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Chapter 7

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Working memory: the seat of learning and comprehension

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Overview

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Working memory is the small amount of information kept in mind at any time. It is needed for various sorts of learning, comprehension, problem-solving and goal-directed thinking. Humans have a small working memory limit but it can be overcome using strategies such as grouping items together and rehearsing them. Children's working memory capabilities grow with maturity, and educational practices should be based on an understanding of both the limitations and the educational possibilities. These limitations of working memory, and means to overcome the limitations, will be examined with emphasis on the developmental changes from the early elementary school years through adulthood. Educational principles will be proposed to make the most of working memory for optimal learning throughout development.

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The first two sections of the chapter provide a definition of working memory and a description of how it is used in information processing. This is followed by a discussion of several types of working memory limitations (item limits, goal maintenance limits and time limits) and the strategies that are used to overcome the limits. Within this framework, the childhood development of working memory is examined. To gain a complete picture of development one must separately consider the growth of storage capacity, goal maintenance processes, memory persistence and strategy use. Finally, lessons for maximizing education are presented, focusing on the use of materials and instructions that are challenging and stimulating but not beyond the working memory capabilities of the child.

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28 9.1 Introduction

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Working memory is the temporary retention of a small amount of information, which is used in practically every kind of cognitive task. It is critical for learning and comprehension, and it has become a major area of brain research (e.g. Baddeley, 2003; Chein & Fiez, 2010; Cowan, 1995, 1999, 2009; D'Esposito, Postle, Jonides & Smith, 1999; Jonides et al., 2008; Majerus et al., in press; McNabb & Klingberg, 2008; Todd & Marois, 2004; Xu & Chun, 2006). The present review, however, summarizes the behavioural research on working memory. It includes a more detailed discussion of what working memory is and how it is used; limitations in working memory, and how one can use strategies to overcome them; the childhood development of working memory abilities, in which the basic abilities increase along with increasing uses of strategies to overcome



1 the limits; and suggestions for how this information about working memory can be used to
2 improve educational practices (see also Chapter 8, this volume).

3 9.2 Working memory and how it is used

4 Back in the days of the first few laboratories of psychological experimentation, Wilhelm Wundt
5 was extensively studying conscious perception and thought in Leipzig, Germany. His work is still
6 germane to modern psychology but much of it has still not been translated into English (only into
7 Hungarian and Russian, the other two leading academic languages of the time and locale). William
8 James, working from Harvard University, summarized the gist of much of the early research by
9 Wundt and others in his 1890 text, *Principles of Psychology*. He noted two basic kinds of memory,
10 primary and secondary. Primary memory referred to a lingering residue of our consciousness of
11 recent events; that is, conscious awareness of what is and what recently was. In contrast, secondary
12 memory referred to the nearly limitless amount of information stored away in the brain from a
13 lifetime of experience. Primary memory is the core of what we now call working memory.

14 American psychology went into a long era of concentrating on the lawful relationship between
15 stimuli and responses, with little use for speculation about what happened in the brain or mind
16 between those points. This attitude was furthered by what is known as Watson's (1913) behaviour-
17 ist manifesto, and it continued until the cognitive revolution that began in the middle 1950s
18 (Gardner, 1985). As part of that cognitive revolution, George Miller (1956) wrote a seminal review
19 paper on the basis of his own research in several areas, which did suggest that we can use experi-
20 ments on behaviour to make important inferences about the properties of the mind and brain.
21 He noted that there are severe limits in humans' ability to process information.

22 In some ways, the limits described by Miller (1956) resemble channel capacities of electronic
23 communication devices that were studied in depth in the process of fighting the First and Second
24 World Wars. For example, one cannot transmit a message as efficiently over a telegraph as one can
25 over a radio because any one telegraph signal carries only a limited amount of information; a
26 single dash or a dot only narrows down the choices for the letter that is about to be conveyed.
27 Somewhat analogously, humans can identify a simple property such as the length of a line or the
28 loudness of a tone only in a limited fashion: they can identify it out of about seven distinct choices,
29 but not much more. The transmission of information is limited by the properties of the electronic
30 device or human mind.

31 In a critical way, though, Miller (1956) also found that the human mind has a means to leap
32 beyond the basic limits. If one is asked to repeat a list of, say, random letters, one can do so if there
33 are at most about seven letters. If, however, one can capitalize on past knowledge, the letters can
34 be organized into larger chunks in order to reduce the load on primary memory. Suppose a list of
35 nine letters forms three well-known initialisms, as in the series *IBM, CIA, FBI*. Then it becomes
36 an easy matter to retain the letters. So, the human mind is a device that organizes information and
37 thereby allows much more efficient transmission or storage of information, compared to basic
38 electronic devices.

39 The limits of working memory and the ability to overcome these limits both have profound
40 implications for how learning is accomplished. A new concept requires that memory be put to use
41 to form new amalgams. Take the concept of a fraction. The ratio 1:2 is the same as the ratio 3:6
42 and both pairs of numbers form an equivalent fraction, with a value of 0.5. When a child first
43 endeavours to understand the concept of a fraction, the data that must be kept in mind (in work-
44 ing memory) include the first number, the second number and the comparative magnitude of
45 the two (cf. Hecht, Vagi & Torgesen, 2007). If the child loses sight of that principle, he or she might
46 be swayed by the magnitude of one of the numbers rather than the comparative magnitude. The

1 formation of new ideas requires that old ideas be combined, metaphorically speaking, in the
2 working memory cauldron.

3 Further thoughts into how the mind uses information were articulated in a short book by
4 Miller, Galanter and Pribram (1960), who appear to have coined the term working memory. They
5 noted that human activities must be planned and executed on many levels. In order to get to
6 school in the morning, a child must think of all the activities that need to be finished first. These
7 may include collecting homework and books, getting dressed, eating breakfast, brushing teeth
8 and so on. Any one of these activities requires further thought, such as remembering where the
9 homework was placed the night before, