal’ because it was similar to various other models at the time; see Norman, 1970; Waugh & Norman, 1965). It proposed three memory stores, and made the distinction between a long-term store (LTS, or also LTM) and a short-term store (STS, or STM). The model was heavily influenced by the growing use of the **computer metaphor** in cognitive psychology, and made a distinction between permanent, structural aspects of memory and flexible control processes, which could vary depending on task requirements, analogous to the distinction between hard drive storage and active (RAM) memory in a computer.

Computer metaphor
in cognitive psychology, an analogy drawn between human cognitive processing and information processing in a computer, which provides a tool for thinking about how the mind operates.

Rehearsal
a set of processes by which we can act on currently active information.

According to the Atkinson–Shiffrin model, information is first registered in the sensory store, and salient information is transferred to STM. A number of control processes are supported by STM and the type of processing carried out will determine whether information will be stored in LTM. **Rehearsal**

Maintenance rehearsal
retains information in STM.
Elaborative rehearsal
organizes the information so that it can be integrated into LTM.
Decay
a process by which information is lost from STM over time.
Displacement
a process by which information coming into STM causes information already held there to be lost.

involves recycling the information (such as repeating it to yourself to keep the information refreshed in memory; **maintenance rehearsal**), encoding involves the extraction of some information in order to transfer to LTM (**elaborative rehearsal**), and retrieval strategies allow access to LTM. Information is lost from STM through **decay**, a time-based limitation, and **displacement**, a capacity-based limitation by which incoming information gains precedence over previously active information (Atkinson & Shiffrin, 1968).

The basic assumptions of the modal model were that:

- there are separate short-term and long-term stores
- processing in the short-term store determines memory storage in the long-term store, and
- short-term memory is a limited-capacity store.

Digit span
the number of digits that can be held in memory and is used as a measure of STM.

There was general agreement that STM had a limited capacity. Attempts to measure its capacity made use of tasks involving digit span and the recency effect in free recall (described below). **Digit span** tasks present participants with digit strings of increasing lengths; participants have to repeat them back in the order they were presented. The task becomes more difficult as the length of the string increases, and the point at which errors begin to occur indicates the limits of the participant's STM. Miller (1956) is often cited as quantifying the functional limit of STM as 7 ± 2 items (the so-called 'magical number seven'), suggesting that, on average, people will be able to report about seven items (plus or minus 2), whether those items are individual letters or digits, or larger 'chunks' of information. For example, the digit strings on a credit card could be read as individual digits or as chunks: for example, 1010 2543 6754 2194. Taken as individual digits there are 16 digits, but read as four sets of four numbers there are four 'chunks'. Therefore more than seven individual digits might be recalled in this case. **Chunking** increases the capacity of STM; as Miller (1956, p. 95) noted: 'the span of immediate memory imposes severe limitations on the amount of information that we are able to receive, process and remember. By organizing the stimulus input simultaneously into several dimensions and successively into a sequence of chunks, we manage to break (or at least stretch) this informational bottleneck.' Information from LTM can be used to facilitate chunking (see Chapter 1 for some examples used by world memory champions). The string FBICIAMI5 is easier to recall if we break it into more meaningful components FBI CIA MI5. The larger the chunks, the more memory is required, however, and fewer will be recalled. Chunking is seen as a key contribution of the Miller paper (Cowan, 2015).

Chunking
a strategy to improve memory by grouping smaller units together into a larger unit, or 'chunk'.

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Miller's estimation of seven items, give or take two, was approximate and, given the humorous tone of his highly cited article, it may have been meant as a rhetorical device (see Cowan, 2015, for an interesting discussion on this point). Various sources have proposed a limit that is closer to four (e.g., Broadbent, 1975; Henderson, 1972; Mandler, 1967; see Cowan, 2001, for a review). Cowan et al. (2007) noted that Sperling's research, described above, showed that, of a large amount of information in sensory memory, only a small number of items make it through to STM; when participants are shown 12 characters at once, they can typically only report around four items. A number of other sources suggest that it is the capacity of STM, rather than the decay rate of sensory memory, that is reflected in these four items (Cowan, 2010).

Recency effect
the tendency, given a list of items to remember, to recall those from the end of the list more readily than items from the middle.

The **recency effect** in free recall refers to the fact that people recall more items from the end of a presented list than from the middle of the list.

This pattern was first reported in the 1920s (Welch & Burnett, 1924), but it was only in the 1960s that it was interpreted in light of differences between STM and LTM. In the task graphed in Figure 6.6, participants hear a list of 12 unrelated words. They are then required to report the words in any order. The performance of participants is then graphed as shown in Figure 6.6 to give the **serial position curve**, with the word's position in the list graphed along the x-axis, and probability of recall shown on the y-axis. The typical serial position curve shows an advantage for more recently presented items (the recency effect). Performance is also relatively good for items at the start of the list (the **primacy effect**). Compared to words at the end and at the start of the list, recall is relatively poor for items that are presented in the middle of the list.

Serial position curve used to plot recall of a word list such that performance is examined as a function of a word's position in a list.

Primacy effect enhanced recall of items at the start of a list compared to those in the middle.

The recency effect reflects items held in STM. The primacy effect reflects items that have already been transferred to LTM; as more items are added to the list, there is less time to transfer them to LTM, and so some items are not successfully transferred to LTM and are displaced from STM. If the recency effect reflects items stored in STM, then it should be relatively straightforward to disrupt it without affecting the primacy effect, which reflects another aspect of memory (LTM). Studies have attempted to support this distinction between STM and LTM by examining the effects of distraction on the primacy and recency effects. For example, participants might be required to count backwards in threes immediately after presentation of the list: this should interfere with the information that was being held in STM by preventing the participant from rehearsing it. But the counting task should not affect recall of the items that have already been successfully transferred to LTM. In other words, the counting task should affect the recency effect but not the primacy effect. This is precisely what is found in such studies.

The capacity of STM should therefore be reflected in the number of items in the recency effect, but this has proved rather difficult to estimate, as it varies depending on the nature of the information to be recalled. Glanzer and Razel (1974) conducted a series of free recall experiments and initially estimated the size of the recency effect as being 2.2 words. When they used proverbs in the recall task, they found recall of 2.2 proverbs, but

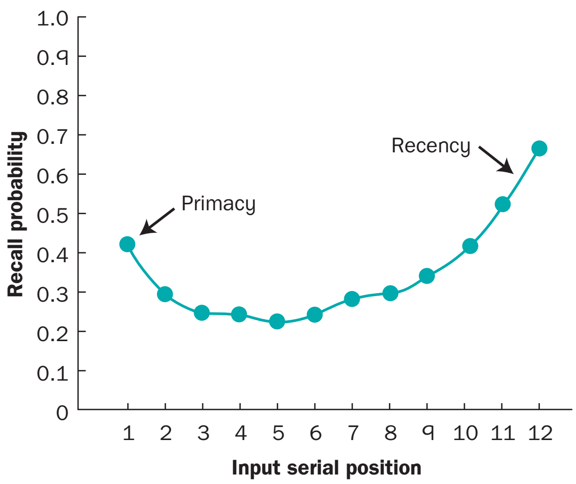

Figure 6.6 The serial position curve.
The serial position curve shows the probability of free recall of a word as a function of the position in which it was presented in a word list. Items at the end of the list show increased recall, a pattern called the recency effect. Items at the start of the list also show better recall than those in the middle, a pattern referred to as the primacy effect.

Source: Adapted from Parkin (2000).

for unfamiliar sentences performance dropped to 1.5 sentences. Cowan (2001), assessing the available evidence, identified a capacity limit of on average four chunks and outlined the task conditions under which this estimate might be predicted to differ.

Negative recency effect the tendency for recall of items from the end of a list to be poorer than for those from the start or middle of the list in a final, cumulative recall task.

The **negative recency effect** provides further support for separate short-term and long-term stores. Craik (1970) had participants immediately recall 19 lists of 15 words. He later had participants report any words they could remember from any of the lists in a final free recall task. If the recency effect reflects items in STM, we would expect to see a recency effect in the immediate recall task but no such effect in the final free recall task, as this task required reporting from LTM. Craik's data showed that not only was this the case, but in fact performance for list-end items was poorer than mid-list items in the final free recall task; this is the negative recency effect. This pattern supports the idea of separate short-term and long-term memory stores. In the immediate recall task, participants held the list-end items in STM and did not transfer them to LTM. This meant those items were at a disadvantage in the final recall task.

A Double Dissociation of Function?

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Amnesia a pattern of memory loss affecting elements of long-term memory, while short-term memory remains intact.

Amnesic syndrome a pattern of memory loss characterized by impaired long-term memory and spared short-term memory.

If recency reflects storage in STM, we might expect to find it spared in individuals who have had a brain injury affecting LTM, but leaving STM intact. Individuals with **amnesia** (see Chapter 7) show this pattern of memory impairment. In the next chapter, we look at long-term memory and a pattern of memory impairment called the **amnesic syndrome**. The amnesic syndrome is characterized by impairments in long-term memory function, particularly affecting the person's knowledge of their own life events, while short-term memory is spared. The affected individual may be able to hold a conversation with a visiting friend, for example, but as soon as the friend leaves their presence the information is lost; they may not even recall the visit.

In Chapter 7, we will look in detail at one of the most cited cases of amnesia in neuropsychology, that of H.M. As a young man, H.M. underwent an experimental surgical procedure in an attempt to alleviate his medically intractable epilepsy. The surgery reduced his seizures, but had the unanticipated consequence of severely damaging his long-term memory (Squire, 2009). H.M. retained some childhood memories, but he had a severe and lasting deficit affecting his memory for ongoing events. He did not remember people he had met; he could not retain his doctors' names; he could not recall activities he had just completed; he could not find his way around the hospital. However, he could answer questions, and he could repeat back a sequence of digits, though he later had no memory of having done so. His STM was intact, while his LTM was defective.

Consistent with this pattern, Baddeley and Warrington (1970, 1973) found that individuals with amnesia had intact recall for items presented at the end of the list (a normal recency effect) while memory was impaired for other list items, reflecting the impairment of LTM. This dissociation of function between STM and LTM (that is, intact STM but impaired LTM) might also be taken as evidence for separate stores; however a **double dissociation of function** would provide more persuasive evidence.

Double dissociation of function contrasting patterns of deficit in two patients or patient groups; provides evidence for functionally independent systems.

A double dissociation of function provides evidence of a functional dissociation between two tasks or cognitive processes. It was first described by Teuber (1955, p. 283) and has become a key pattern in cognitive neuropsychology. As Shallice (1979, p. 260) noted, 'strong neuropsychological evidence for the existence of neurologically distinct functional systems depends on double dissociation of function'. A dissociation occurs when a brain lesion causes impaired performance on one task (Task A), while performance on a second task (Task B) is unaffected. This provides, at best, weak evidence that the two tasks are controlled by different brain regions only one of which has been damaged by the lesion. After all, it could be the case that task B is simply easier than task A and less taxing for the individual with a brain injury. The site of the brain injury might not be directly relevant to the task. However, if the reverse pattern is also found, in a different patient, this provides stronger evidence, as it cannot be the case that the 'harder' task can be completed but not the 'easier' task. Such evidence would suggest that two different lesion sites are associated with the performance in Task A and Task B – the double dissociation shows that the two tasks are differentially localized (Jones, 1983).

If human memory is a unitary system, a double dissociation of function between LTM and STM would not be predicted. We have seen that in the amnesic syndrome there is a dissociation between STM and LTM, with STM being intact while (much of) LTM is deficient. While the reverse pattern – that is, impaired STM with intact LTM – is rare, such cases have been reported. The first reported case was that of K.F. (Shallice & Warrington, 1970), a man who sustained severe damage to the left parieto-occipital region of his brain in a motorcycle accident. In addition to language problems (a pronounced **aphasia** affecting speech, reading and spelling; for more on aphasia see Chapter 10), K.F. had impaired STM, as measured by digit span and recency. However, K.F. had relatively intact LTM. He had a digit span of just 2 (an average of 1.8 on letters, 2.3 on words and digits) and yet performed normally on a paired-associate task (requiring LTM). Warrington and Shallice (1972) found that K.F.'s STM deficit was more pronounced in auditory memory than in visual memory, and his long-term memory processes were normal (Warrington & Shallice, 1969). Shallice and Warrington (1974) found that K.F.'s problems were further limited to verbal stimuli such as words and digits, while his immediate recall of other sounds (e.g., cats meowing, a ringing telephone) was unimpaired. Since K.F., a number of similar cases have been reported involving impaired STM as measured by span-type tasks and intact LTM function (e.g., Saffran & Marin, 1975; Shallice & Butterworth, 1977; Warrington et al., 1972).

Aphasia
the term given to a group of language disorders that occur following brain injury.

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The case of P.V., an Italian woman with similar deficits to K.F., has been studied over many years. She showed a stable pattern of selective STM impairment (as measured by digit span and other such measures) with spared LTM after a left hemisphere stroke (Basso et al., 1982; Vallar, 2019). P.V.'s performance on a non-word repetition (span) task showed that she performed reliably only when repeating back single disyllabic items. When the non-words had three syllables, a 20 per cent error rate was seen. Her error rate rose to 100 per cent for four- and five-syllable non-words. By contrast, she showed normal long-term learning when presented with meaningful material; compared to a control group her scores fell within the normal range, albeit towards the lower end of that range (for these data see Baddeley et al., 1988). While such cases tend to be rare, and differ from one another due to the nature and sites of brain injury, this contrasting pattern of impaired STM and intact LTM processes has now been documented on many occasions. Reviews by Logie (2019) and by Shallice and Papagno (2019) show that there are now around 20 such cases in the literature, providing good evidence for separate short-term and long-term stores and for the fractionation of short-term memory. Such cases have played an essential role in the development of models of working memory, a topic we will look at in the following section.

Evaluation

The double dissociation of function in LTM and STM was an important development for theories of memory. The Atkinson and Shiffrin model suggested that information passes through a unitary STM in order to enter LTM. The characterization of STM as a unitary store did not explain the pattern of function seen in individuals such as K.F., who have impaired STM function, but whose LTM is relatively unimpaired. If STM is compromised, how is information getting access to long-term memory? It would seem that STM is not a single, unitary store. The early models focused on the verbal aspects of STM, but are there other kinds of STM? Furthermore, short-term memory allows us to hold information in an accessible state so that we can act on it, but there is also a range of processes we can apply to allow us to manipulate and use the information so as to set and achieve goals. What is the relationship between these processes and STM? The idea of a unitary STM store was abandoned, and replaced with a concept called **working memory**.

Working memory
the system in which information is held and manipulated in order to perform a task.

Miller et al. (1960) introduced the term 'working memory' to refer to memory that allows us to make plans and to keep track of goals. The concept of working memory overlaps substantially with that of short-term memory, and includes storage and processing components. Miller and colleagues described working memory only very briefly and they did not provide any detail on its components. They wrote that when a plan is being executed it has 'special access to consciousness and special ways of being remembered. . . . We should like to speak of the memory we use for the execution of our plans as a kind of quick-access, "working memory"' (p. 65). This leaves the term 'working memory' open to interpretation so that it has come to mean different things to different theorists. The most influential account of working memory was developed and empirically tested in a series of studies, beginning with Baddeley and Hitch (1974). Working memory has become one of the most important and debated concepts in cognitive psychology, and it is to this concept that we now turn.

Box 6.2 Practical Application: Cognitive lockup – working memory, attention and human error

Chapter 4, p114

In Chapter 4, we looked at attention and the central role it plays in cognition. Attention is closely related to working memory – that is, the memory that supports the cognitive operations currently in mind, whether that is reading a textbook or solving a puzzle. When attention fails, various cognitive errors can result. One such error is **cognitive lockup**. Cognitive lockup refers to a pattern of cognitive error that results from the human tendency to detect and deal with faults sequentially. It leads to a delay in responding to consecutive failures and is one of a number of cognitive error-producing mechanisms that has serious real-world practical applications. It is particularly troubling in automation contexts, which often require attending to, and switching attention across, multiple variables.

Cognitive lockup
a type of cognitive error that results from the human tendency to detect and deal with faults sequentially.

The term 'cognitive lockup' was introduced by Moray and Rotenberg (1989) in a study that examined the behaviours of student participants acting as operators during a fault-detection task. The task involved controlling set points for temperature, level and flow rate in a simulated thermal hydraulic system. Various disturbances were applied to the system, and participants had to respond to and deal with the failures as they arose. The participants' eye movements were recorded as an index of their locus of attention, along with their behavioural responses to the failures (key presses on a computer). The behavioural and eye movement data revealed a preference for serial fault management and a tendency for the participants to examine faulty subsystems more frequently. This led to a failure to switch attention appropriately and delayed action on other subsystems.

A real-world example of cognitive lockup resulted in the Eastern Air Lines Flight 401 crash of 1972. Flight 401 was a scheduled flight from New York to Miami, which crashed into the Florida Everglades, killing 101 people; 75 passengers and crew survived. An experienced crew flying a new aircraft had an unremarkable flight until coming towards landing. On approach to Miami airport, the crew lowered the landing gear. The nose landing gear indicator light failed to engage. Not knowing whether this was due to a faulty bulb or a failure of the nose gear, the captain requested clearance to circle and climbed to 2000 feet. The crew then investigated the faulty bulb. One member removed the bulb casing and attempted to replace it. Another crew member climbed out of the cockpit to get a view of the landing gear in order to confirm it had engaged. At some point, the captain inadvertently nudged the control wheel, disengaging the autopilot and causing the plane's nose to tilt downwards. This went unnoticed by the crew, as did an auditory alarm signalling a drop in altitude. While the crew were still focused on the landing gear light, the aircraft dropped to 900 feet. By the time the crew noticed, it was too late. The aircraft lost too much altitude and crashed. The accident report released by the National Transportation Safety Board noted that the likely cause was the failure of the crew to monitor the flight instruments during the final four minutes of flight and to detect the unexpected descent in time to correct for it. They were preoccupied with the malfunctioning landing gear light and did not switch attention appropriately to deal with the drop in altitude.

Such incidents are referred to as 'loss of control' incidents and are, unfortunately, not uncommon. The Air France AF447 crash of 2009 resulted from a similar loss of control, when the autopilot disengaged and the aircraft stalled, leading to the loss of the aircraft and all 228 passengers and crew on board. As in Flight 401, the catastrophic failure in cognition occurred over just four minutes of an otherwise competent and uneventful flight (Oliver et al., 2017).

Human error is often not the only factor at work in loss of control incidents. In the case of Flight 401, a safety feature of the aircraft allowed the autopilot to be disengaged easily by nudging the control wheel. An unintended consequence of this was that it became too easy to disengage the autopilot inadvertently. Scheduled civilian air travel is statistically 'ultra-safe' – that is, the risk of disastrous accident is below one accident per million events. As technology has advanced to control more systems, a paradox has arisen, referred to as 'the paradox of almost totally safe systems' (Amalberti, 2001). In the case of aviation, technology has improved safety by controlling and providing information on many of the aircraft's systems, reducing the complexity of the environment in which the crew is operating. However, in doing so, it has also reduced a pilot's situational awareness in that he or she spends much of their time monitoring digital indicators (the 'glass cockpit') and not so much time actually flying the airplane. This means that when an unexpected occurrence arises, the cognitive system may be less prepared to deal with the novel event, leading to errors. The paradox means that ultra-safe systems behave differently than less safe systems, and therefore require a different approach to detect and prevent errors (Amalberti, 2001; Oliver et al., 2017). A complex web of factors rather than one single cause tends to account for disastrous errors in such cases, with issues around machine–human handover requiring particular attention (for further examples from aviation see Dismukes et al., 2007).

Recent research has shown that individuals with better working memory and sustained attention have an advantage when detecting these kinds of failures, and that this advantage is particularly evident in situations involving consecutive failures. A study by Jipp (2016) examined individual differences in the memory factors underlying cognitive lockup. Participants were required to monitor automated aircraft functions. An initial automation failure was applied to the system. It occurred alone or was followed by a consecutive failure. Participants' reaction times to respond to the failures were recorded and standardized tests were used to assess their working memory capacity and sustained attention.

The results showed that participants' reaction times were slower for consecutive failures compared to initial failures. However, this effect was stronger for those with poorer working memory and sustained attention scores. Participants who performed strongly on the tests of working memory and sustained attention showed a small advantage over those with poorer working memory and attention when responding to initial failures. This advantage was seen to increase, however, when consecutive failures occurred. The study has implications for both the selection and training of personnel in tasks where cognitive lockup might be predicted or where it might have serious consequences.

Research is beginning to explore the interactions between working memory and attention that might allow an operator to avoid cognitive lockup. Unsworth and Robison (2019) have proposed a *cognitive-energetic* account of individual differences in working memory capacity and sustained attention that relates to differences in intrinsic alertness, whereby participants who are lower in working memory capacity are less skilled at controlling the intensity of attention compared to individuals who have high working memory capacity. Such accounts may be useful in understanding loss of control incidents and avoiding disastrous consequences. They are also relevant to individual differences in mind wandering, a topic explored in Box 6.5.

WORKING MEMORY

As previously discussed, if LTM is dependent on STM processes, then findings from patients such as K.F. and P.V. cannot be explained if we retain the assumption that STM is a unitary store. K.F. had severely deficient STM, as measured by digit span and the recency effect, and yet he showed intact long-term memory, and performed normally on tasks requiring information to be transferred to LTM, such as the paired-associate task. This finding suggests that different subsystems must underlie tasks such as digit span and word list learning. For K.F., and individuals with a similar pattern of performance after brain injury, the subsystem of STM underlying digit span is impaired, but some components of STM remain intact and allow relatively spared performance on tests of LTM. In other words, K.F. must have some intact short-term memory in order to demonstrate the pattern of performance he does on memory tasks. The concept of working memory (WM) has been helpful in understanding the pattern of ability in such neuropsychological case studies as well as in other real-world scenarios such as that illustrated in Box 6.3.

Working memory has been described as the 'workbench' of human cognition (Klatzky, 1980). It is 'the collection of mental processes that permit information to be held temporarily in an accessible state, in the service of some mental task' (Cowan, 1998, p. 77). It can be thought of as 'the small amount of information held in a readily accessible state, available to help in the completion of cognitive tasks' (Cowan, 2010, p. 447). Miyake and Shah (1999, p. 450) proposed a comprehensive definition of working memory that can be applied across the various models:

> *working memory is those mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition, including novel as well as familiar, skilled tasks. It consists of a set of processes and mechanisms and is not a fixed "place" or "box" in the cognitive architecture. It is not a completely unitary system in the sense that it involves multiple representational codes and/or different subsystems. Its capacity limits reflect multiple factors and may even be an emergent property of the multiple processes and mechanisms involved. Working memory*

is closely linked to LTM, and its contents consist primarily of currently activated LTM representations, but can also extend to LTM representations that are closely linked to activated retrieval cues and, hence, can be quickly activated.

Miyake and Shah's (1999) definition emerged from a small conference on working memory in which presenters were each asked to give their definition of working memory; no two definitions agreed (Cowan, 2010). The term working memory means different things to different people, with researchers using the term in at least three ways (see Beaman, 2010; Cowan, 1998). Researchers may view working memory as:

- the focus of attention, consistent with James's (1890) view of primary memory (e.g., Engle, 2002)
- the information that is temporarily activated in the system, including information about our current goals and plans, consistent with Miller et al.'s (1960) original use of the term working memory
- a sensory-specific multicomponent storage system for short-term storage and processing of information (e.g., Baddeley & Hitch, 1974).

Accounts of working memory also vary in their approach to the relationship between working memory and long-term memory. Cowan's embedded processes model (e.g., 1995a, 1999) presents WM as consisting of a capacity-limited focus of attention and a temporarily activated subset of long-term memory (see Figure 6.7). This account places emphasis on the interaction of attention and memory, and considers WM in the context of LTM. Thus, by this account, three components contribute to WM: temporarily activated information that is not yet accessible to conscious awareness; memory within the focus of attention; and information stored in LTM, which is currently inactive but could be retrieved/activated if relevant to the task (Cowan, 1999; see also Oberauer's (2002) three-embedded-components model). The model proposes that these key components contribute to WM as embedded processes, with the current focus of attention being a subset of active memory and active memory presented as a subset of LTM (see Figure 6.7). By this account, information is lost from WM through processes of both decay and displacement. The focus of attention is capacity limited and information can

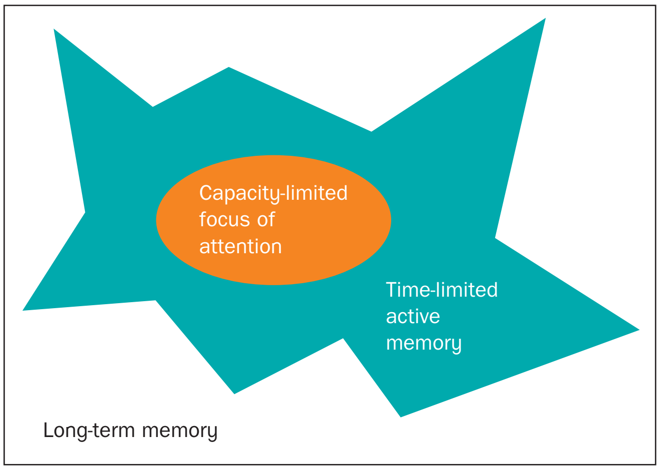

Figure 6.7 Cowan's embedded processes model.
The embedded processes model presents WM as three components: temporarily activated information that is not yet accessible to conscious awareness; memory within the focus of attention; and information stored in LTM, which is currently inactive but could be retrieved/activated if relevant to the task.

Source: Reprinted from Cowan (1998), with permission from Elsevier.

easily be displaced from it, while the activated memory is time limited, and information can decay if not rehearsed. In contrast to the multiple component model discussed below, in Cowan's model, the nature of the representation may vary in WM but it does so within a single structure that has fixed properties (see also Engle & Oransky, 1999), thus 'the distinctness and non-interchangeability of phonetic and spatial information occurs because different types of features are being activated, not because of distinctly different storage modules' (Cowan, 1995a, p. 36).

On the other hand, multiple component models of WM propose that WM can be fractionated into component parts. This approach sees the principal function of WM as the coordination of resources, and focuses on identifying and examining the nature of the structures that carry out this function (Baddeley, 1986; 1992a, 1992b). WM consists of both storage and processing components (Baddeley, 1986) and might be defined as 'the simultaneous processing and storage of information' (Salthouse, 1990, p. 104). Towse and Hitch (2007, p. 110) see WM as a 'multicomponent, limited-capacity system responsible for retaining as well as transforming fragile representations'. For Baddeley (1992b), the term working memory 'refers to a brain system that provides temporary storage and manipulation of the information necessary for such complex tasks as language comprehension, learning and reasoning' (p. 556). Baddeley and Hitch's (1974) working memory model (and its subsequent versions) has been the most influential of such accounts, and it is to this model that we now turn.

Box 6.3 Practical Application: Fatal distraction? Working memory and driving performance

The ability to multi-task is a key component of safe driving. As the task requirements increase, so too does the working memory load, and performance on one or other task will begin to suffer. Working memory (and in particular the central executive, a component we will learn about shortly) plays a central role in controlling the allocation of resources across competing tasks. Many of the difficulties facing drivers involve what are essentially dual-task demands: paying attention to, or avoiding being distracted by, features of the environment that may not be central to the primary task of safely navigating and controlling a motor vehicle. We can be distracted by factors external to the vehicle – a dog running onto the road, seeing a person we know – or by factors inside the vehicle – a radio commentary or a conversation with a passenger, for example. Even mundane cognitive tasks, such as recalling a grocery list, can impair driving performance (Louie & Mouloua, 2019).

This was demonstrated in a dual task procedure by Strayer and Johnston (2001), who had participants complete a driving-analogous task (pursuit tracking) while conducting a conversation by mobile phone (hand-held or hands-free) or listening to talk radio. Participants were required to react to red and green lights, simulating responses to traffic lights. Reactions to the lights were measured in terms of failures to detect lights and delayed reactions. The results showed that the probability of a failure to detect the light and react appropriately doubled for participants using a mobile phone, whether hand-held or hands-free. Passively listening to talk radio did not affect performance. Further research has shown that driving performance is significantly worse for mobile phone conversations compared to driver–passenger conversations (Drews et al., 2008), reflecting the shared environment of in-person exchanges (see also Oviedo-Trespalacios et al., 2016).

A secondary task may even be advantageous in some conditions. Traffic conditions are a clear determinant of working-memory load. A study by Nijboer et al. (2016) used a simulated multi-lane driving task in which participants were assigned to one of two scenarios. One scenario required the driver to navigate a quiet road, with no traffic. The second scenario required driving in traffic and overtaking

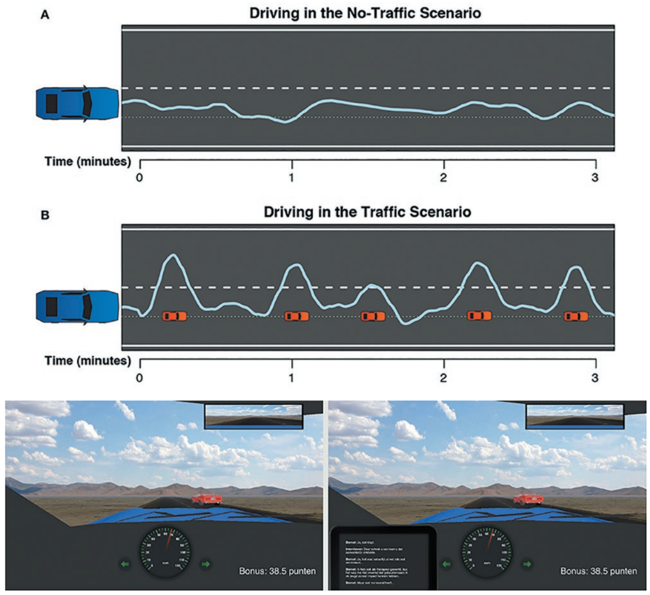

Figure 6.8 Nijboer et al.'s driving task.

The top panel shows two examples of driving paths in the (A) No-Traffic and (B) Traffic scenarios. The blue line shows the path taken by the participant, while the green dotted line shows the middle of the lane, and the white dashed line shows the boundary of the two lanes. The red cars represent slow moving traffic which must be overtaken by participants. The bottom panel shows the simulated driving environment used by Nijboer et al. (2016); left, the view as seen during the single, passive listening and radio-quiz conditions and, right, as seen during the tablet-quiz condition. *(Note that the study was conducted in a country with right-lane driving and the materials reflect this.)*

Source: Nijboer et al. (2016).

vehicles when necessary. Four different secondary task conditions were then applied: no secondary task; listening to a radio talk programme; listening to and giving responses to a radio quiz show using a button press response; and reading and giving responses to quiz items using a tablet device. Measures included driving speed, deviations from lane, overtake distance, direction changes and collisions.

In both driving scenarios (traffic and no traffic), performance was the worst in the tablet quiz condition, which resulted in dangerous driving. This is to be expected given the increased working memory load and the overlap with the task requirements of the primary driving task. It is also consistent with studies examining the effects of texting (e.g., Bayer & Campbell, 2012) and of social media use (e.g., George et al., 2018; Hashash et al., 2019) while driving.

Interestingly, however, Nijboer et al. (2016) found that the best driving performance was associated with passively listening to the radio or answering the radio quiz questions, rather than driving without any secondary task. In the traffic scenario, passively listening to the radio produced the best performance. These results suggest that listening to the radio might be advantageous in monotonous driving conditions and that the nature of the secondary task and the overall driving context are key factors.

Baddeley's Working Memory Model

According to Baddeley (1986), 'the essence of the concept of working memory lies in its implication that memory processes play an important role in non-memory tasks' (p. 246). WM is not just a store for maintaining information in consciousness – it plays an integral role in ongoing or 'online' cognitive processing. Baddeley and colleagues' multi-component working memory model proposed three main components to working memory: the **central executive**,

Central executive
the component of working memory proposed to control and coordinate the activity of the other components, including the phonological loop and the visuo-spatial sketchpad.

Visuo-spatial sketchpad
the component of working memory proposed for the temporary storage and manipulation of visual and spatial information.

Phonological loop
the component of working memory proposed for the temporary storage and manipulation of sound or phonological information. It comprises a short-term phonological store for auditory memory traces and an articulatory rehearsal component to reactivate memory traces.

Episodic buffer
the component of working memory proposed for the temporary storage of information integrated from the phonological loop, the visuo-spatial sketchpad and long-term memory into single structures or episodes.

the **visuo-spatial sketchpad** and the **phonological loop** (e.g., Baddeley, 1986; Baddeley & Hitch, 1974). A further component, the **episodic buffer**, was subsequently added (see Baddeley, 2000). Figure 6.9 illustrates the relationships between the main components of this WM model. Baddeley and Hitch (1974, p. 76) described the core of the WM system as 'a limited capacity "work space" which can be divided between storage and control processing demands'. This idea of a limited capacity system remains a basic assumption of the approach in later formulations (e.g., Baddeley, 1986).

The central executive provides the attentional control of working memory (Baddeley, 1996a). It is modality-free, in that it can deal with input from any modality (visual, auditory, etc.), and is similar to attention. The central executive is served by two subsystems that are specialized for visual-spatial and auditory-verbal information; these are the visuo-spatial sketchpad and the phonological loop, respectively. These components hold and manipulate modality-specific information, the visuo-spatial sketchpad dealing with visual information and the phonological loop dealing with speech-based information. The pattern of deficit described in the case of K.F., encountered above, suggests damage to the verbal aspect of working memory, while the other components remain unaffected by the brain injury, thus allowing access to long-term memory and effective long-term memory functioning. While Baddeley's model focuses on visuo-spatial and verbal-auditory input, research is beginning to explore modalities other than these (see Lawson et al., 2015, for a discussion of tactile and haptic working memory). We will first look at the component of WM that has received the most scrutiny: the phonological loop.

The phonological loop

The phonological loop is specialized for speech-based information. This component of WM is closest to earlier notions of a short-term memory store (e.g., Atkinson and Shiffrin, 1968), and is implicated in tasks involving verbal materials, such as digit span and serial position tasks (see Figure 6.11). While Baddeley and Hitch (1974) initially called this component the 'articulatory loop', the term 'phonological loop' replaced it, to reflect the more central processing involved in subvocal articulation; the 'inner voice' does not rely on the speech musculature, and is retained in individuals who have brain damage affecting overt articulation (conditions such as **anarthria** for example; see Baddeley & Wilson, 1985).

Anarthria
a disorder affecting the motor function underlying speech.

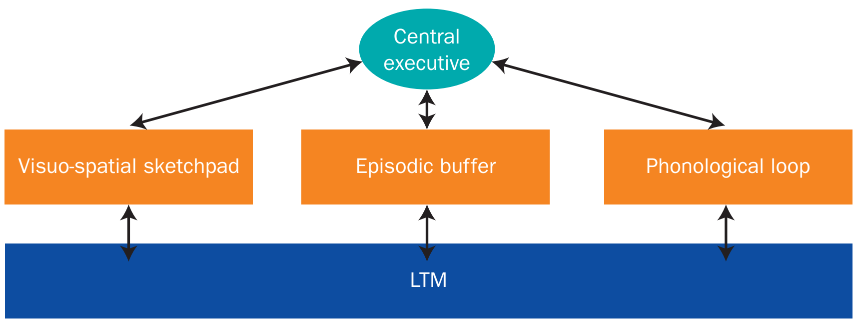

Figure 6.9 The working memory model showing the interaction with long-term memory structures and the episodic buffer.
The three main components of working memory – the central executive, phonological loop and visuo-spatial sketchpad – interact with structures in long-term memory.

Source: Adapted from Baddeley (2000).

Baddeley et al. (1975) proposed that the phonological loop has a limited capacity restricted by temporal duration, and that it holds as many verbal items (words, letters, etc.) as a person can say in about two seconds.

The WM model proposes that the phonological loop has two subcomponents: a phonological store, which holds speech-based information for a period of about two to three seconds (unless the information is rehearsed), and an articulatory control process, which allows the maintenance of information in the store and converts visual information (such as a written word) to a speech-based form. The articulatory control process uses subvocal rehearsal to fulfil these functions, a process that can be likened to '**inner speech**' (Baddeley, 1986, 1992). Auditory presentation of phonological (speech-based) information gains direct access to the loop, while visually presented information gains access via subvocal articulation by the articulatory control process. **Rehearsal**, which refers to a number of processes by which content being held in working memory is refreshed, is assumed to play a key role in verbal working memory in particular (the nature of that role continues to be debated; see for example Oberauer, 2019). Evidence for the phonological loop comes from four main sources or benchmark findings (e.g., see Baddeley, 2012), which we will now examine.

Inner speech
the subjective experience of hearing our thoughts, as if 'spoken' by an inner voice, when reading silently for example.

Rehearsal
a set of processes by which we can act on currently active information.

Word length effect
the recall advantage for shorter words compared to longer words when immediate serial recall is tested.

1. The word length effect

If participants can hold in memory as many words as they can say in two seconds, then one might reason that the shorter the words are, the more of them that will be remembered. The **word length effect** refers to the advantage found for recall of lists of short words (e.g., car, lake, pen, chair) compared to longer words (e.g., television, university, candlestick, hippopotamus). The duration it takes to articulate the word is the crucial factor, not the number of syllables (Baddeley et al., 1975). The words 'ticket' and 'harpoon' both contain two syllables, but 'harpoon' takes longer to say than 'ticket'. The longer the word, the more time it takes to refresh the word in the phonological store by subvocal articulation, therefore fewer long words can be accommodated in the store. This difference in rehearsal underlying the word length effect is supported by the finding that the effect is eliminated by subvocal rehearsal; if a participant has to repeat an irrelevant string (e.g., saying 'the' over and over) while learning the list, the advantage for shorter words disappears (Baddeley et al., 1975).

While the word length effect is well established, there have been some contradictory findings. The difference in effect for words with the same number of syllables but different articulation speeds ('ticket' versus 'harpoon') has not always been replicated using different word sets (for a discussion see Mattys et al., 2018). Furthermore, some studies have shown that the word length effect may be affected by orthographic neighbourhood size – that is, number of words that differ from the target word by one letter (e.g., *plant* and *plank*). Shorter words tend to have more neighbours, and while the words used in experimental word lists are carefully controlled for factors such as concreteness and imageability, neighbourhood size had not been controlled in demonstrations of the word length effect. A confounding variable had therefore been introduced into such studies. Jalbert et al. (2011) identified this issue, and found that the word length effect disappeared when short (one syllable) and long (three syllable) words were controlled for neighbourhood size (see also Derraugh et al., 2017). This suggests that linguistic properties other than word length are also of relevance and points to a role for LTM in WM tasks (information about the properties of words is stored in LTM). However, Guitard et al. (2018) failed to replicate the effect, and found a large and reliable word length effect after controlling for neighbourhood size.

We might predict cross-linguistic differences in memory span that reflect variation in word length across languages. This has been demonstrated in a number of languages, with estimated spans of 9.9 in Chinese (Hoosain, 1984), for example, compared to 5.7 in Arabic (Naveh-Benjamin & Ayres, 1986). Mattys et al. (2018) reported a digit span of 8.8 for Chinese compared to 6.9 for English speakers, and a word span difference of 7.1 for Chinese and 5.2 for English. Chen et al. (2009) found that the mean digit span of a sample of English speakers was equivalent to the lowest individual score of their Mandarin-speaking sample (see also Mattys et al., 2018). The relatively larger digit span of Chinese speakers has been argued to reflect faster articulation rates for Chinese digits, a finding demonstrated both with Mandarin (Hoosain, 1984; Hoosain & Salili, 1988; Mattys et al., 2018) and Cantonese (Stigler et al., 1986). Ellis and Hennelly (1980) reported a shorter digit span in Welsh compared to in English, reflecting longer articulation times for Welsh words and the smaller number of Welsh words that could be articulated in two seconds. **Coarticulation effects** of words (see Chapter 10) have also been shown to be an important factors in the Welsh–English difference however (Murray & Jones, 2002). Such data provide further evidence for a speech-based store with temporal limits. The cross-linguistic data concur with developmental data showing that span increases through childhood (from about the age of 4 years) as speech rate increases (e.g., Hulme et al., 1984). It is important to understand such cross-linguistic differences, not least because digit span measures form the basis of many neuropsychological and educational test batteries (e.g., see López et al., 2016).

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Coarticulation effects
the modification that occurs to any given speech sound due to the sounds that occur before or after it in the speech chain.

2. The effects of articulatory suppression

As observed above, the ability to rehearse subvocally can be disrupted if we require a participant to rehearse a string that is not relevant to the current task. For example, the participant might be required to repeat the word 'the' or to count to three over and again, a process referred to as articulatory suppression (Murray, 1965). **Articulatory suppression** reduces memory span (Peterson & Johnson, 1971) and eliminates the word length effect (Baddeley et al., 1975). It also disrupts transfer of visually presented material to the phonological store, leading to poorer memory (Baddeley et al., 1984). This difference between visual and auditory material has been interpreted as reflecting direct access to the store for auditory information (e.g., spoken words), while visually presented information (e.g., written words) requires sub-vocalization for access (e.g., Baddeley, 2012). The repetition of an irrelevant word or string uses the capacity of the articulatory control process, and prevents information in the phonological store from being refreshed, leading to a detriment in performance. Articulatory suppression does not eliminate phonological recoding completely, but does reduce it considerably. For example, Norris et al. (2018) were able to induce a dramatic deficit in their participants across a variety of tasks, with degraded performance analogous to patients with a phonological STM deficit.

Articulatory suppression
the interference that occurs when participants are required to repeat (non-relevant) verbal material while engaged in a primary task drawing on the same modality.

3. The irrelevant speech effect

Recall of visually presented verbal material is poorer when irrelevant speech is presented during learning (e.g., Larsen & Baddeley, 2003). One does not need to understand what is being said in order for the speech to disrupt processing – even hearing irrelevant speech in an unfamiliar language (Colle & Welsh, 1976) or nonsense words (Salame & Baddeley, 1986) produces the effect. Any speech gains access to the phonological store and therefore irrelevant speech uses some of the available capacity, reducing performance on the target task. Initially it appeared that non-speech sounds did not elicit the effect; Colle and Welsh (1976) found no effect for white noise, for example.

But in fact some non-speech sounds, particularly changing-state sounds, do disrupt STM. Jones and Macken (1993) showed that a stream of fluctuating tones disrupted recall of visually presented material in the same way as speech. Box 6.4 examines a number of other ways in which extraneous sound can affect working memory.

Box 6.4 Practical Application: Understanding the effects of background noise

Many people work or study in open-plan office settings, relying on working memory to reduce the influence of distracting stimuli and to allow resources to be allocated to the task at hand. However, it is not always easy to dismiss the distracting influence of background noise. Banbury and Berry (2005) found that 99 per cent of workers in open-plan offices reported impaired concentration caused by various office noises; the sound of telephones ringing at unattended desks and background speech sounds were particularly distracting. Banbury et al. (2001) noted that the distraction effect is rooted in the changing nature of the acoustic signal, which gains our attention; repetitive sounds or tones are not as disruptive and the sound level itself would also seem to be relatively unimportant. If reducing the sound level does not eradicate the ill effects on cognition, how might workplace design compensate for the effect?

One way to reduce the effect on cognitive performance is to mask the office sounds by adding a continuous noise signal. It may seem paradoxical to address the problem by adding more sound, but the continuous signal is designed to reduce the perception of acoustic change, which is the basis of the distraction. A study by Schlittmeier and Hellbrück (2009) examined the use of background music compared to continuous noise for masking office sounds. Their participants completed a serial recall task while office noise was played at 55 dB, a typical sound level in open-plan offices. The office noise was presented alone, or was overlaid with legato music, staccato music or continuous noise. A silence condition was also included. While the participants reported preferring the music to the continuous sound, memory performance was better only in the continuous noise condition. That is, office noise affected serial recall performance negatively, in comparison to silence, whether it was presented alone or overlaid with music. Only the office noise with continuous noise produced similar performance to the silence condition. So, while the subjective ratings did not favour continuous noise, cognitive ill effects were minimized only in that condition.

The type of noise and the interaction of noise type and task type are also of relevance. Schlittmeier et al. (2015) examined the effects of different levels of road traffic noise within a moderate range of 50–70 dB(A) on cognitive performance. Four traffic noise conditions were compared with background speech and a silence (control) condition. The tasks used varied in terms of reliance on attention or storage functions of working memory. Three experiments allowed comparison of performance on the Stroop task, which relies on attention, a mental arithmetic task, which makes use of both sustained attention and short-term storage, and a verbal serial recall task, which relies on WM storage functions.

The results showed that road traffic noise disrupted performance in tasks that require attentional control, namely the Stroop test and the mental arithmetic task. However, consistent with the irrelevant sound effect, none of the road traffic noise conditions had an effect on serial recall. Performance in the serial recall task was disrupted however by background speech. Performance on the mental arithmetic task was also found to be disrupted by background speech. These results demonstrate the effect of temporal-spectral variability in background speech on WM storage functions; the traffic noise, lacking this variability, had no effect. Similar effects can be seen for aircraft noise, with working memory seen to be largely immune from the detrimental effects evident in long-term memory tasks (Molesworth et al., 2017; see also Hygge, 2003; Sörqvist, 2010). In addition, easier tasks may be more affected by noise level, while difficult tasks are more sensitive to the type of noise (Golmohammadi et al., 2020).

4. The phonological similarity effect

Phonological similarity effect the finding that recall is poorer for an ordered list of verbal items when the items sound alike, compared to performance on lists of items that do not sound alike.

Recall is poorer for an ordered list of verbal items when the items sound alike, relative to performance on lists of items that do not sound alike. This is referred to as the **phonological similarity effect**. Items that are similar in meaning (as opposed to sound) do not show this effect. For example, the sequence 'pit, day, cow, pen, rig' is easier to recall than the sequence 'man, cap, can, map, mad' (Baddeley, 1992b). The second list contains items that sound more alike than the first list. Similarly, recall of lists of similar-sounding letters (e.g., c, b, d, v) is poorer than for lists of dissimilar letters, (e.g., c, r, m, k) (Conrad, 1964). If we assume that the phonological store uses a speech-based or phonological code, then refreshing the items in the store makes use of phonological fragments within the items; confusion arises as the number of shared fragments increases. The phonological similarity effect disappears under conditions of articulatory suppression, supporting the use of a basic phonological code (Richardson & Baddeley, 1975). However, when information from LTM comes into play, the phonological similarity effect may be diminished or absent. Nursery rhymes and song lyrics commonly utilize words with shared sounds, and memory for such sequences may well be improved (e.g., Copeland & Radvansky, 2001). Under some conditions, a phonological similarity *facilitation* effect can even be observed in working memory span tasks (Chow et al., 2016).

Functions of the phonological loop

Given that the phonological loop holds and manipulates speech-based information, we could expect to see a substantial and obvious role for this WM structure in language and related cognitive processing. However, in adults, the role is not as obvious as one might expect. As Baddeley (1992b) notes, individuals who have a brain injury affecting phonological loop functioning show relatively few signs of general cognitive impairment. For example, the case of P.V. (discussed above) described by Baddeley et al. (1988), involved a severely reduced digit span (of one or two items) following a left hemisphere stroke, yet her day-to-day life was relatively unaffected. She ran a shop successfully and she raised a family. Her intelligence and short-term *visual* memory were normal and her language function was relatively intact, with normal language comprehension for all but the most convoluted of embedded sentences (sentences that require you to hold the beginning of the sentence in mind until you get to the end, with a number of intervening clauses). The case of P.V. and other single case studies in neuropsychology have been tremendously important in the development of the concept of the phonological loop (Baddeley & Hitch, 2019).

What, then, are the functions of the phonological loop? The phonological loop is known to play a key role in the acquisition of new vocabulary, not just in the person's native language but also in a second language (Service, 1992). Baddeley et al. (1988) found that P.V., who had intact long-term memory as measured by performance on a paired-associate task, showed a severely reduced ability to learn words in Russian, a language with which P.V. was not familiar. The loop's precise role in other aspects of adult language processing, such as complex speech comprehension, remains controversial (see Caplan & Waters, 1999; Engle & Conway, 1998; Was & Woltz, 2007). In children, poor performance on measures of phonological loop function is associated with poor vocabulary learning (e.g., Gathercole & Baddeley, 1989; Gathercole et al., 1997; Service, 1992), and very poor phonological loop skills are associated with developmental disorders such as specific language impairment (SLI; see Gathercole & Baddeley, 1990). The phonological loop would also seem to play an important role in learning to read (for an overview see Baddeley & Hitch, 2019). There is evidence that the phonological loop is involved in the temporary storage of part solutions during mental arithmetic, while the central executive performs the more demanding manipulations. For example, Logie et al. (1994) found effects of both articulatory suppression and irrelevant speech on an addition task using a series of two-digit numbers (e.g., 12 + 43 + 18 + 26 + 35 = ?). Such data suggest a specific role for the phonological loop in mental arithmetic, although a more substantive role is performed by the central executive (Adams & Hitch, 1998). The phonological loop may also have a role in action control (see Baddeley et al., 2001).

The visuo-spatial sketchpad

Suppose you are asked to say how many windows there are on the front of your house. To answer this question, you will most likely construct a mental image of your house and inspect that image in order to count the number of windows. Or suppose you are asked to describe the Sydney Opera House. Again, it is likely that you will try to visualize the building in your mind's eye, and try to describe what it looks like based on the visual image. The ability to manipulate visual images relies on visual short-term memory, and Baddeley and Hitch's model proposed that this type of memory is provided by a separate component, the visuo-spatial sketchpad (VSSP).

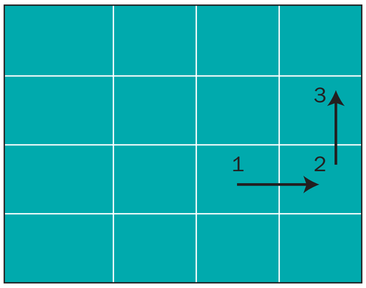
We saw above how neuropsychological case studies of individuals with very short verbal memory spans have been used to support the existence of the phonological loop component of working memory. There are fewer cases of selective impairments affecting visuo-spatial working memory, but some cases have been reported that support a WM component specialized for visuo-spatial processing. Hanley et al. (1991) described the case of E.L.D., who reported difficulties learning to recognize new faces and routes after a right-hemisphere brain injury. E.L.D. had moved to a new part of the city, and reported difficulty in forming a mental picture of routes she had taken; instead she found herself having to rely on landmarks to find her way around. Her verbal memory span was similar to that of controls, and visual perception was normal, but she performed extremely poorly on tasks that required the temporary storage of visual and/or spatial information (see also Hanley & Young, 2019). Studies showing activation of the same inferior temporal areas during visuo-spatial, but not verbal, working memory tasks further support the fractionation of WM (e.g., Hamamé et al., 2012).

While the phonological loop is specialized for speech-based information, the VSSP is specialized for dealing with visual and spatial information. The VSSP, like the phonological loop, has a limited capacity, of about three or four objects according to Baddeley (e.g., 2003). Logie (1995) suggested that two components comprise the VSSP. A **visual cache** stores information relating to visual form and an **inner scribe** allows spatial processing. Evidence supports the notion of separate but strongly interconnected components for visual and spatial information. Logie (1995) proposed that the VSSP is analogous in structure to the phonological loop. By this account, the visual cache is similar to the phonological store, in that it is a passive store that holds information, while the inner scribe (similar to the articulatory control process) maintains information in the store through a type of rehearsal process. Logie's account (e.g., 1995) sees long-term memory involvement as central to VSSP functioning.

Visual cache
the component of the visuo-spatial sketchpad, within working memory, that stores visual information.

Inner scribe
the component of the visuo-spatial sketchpad, within working memory, that allows spatial processing.

VSSP processing is evident in performance on the Brooks matrix task. Brooks (1967) devised a matrix task in which participants were presented with sentences to commit to memory; the sentences were either easy to visualize or could not be visualized (see Figure 6.10, overleaf). In a 'spatial condition', the sentences were accompanied by a 4 × 4 matrix, which could be used to aid memory, as the sentences could be visualized. Sentences such as 'in the starting square put a 1', 'in the next square to the right put a 2',



Visualizable/spatial instructions
in the starting square put a 1
in the next square to the right put a 2
in the next square up put a 3
Non-visualizable/nonsense instructions
in the starting square put a 1
in the next square to the quick put a 2
in the next square to the good put a 3

Figure 6.10 Depiction of the Brooks matrix task.
In the Brooks matrix task, instructions are either easy to visualize using a 4 × 4 grid matrix or they cannot be visualized using the matrix. Memory for the sentences is then tested.

'in the next square up put a 3', were used in the spatial condition. In a 'verbal condition', the adjectives 'up-down' and 'left-right' in the sentences were replaced with the non-spatial adjectives 'good-bad' and 'quick-slow'. This produced sentences that could not be readily visualized using the matrix (e.g., 'in the starting square put a 1', 'in the next square to the quick put a 2', 'in the next square to the good put a 3'). Memorizing these sentences required verbal coding, using the verbal component of WM, the phonological loop. Participants were required to recall the sentences. In the spatial condition, they typically recalled about eight sentences compared to six in the verbal condition. Brooks then compared auditory and visual presentation of the sentences and found that for the spatial task auditory presentation was best, but for the verbal task visual presentation produced better performance. Auditory presentation in the spatial condition frees up the VSSP for the primary task, while visual presentation in the verbal task frees up the phonological loop for the primary task.

A neuropsychological case study reported by Hanley and Young (2019) showed a contrasting pattern of performance on the Brooks matrix task. While the typical pattern is superior recall of sentences in the spatial imagery condition compared to the 'nonsense' condition, E.L.D. showed significantly better performance in the nonsense condition, producing four times as many errors in the spatial condition (Hanley et al., 1991, p. 105). This pattern of performance is consistent with an account suggesting selective damage to the VSSP.

Baddeley et al. (1975) developed a task designed to interfere with performance on the Brooks task. In their pursuit rotor task, participants were required to track a moving target using a hand-held stylus (requiring visuo-spatial involvement) while sentences were presented auditorily. This dual-task requirement interfered with performance in the spatial condition, but not in the verbal condition (see Figure 6.11), providing further support for the involvement of the VSSP in the task. Baddeley and Lieberman (1980) later tried to separate out the effects of the visual and spatial components of this task using two secondary task conditions. In one condition, participants made brightness judgements, a task requiring visual but not spatial processing. In a second condition, blindfolded participants were required to track a moving pendulum with a torch. The pendulum contained a photosensitive cell that, when in contact with light from the torch, caused an auditory tone to be emitted. Sentences were again presented auditorily. The researchers found greater disruption of performance in the spatial condition, relative to the brightness judgement condition.

Data from dual-task performance shows selective interference of visual and spatial working memory tasks (e.g., Della Sala et al., 1999). Further evidence supporting the distinction between the visual cache and the inner scribe comes from neuropsychological

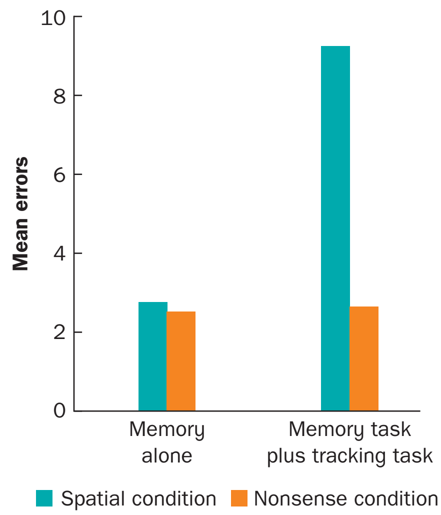


Figure 6.11 The effect of concurrent tracking on memory for visualizable (spatial) and non-visualizable (nonsense) sentences in Baddeley et al's., (1975) task.
Disruption of performance (mean errors per participant) is evident in the spatial condition, compared to the verbal condition. Data from Baddeley et al. (1975).

Source: Gathercole & Baddeley (1993).

case studies. Farah et al. (1988a) studied a patient, L.H., who sustained bilateral damage to the occipito-temporal regions of the brain in a traffic accident, while his parietal lobes were unharmed. L.H. performed well on tasks that involved manipulation of spatial imagery. He performed well on the Brooks task and on mental rotation tasks. He could point out locations on a map and he could also describe routes he was familiar with in the city where he lived. However, he showed impairments on visual tasks that required him to make judgements about relative size, colour and form. L.H.'s pattern of deficit suggested an impaired visual cache but an intact inner scribe, and his performance on spatial and visual imagery tasks supported Farah and colleagues' distinction between visual mental imagery and spatial imagery.

A second patient, R.T., showed the reverse pattern (Farah & Hammond, 1988). Following a stroke, R.T. had lesions affecting the right parietal lobe and part of his right temporal lobe. He had impaired spatial manipulation abilities, with poor performance on mental rotation tasks, for example, but reading and object recognition were intact. A further case (M.G.) reported by Morton and Morris (1995) presents a similar profile of spared visual imagery despite impaired spatial imagery. Luzzatti et al.'s (1998) case, E.P., demonstrated a similar impairment of spatial imagery while her ability to represent objects visually remained intact. Neuroimaging data support this dissociation, with separate brain areas for visual and spatial processing identified within the occipital, parietal and frontal lobes (e.g., Jonides et al., 1993; Sack & Schuhmann, 2012) consistent with the visual dual-pathway model (see Chapter 2).

Chapter 2, p46

The central executive

The central executive has been described as 'the workhorse and mastermind of human cognition' (Caplan & Waters, 1999, p. 77). It is the most important component of working memory – it is also the least well understood. Baddeley and Hitch's original model presented the central executive as a general processing mechanism that handled the more complex types of short-term memory task that were not delegated to the phonological loop or the VSSP. It was presented as a supervisory system that played a key role in controlling and regulating working memory function. It coordinated the activities of the phonological loop or the VSSP, and focused and switched attention. The central executive is generally seen as being involved in controlling active information, but not in storage per se (e.g., Baddeley & Logie, 1999), and it is useful to separate the storage and control functions of working memory. It is likely that the central executive consists of a number of subsystems, which have yet to be identified. Later versions of the model present the central executive as an attentional controller, similar to Norman and Shallice's (1986) concept of the supervisory activating system (SAS) in their model of attentional control of action, and Baddeley (1986) suggested that the SAS model provides a useful way of describing the functions of the central executive. For this reason the SAS model is examined briefly here.

Norman and Shallice (1986) suggested two types of cognitive control reflecting the distinction between automatic and controlled processes (Schneider & Shiffrin, 1977). The automatic system of control allows us to perform routine and well-practised actions through the selection of learned habits and **schemas** without the need for deliberate cognitive control. We can perform quite complex sequences of actions through this mode of operation, using a system Norman and Shallice refer to as the contention scheduling system. Our actions are directed by relevant schemas, activated by triggers in the environment. For example, we can drive home along a familiar route without fully concentrating on the route; we may even make it all the way home without being fully aware of key stages along our route ('Were the traffic lights green?'; 'What car was ahead of me?'). A second type of process makes use of an attentional control mechanism (the supervisory activating system, or SAS), which can interrupt automatic processing, select an alternative schema and allow attention to be directed towards a goal. Staying with the example of driving, if you go abroad and are required to drive on the opposite side of the road than you normally would, you have to exert more effort and deliberate control over what might otherwise be highly automated actions. It is important that routine actions do not dominate on such occasions. These two qualitatively distinct control systems allow three levels of functioning, according to the Norman and Shallice model:

Schema
a framework that represents a plan or a theory, supporting the organization of knowledge.

1 a fully automatic mode for routine actions
2 an intermediate, partially automatic mode, which allows attentional control of actions, and
3 the deliberate control of action for non-habitual or novel tasks.

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Thus, according to this approach, 'contention scheduling – the system responsible for routine selection of action – was held to operate in the intact adult human modulated by a second system – the supervisory system – held to be responsible for the organization of non-routine (novel) behaviours' (Cooper & Shallice, 2000, p. 303).

Evidence for two separate control systems, one governing performance of routine actions and the other allowing control of non-routine action comes from studies of individuals with frontal lobe damage. Patients with damage to the prefrontal cortex experience problems completing tasks that require SAS-type attentional control and their errors often reflect intact contention scheduling (Shallice, 2002). For example, 'capture errors' are associated with prefrontal damage. **Capture errors** involve a failure to override a routine set of actions; for example, we might leave the house on a Saturday and drive to work or to college instead of to our intended destination. William James (1890) recounted an occasion when he went upstairs with the intention of changing his clothes, but instead went to bed. In the **Stroop task** (see Chapter 11)

Capture errors
involve a failure to override a routine set of actions; a routine or well-practised action is performed when another action was intended.

Stroop task
used to demonstrate the Stroop effect, whereby the naming of colours shows interference when the colour of the word and meaning of the word are incongruent.

the automatic reading of a word when the task requires us to simply name the colour provides another example of a capture error.

Baddeley and Wilson (1988) used the term **dysexecutive syndrome** to refer to the type of impairment that specifically involves deficits in executive function, and which is often associated with dorsolateral prefrontal damage. Affected individuals may demonstrate 'disturbed attention, increased distractibility, a difficulty in grasping the whole of a complicated state of affairs . . . [they are] well able to work along old routine lines. But they cannot learn to master new types of task' (Rylander, 1939, p. 20). Dysexecutive syndrome is characterized by an inability to exert control over one's behaviours and it may involve difficulties initiating, ceasing, suppressing or modifying actions as environmental cues change. For example, some individuals demonstrate **perseveration**, the inappropriate repetition of an action. On the **Wisconsin Card Sorting Test**, a test of frontal lobe function, the participant is required to alter his or her card selection as a 'rule' supplied by the examiner changes (Milner, 1963). A number of trials follow one rule (for example, 'sort the cards according to colour'), then the rule changes (to, for example, 'sort the cards according to pattern'). Individuals with frontal lobe damage often show perseveration in continuing to respond with the old rule even though the rule has now changed. Patients are aware that the rule has changed and are often aware that they are making errors – despite this they continue to apply the inappropriate rule.

Dysexecutive syndrome
a range of deficits reflecting problems with executive function and control, and often associated with injury to the frontal areas of the brain.

Perseveration
the inappropriate repetition of an action.

Wisconsin Card Sorting Test
a standardized neuropsychological test that assesses set-shifting, an aspect of executive functioning that allows us to change cognitive strategy as the demands of a task require.

The central executive also allows us to maintain focus and to keep our attention on the task at hand, ignoring competing input from the environment; individual differences in working memory capacity, for example, predict the likelihood that one's mind will wander while engaged in a task requiring concentration (see Box 6.5 for further discussion of 'mind wandering'). A patient may show spontaneous and apparently uncontrollable imitation of a doctor, for example, or a compulsion to interact with objects (such as picking up and miming the use of an object, when not asked to do so), a tendency referred to as **utilization behaviour**. The ability to control responses to environmental cues is compromised: 'in the absence of control from the SAS, the patient simply responds to any cues of opportunities afforded by the environment (Baddeley, 2009, p. 54). The case of E.V.R. (Box 6.6) illustrates such a pattern of deficit.

Utilization behaviour
dysfunctional automatic reaching for and use of objects in the environment.

Baddeley (2012) notes four key functions of the executive: focusing attention; dividing attention; switching between tasks; and interfacing with LTM. The variety of executive deficits seen in such patients suggests that the central executive is further fractionated into subsystems or subprocesses, maybe suggesting a 'series of parallel but equal processes, an executive "committee" perhaps' (Baddeley, 1996a, p. 13,471). Shah and Miyake (1996) suggest visual and verbal subcomponents, but, as yet, the executive has not been refined into subcomponents in the way that the phonological loop and visuo-spatial sketchpad have been.

Box 6.5 Research Close Up: Working memory and mind wandering

Source: Kane et al. (2017).

INTRODUCTION

A significant proportion of our waking day is spent engaged in task-unrelated thoughts (TUTs) and can be considered to constitute 'mind wandering'. While sometimes associated with cognitive error, mind wandering often occurs without negative consequences, as a natural shift in attention from external to internal focus.This type of spontaneous thought, far from being a cognitive weakness, may reflect fundamental properties of the architecture of the mind, helping us to consolidate memory, and to integrate and categorize experiences throughout the day (Christoff et al., 2008). If this is the case, we might expect to see an association between aspects of working memory capacity (WMC) and mind wandering. As it turns out, this relationship is not uncomplicated and varies with the nature of the task and its complexity, as well as many individual difference variables including WMC.

A study by Kane et al. (2007) examined daily life mind wandering, using an experience-sampling approach, a technique in which participants are required, at various times during a day, to report on their current thoughts, and to categorize those thoughts as being 'on task' or 'off task'. That study produced three notable findings. Participants reported that their minds had wandered off-task on almost a third of occasions on average, with considerable individual differences observed. Context was important: participants were less likely to report their minds wandering when they felt happy and competent, were concentrating or when enjoying their current activity. WMC predicted mind wandering only as a function of the cognitive demands of the task. Participants with higher WMC were less likely to report their minds wandering while engaged in tasks for which concentration was required. However, when engaged in tasks requiring little concentration, individuals with high WMC were significantly *more* likely to mind-wander compared to participants with lower WMC. Participants with lower WMC reported more incidents of mind wandering as the challenge and effort involved in their current task increased (see Figure 6.12). Kane et al. (2017)replicated and extended their earlier study with a larger sample, measuring WMC more broadly and comparing reports of mind wandering probed during laboratory tasks and daily life contexts.

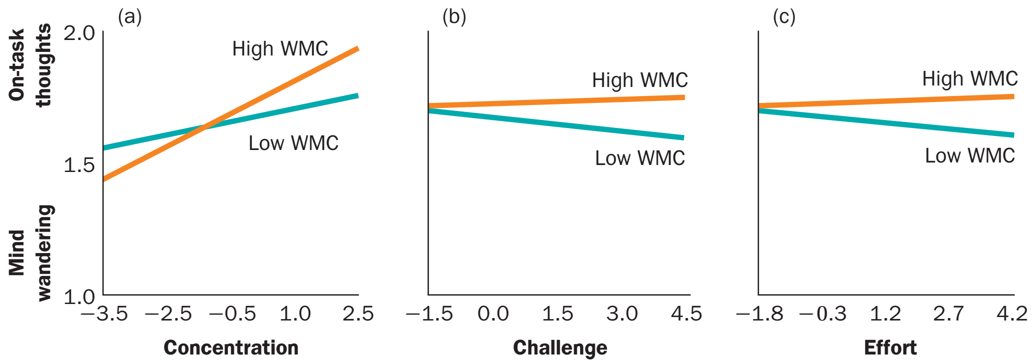

Figure 6.12 Differences in working memory capacity (WMC) reflect differences in mind wandering during a cognition task.

The lines show the means for participants in two groups, the top and bottom quartiles of the working memory scores. The y-axis shows whether the participant was on task; a lower score indicates mind wandering. The x-axis shows self-ratings indicating whether the participants found the task to require concentration, whether they found it challenging and whether they rated it as requiring effort.

Source: Adapted from Kane et al. (2007).

METHOD

Kane et al. (2017)used the experience-sampling methodology to collect data on mind wandering in participants' daily lives but they also probed mind wandering during a series of experimental tasks completed in the laboratory. Thought probes appeared at unpredictable intervals during a series of computer-based experimental tasks, including the Sustained Attention to Response Task (SART) and the Number Stroop task. These are tasks requiring attentional control. The SART required participants to press a key when animal names were presented and not to respond when vegetable names were presented. In the Number Stroop task, a row of two to four digits was presented on each trial. Participants were required to press the key corresponding to the number of digits present, while ignoring the meaning (for example, given '4 4 4' respond by pressing key 3. Trials could be congruent ('2 2' respond 2) or incongruent (e.g., '3 3 3 3' respond 4) (for more on the Stroop task, see Chapter 11).

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At each probe, subjects indicated which of eight presented options was closest to the content of their immediately preceding thoughts (for example, 'everyday things', 'current state of being', 'personal worries', 'daydreams'). Outside of the laboratory tasks, participants completed eight questionnaires per day over seven days, when prompted at various points by a mobile device alert. WMC was measured through a series of complex span tasks including reading span.

RESULTS

Participants reported that their mind had wandered, on average, for 32 per cent of the probes, with considerable individual differences (SD = 17 per cent, range = 2–97 per cent). This is consistent with previous estimates that participants' thoughts are off-task on a third of probes (Kane et al., 2007).

The results showed that participants tended to be aware of daily life TUTs and that the content of such thoughts was often focused on everyday plans and goals. Participants tended to remain mentally on task when concentrating. Mind wandering was associated with negative affect (feeling anxious, sad, irritable or confused), tiredness or boredom. The interaction effect reported by Kane et al. (2007) between WMC and task demand was replicated and extended, as WMC only predicted mind wandering as a function of participants' concentration level. When participants reported concentrating, those with higher WMC were more likely to have remained on task compared to those with lower WMC. In tasks requiring less concentration, participants with higher WMC were more likely to report their mind had wandered. Furthermore, participants' scores on WMC and attention correlated with TUTs in the lab, but not in daily life and, interestingly, the laboratory TUT rate did not significantly predict daily life mind wandering, the effect falling just outside statistical significance (*p*= .07).

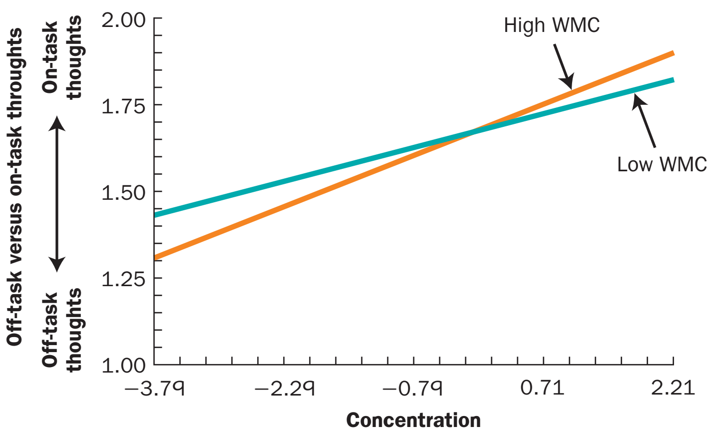

Figure 6.13 The relationship between daily-life mind wandering and working memory capacity (WMC) as a function of self-reported concentration.

The y-axis shows whether the participant was on task; a lower score indicates mind wandering. The x-axis shows self-ratings indicating whether the participants found the task to require concentration.

Source: Kane et al. (2017, Figure 1, panel 1).

DISCUSSION

Kane and colleagues' study shows the importance of considering individual differences such as WMC, but also the context of the task, and the cognitive demands posed by it. It also highlights important differences between measurements taken in laboratory studies and those sampled in daily life. Laboratory mind wandering did not significantly predict daily-life mind wandering, the correlation falling just outside significance. Before concluding that there is no relationship between these measures, however, the reliability of the self-report method would have to be questioned. Self-report methods of thought sampling can be *self-caught* (the participant reports when they notice that their mind has wandered) or *probe-caught* (a probe occurs at various points), as in the Kane et al. studies, and the participant reports whether their mind had wandered at that point in time. The latter method provides an estimate of the proportion of the time the person was in a mind-wandering state. It does however require a level of insight and relies on self-report accuracy and therefore some have questioned whether better methods are needed (e.g., see Voss et al., 2018).

Recent research has pointed towards mind-wandering as a heterogeneous set of processes, some beneficial and some detrimental, with some theorists advocating for a 'family-resemblances' approach to the study of mind-wandering, recognizing the variety of experience that can fall within that construct (Seli et al., 2018). Research has also differentiated between spontaneous and deliberate mind wandering (e.g., Vannucci & Chiorri, 2018), and is beginning to examine the relationship between mind wandering and mindfulness, which might be seen, in some aspects, as an opposing construct (Ju & Lien, 2018; Mrazek et al., 2012).

The episodic buffer

Baddeley's working memory model (e.g., Baddeley, 1996b) originally considered the role of the central executive in focusing, dividing and switching attention, and in linking WM to LTM, but it did not seem to have a storage component of its own (Baddeley, 2012). But some verbal learning tasks involve a larger storage capacity than is supported by data on the phonological loop, suggesting that working memory can make use of additional storage capacity. For example, when unrelated words are presented in a span task, a limit of about five or six items is typically found, but if the words are presented in a sentence, memory span increases to about 15 words (Brener, 1940). If the loop holds only seven or so items, where is the extra storage capacity coming from?

Furthermore, performance is facilitated when the sentences presented are grammatical, yet judgements of grammaticality require LTM involvement. LTM access has also been shown to affect VSSP function. For example, studies of boundary extension errors show that participants' visuo-spatial memory for a visual scene can be distorted (see Figure 6.14), such that the scene is often remembered as extending beyond the boundary originally presented (e.g., Intraub, 1997; Intraub et al., 1998; Intraub et al., 1996). Such errors occur after even very brief presentations and suggest 'a seamless integration of information physically presented in the picture and information that was inferred' (Intraub, 1997, p. 219). This would depend on information in the VSSP making contact with relevant information stored in LTM (Radvansky, 2006). The original WM model of Baddeley and Hitch did not suggest how this might occur, but other accounts speculated on the interaction of these memory systems. For example, Ericsson and Kintsch (1995) proposed a 'long-term working memory', whereby information from long-term memory can be used to compensate for the limited capacity (short-term) working memory.

The need to explain how WM interacts with LTM and how WM can sometimes involve a larger storage capacity led to a proposed further component within WM. Baddeley's (2000) WM model differs in two ways from the earlier model. First, it shows that the WM modality-specific subsystems (phonological loop and visuo-spatial sketchpad) link to

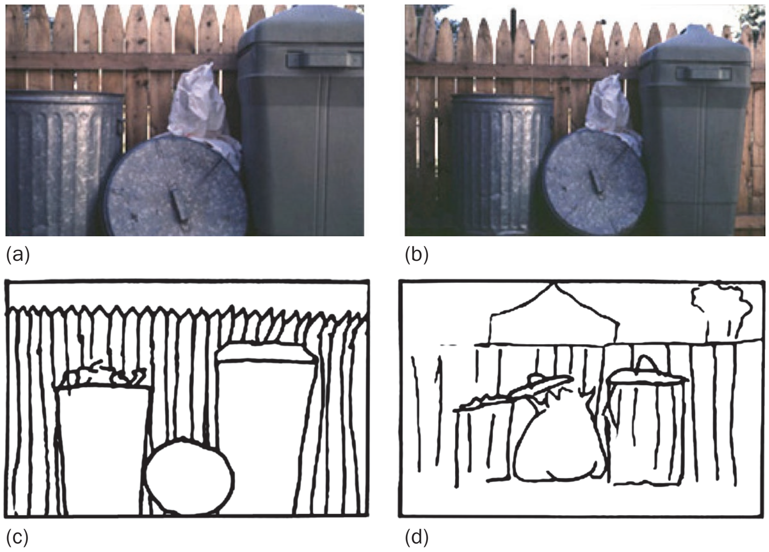

Figure 6.14 Viewers tend to remember seeing the area of a scene as extending beyond the boundary of the original photograph.

Panels a and b show similar scenes; panel b had a wider, broader frame than panel a. When asked to draw what they had seen, participants tend to extend beyond the actual boundary. Panel c shows a participant's recall of seeing panel a, and panel d shows a participant's recall of seeing panel b. The drawing in panel d shows the roof of a house and an outline of a tree that were not in the original photograph (panel b).

Source: Reprinted from Intraub (1997), with permission from Elsevier.

LTM, and, second, the episodic buffer was introduced, which can be accessed by the central executive or by the modality-specific subsystems, and which links to LTM (see Figure 6.8). The buffer is 'a crucial feature of the capacity of working memory to act as a global workspace that is accessed by conscious awareness' (Baddeley, 2003, p. 836). The episodic buffer is a temporary storage structure of limited capacity (it can hold about four chunks of information; Baddeley, 2009) that is controlled by the central executive and allows information from different sources (visuo-spatial sketchpad, phonological loop, LTM) to be integrated, essentially providing a means of interface between the modality-specific systems of WM and LTM. It can be considered to be the storage component of the central executive (Baddeley, 2003) and it 'is episodic in the sense that it holds episodes whereby information is integrated across space and potentially extended across time . . . it is assumed to be a temporary store . . . [and is] assumed to play an important role in feeding information into and retrieving information from episodic LTM' (Baddeley, 2000, p. 421). Baddeley (2012) provides a useful overview of the development of the various components of the WM model.

! Box 6.6 When Things Go Wrong: Case E.V.R.

Executive function is crucial for effective planning and goal-directed behaviour. What happens when brain injury affects this function? Eslinger and Damasio (1985) described the case of E.V.R., an accountant, who at the age of 35 had a brain tumour – a large orbitofrontal meningioma that had been compressing both frontal lobes – removed, leading to bilateral damage to the ventro-medial frontal areas. His intellectual abilities remained largely intact. He had above average intelligence, scoring in the top 1–2 percentile, with a verbal IQ of 132 and a performance IQ of 135. Before his illness he was responsible, hard-working and had been promoted at his job. He was sociable and active in his community.

But, after his surgery, E.V.R. could not keep a job, his planning of activities both immediate and into the future was severely impaired, and even minor decisions (what to wear, where to eat out) took an inordinate amount of consideration. He could no longer plan his finances and his business ventures ended in bankruptcy. His altered social behaviour and personality profile led Damasio (1994) to suggest that E.V.R. presented a case of 'acquired sociopathy' (see also Damasio et al., 1992). While E.V.R.'s intellectual capacity remained largely unaffected by his illness, he lacked the emotional or social intelligence to be able to flexibly alter his behaviour or predict the consequences of his actions. As Damasio put it, 'we might summarize [his] predicament as to know but not to feel' (1994, p. 45). This case illustrates the important role that emotion plays in cognition, an issue we will return to in Chapter 15.

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Abnormal performance on everyday tasks despite apparently intact intellectual functioning is a commonly reported feature of frontal lobe damage. Shallice and Burgess (1991) had three people who had frontal brain damage attempt a real-world task called the multiple errands task. The test required the participants to complete a number of tasks within an unfamiliar shopping centre. The tasks varied in complexity (e.g., buy a postage stamp or find out the euro–sterling exchange rate) and there were a number of rules the participants had to follow (e.g., 'do not go into a shop except to buy something that's on the list'). All three participants scored normally on tests of language and intellectual ability, yet all three performed poorly on the multiple errands task, having deviated from the rules (e.g., gone into shops when they were not supposed to) or failed to complete tasks. A number of socially inappropriate behaviours occurred (see Burgess et al., 2007). One participant left a shop without paying for the goods, while another offered sexual favours in lieu of payment, an unusual and socially inappropriate offer.

Such cases demonstrate the key role played by executive functioning in everyday planning and goal-directed behaviour. It is important to note however that a range of outcomes is possible following frontal lobe damage and that even very severe injuries can be associated with good recovery of function. The classic case of Phineas Gage, reported by Harlow (1848), is one of the earliest reports of executive dysfunction after a frontal lobe injury (see Chapter 15, Box 15.1). Gage suffered a severe frontal lobe injury while blasting through rocks during his on the railroads. Gage is one of the most cited cases in cognitive neuropsychology, and is generally presented as showing severe personality change and executive dysfunction after frontal lobe damage. It is now generally accepted that Gage must have shown some recovery, as he spent many years subsequently working as a stagecoach driver. This would have been a demanding job in terms of executive functioning, requiring interaction with passengers, taking payments, loading luggage, remembering routes and caring for the horses (see Macmillan, 2000, pp. 104–106). A modern case described by Mataró et al. (2001) also suggests some recovery of function.

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Evaluation

Baddeley's working memory model was proposed as a replacement for the concept of a unitary short-term store, and the concept of working memory has provided a useful description of a flexible, adaptable, yet capacity-limited system. It introduced a number of subsystems and showed how WM structures are involved not just in memory functions but in complex cognitive tasks more generally, such as learning and reasoning (Baddeley, 1996a, 2000). The model explained how, following brain injury, impaired STM (as measured by digit span) could accompany normal LTM, and it explained selective deficits in verbal or visuo-spatial processing evident in other case studies. The model detailed a number of components, the activities of which can be tested, through dual task experiments for example. The addition of the episodic buffer went some way towards considering how LTM interacts with WM (although the model does not detail how this interaction occurs) and provided a general multi-modal storage capacity to WM, but other models (e.g., Cowan, 1988) have dealt with LTM involvement more explicitly.

The most successful component of the model is the phonological loop, although there continues to be much debate around the detail of the component. Various accounts continue to debate whether forgetting is best characterized as occurring through time-based decay or interference, a debate that has been ongoing since the 1960s (see Baddeley, 2012). Baddeley's model assumed that information is lost from memory through decay unless it is refreshed. Interference accounts argue that forgetting is due to interference among items in memory (e.g., see Farrell et al., 2016). While most models of working memory assume a crucial role for rehearsal processes, some experimental studies and computational models have called into question the causal relationship between rehearsal and memory (Oberauer, 2019; Souza & Oberauer, 2018).

Furthermore, there remain some data that do not fit with the WM model (e.g., see Ward, 2001) and findings such as the word length effect and the effect of articulatory suppression, which seem to point to a key role of rehearsal processes, may not be quite as reliable as once believed (Oberauer, 2019). On balance, however, the introduction of the phonological loop has been an extremely useful concept for understanding verbal short-term memory and its limits, and has led to many new directions in research.

The central executive, clearly a pivotal component in the WM model, is as yet not fully understood, and further research will be required in order to determine whether it is a single component of WM or actually consists of a number of high-level processes, involving many interacting brain areas. Donald (1991) described the central executive as presented in working memory models as 'a hypothetical entity that sits atop the mountain of working memory and attention like some gigantic Buddha, an inscrutable, immaterial, omnipresent homunculus, at whose busy desk the buck stops every time memory and attention theorists run out of alternatives' (p. 327). This is a weakness common to many models of short-term memory: the central executive as a concept invokes the idea of an executive controller, a 'ghost in the machine' or 'homunculus' that controls the system. And this gives rise to the homunculus problem: if there is an executive controller then who or what controls that controller? There must be another executive controller overseeing the processing of the first executive controller. And then who controls the second controller? Who is deciding what information to act on and how it should be processed? This creates an infinite regress or succession of homunculi, and detracts from the explanatory value of the model. Baddeley (2012) suggests that rather than being a weakness, the homunculus concept can be a useful marker of issues that require explanation (p. 14). Baddeley's model of working memory attempted to avoid the homunculus problem by fractionating working memory into component parts and, as noted by Logie (2016), Baddeley anticipated the issue by treating the central executive as a 'conceptual ragbag' or umbrella term which over time would be elucidated by additional data (Baddeley, 1996). Unpacking the functions of each subsystem reduces the need for a central executive. We may soon arrive at the point where the central executive concept might be given a 'dignified retirement' (Logie, 2016), although as Hopkins (2017, p. 2) points out, what will be left following its retirement is rather unclear.

Alternative accounts of working memory share this weakness, and there remains a need to specify the mechanisms that control working memory and the conditions under which they operate. The relationships between working memory, attention and consciousness are poorly understood, and it remains unclear as to whether working memory is the basis of conscious experience, or whether it arises from consciousness

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(see Chapter 5); WM is closely associated with conscious experience, but they are not one and the same (Baars, 1997). Neuroscientific research is beginning to unpack the complex relationship between memory and attention (e.g., Lewis-Peacock et al., 2012).

Self-efficacy a person's sense of their own competence to complete a certain task or achieve a goal.

Research looking at how to improve working memory, and the role of **self-efficacy** (see Box 6.7) and other individual differences, is also providing new insights into memory functioning (see, for example, Hoffman, 2010; Hoffman & Schraw, 2009; Kingston & Lyddy, 2013).

Baddeley's WM model is arguably at its best when factors relating to LTM are minimized (Cowan, 1995b), and links to LTM are considered to a greater extent in other models of working memory (e.g., Cowan, 1995a; Ericsson and Kintsch, 1995; see also Oberauer, 2002). In practice, it is difficult to separate the processes of LTM and WM in everyday cognition, and research has begun to focus on the interactions between WM and LTM (e.g., see Burgess & Hitch, 2005, for an overview). On balance, however, and despite its detractors, Baddeley's multi-component WM model remains remarkably robust to criticism, having survived coming up to 50 years of scientific scrutiny, retaining much of its predictive and explanatory power in the process (Logie & D'Esposito, 2007). It counts as one of the most influential works in the field of cognitive psychology (see Logie & Cowan, 2015), along with the Atkinson–Shiffrin predecessor (Malmberg et al., 2019).

Box 6.7 Research Close Up: Self-efficacy and working memory

Source: Autin & Croizet (2012).

INTRODUCTION

We often think of working memory capacity as if it were fixed. But, in fact, the performance of our working memory can be affected by situational factors, by aspects of the task and by factors such as stress or emotion. But does self-efficacy affect working memory? Self-efficacy refers to a person's sense of their own competence to complete a certain task or achieve a particular goal. A study by Autin and Croizet (2012) examined this, across three experiments with 11-year-old children; their first two studies will be considered here.

METHOD AND RESULTS

Study 1

In their first study, Autin and Croizet randomly allocated children to three groups. Two groups of children completed an anagram task before their working memory task. The anagrams were so difficult that they could not be solved within the time allocated. One group of children, in the 'reframing' condition, were told that having difficulty with the task was normal and in fact showed that learning was occurring. The second group who did the anagrams did not get this reframing information. A third control group were not exposed to the anagram task, but went directly to the working memory task. All participants performed a listening span test. In the listening span task, participants listen to a series of sentences. After each sentence is presented the participant has to report whether the sentence makes sense or not, and also repeat back the last word in the sentence. At the end of the series, participants have to repeat back as many last words as possible, in the same order as they were presented. The series of sentences vary from two to five sentences, so participants have to remember up to five sentence-final words. The results showed that children allocated to the reframing condition had a greater working memory span than either of the two other groups (see Figure 6.15).

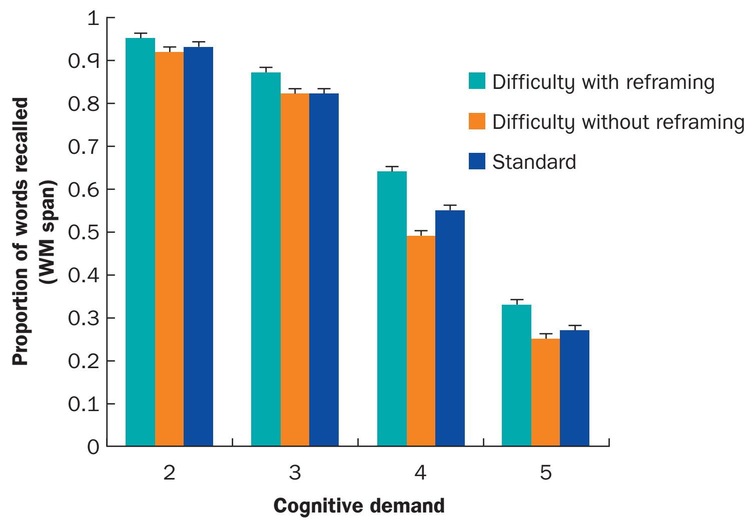

Figure 6.15 Working memory (WM) span as a function of the experimental condition in Study 1.
Having a difficult task but reframing it; having a difficult task without the opportunity to reframe it; and the standard control condition. Cognitive demand of the WM test (two, three, four or five words to remember) is shown along the x-axis. Error bars represent standard errors.

Source: Autin & Croizet (2012). APA; reprinted with permission.

Study 2

In the second study, Autin and Croizet examined whether this effect would extend to higher-level processing that relies on working memory span, in this case reading comprehension. The three conditions from the first study were replicated with a new sample of 11 year olds, with one further condition added. In a ‘success’ condition, children did easier anagrams and got them right. A difficult reading test followed, instead of the working memory test used in Study 1. The results were consistent with those of Study 1. Children in the reframing condition showed better reading comprehension than the other three groups, which did not differ significantly from one another (see Figure 6.16).

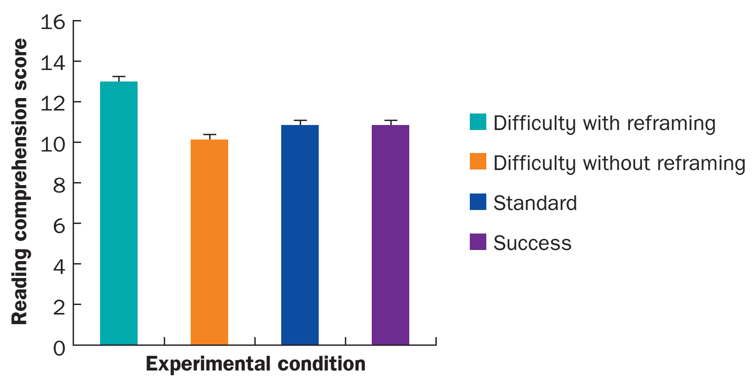

Figure 6.16 Reading comprehension score as a function of experimental condition.
Having a difficult task but reframing it; having a difficult task without the opportunity to reframe it; the standard control condition; and an additional ‘success’ condition. The maximum score was 18. Error bars represent standard errors.

Source: Autin & Croizet (2012). APA; reprinted with permission.

DISCUSSION

These data suggest that a brief psychological intervention that allows the child to reinterpret difficulty with a task in a positive light can support working memory performance both on a standard test of working memory and also on a higher-level reading task that relies on working memory. The findings of Study 2 even suggest that this reframing of difficulty may be more beneficial than an experience of success on a prior task. The study relies on the fact that, in Western cultures at least, experiencing difficulty tends to be interpreted in terms of lower cognitive ability. However, as noted by the authors, some cultures would interpret an experience of difficulty on a task as a more temporary issue, reflecting a lack of mastery, for example, and not as reflecting a person's cognitive ability. In such cultures, a child's experience of difficulty on a task would not affect self-efficacy, potentially bringing an advantage on some cognitive tasks. These findings also have relevance to the depletion of working memory resources under conditions of stereotype threat (Schmader, 2010; Steele & Aronson, 1995), as well as biases relating to educational expectations and social class (Goudeau & Croizet, 2017).

Summary

In this chapter we have considered how information is held and manipulated in memory. Early models of memory, such as Atkinson and Shiffrin's (1968) model proposed three stores: sensory, short-term and long-term stores. We saw that the sensory memory stores are large-capacity stores that hold information for a very short duration, serving to prolong rapidly presented input for processing in the short-term store. Sensory memory contains subsystems specialized for visual, auditory and other types of sensory input. The sensory stores hold information but do not code it in a form that allows categorization or processing of meaning. In order for the meaning of a stimulus to be appreciated, the information must be transferred to short-term memory. Sensory stores are modality-specific and there is now good evidence for separate visual (iconic), auditory (echoic) and haptic/tactile (touch related) stores.

The short-term memory store as proposed by the multi-store account (such as that of Atkinson and Shiffrin) was a unitary store that had a limited capacity of about 7 ± 2 pieces of information. Information had to flow through this store in order to access long-term memory. This, as it turns out, is an over-simplification of the short-term system, which must involve a number of relatively independent processes. Neuropsychological case studies of individuals with left-hemisphere brain injury were extremely useful in coming to this conclusion and much is owed to the individuals who gave up their time to take part in testing, often over many years. Individuals such as K.F. and P.V. had severely compromised short-term memory after brain injury, and yet their long-term memory function was intact. This pattern of deficit contrasted with that seen in individuals with amnesic syndrome (such as H.M. and N.A.; see also Chapter 7), who showed normal short-term memory but severely compromised long-term memory. This double dissociation of function suggested that there were separate stores for long-term and short-term memory, and that short-term memory was not a unitary store. This led to the development of the concept of working memory.

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Working memory as a cognitive capacity has been extolled as 'perhaps the most significant achievement of human mental evolution' (Goldman-Rakic, 1992, p. 111). The working memory (WM) model of Baddeley and colleagues was proposed in order to replace the model of short-term memory as a unitary store. The WM model suggested three components to WM: a central executive, like internal attention (see Chapter 4), which oversees the activities of two modality-specific systems – the visuo-spatial sketchpad for storing and manipulating visual and spatial information, and the phonological loop for storing and manipulating speech-based

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information. Later, an additional component, the episodic buffer, was added to explain the additional storage capacity of the central executive and to link the components of WM and LTM. Other theories of WM have taken a different approach; for example Cowan's account focuses on WM as embedded systems for attentional control with activation of stored knowledge from LTM playing a central role in WM processing. The central executive, a key concept in working memory, remains to be adequately specified, and while various models of working memory have been proposed, no full explanation of executive functioning has as yet been forthcoming. Research has begun to address the relationship between long-term memory and working memory, examining whether they are structurally separate systems and the means by which they interact. The Baddeley and Hitch (1974) model (with later versions) has proved to be a landmark contribution in the history of cognitive psychology, and has spawned what is approaching 50 years of progressively illuminating research.

Review Questions

1 What is meant by working memory?
2 What are the components of the phonological loop?
3 How might we best measure the capacity of short-term memory?
4 What is sensory memory and what is its function?
5 What evidence is there supporting the main components of Baddeley's working memory model?

Discussion Questions

1 How essential has evidence from brain injury – and particularly single cases – been to our understanding of short-term memory?
2 What is the relationship between short-term and working memory? Do these two terms mean the same thing?
3 What is the relationship between working memory and attention?

Further Reading

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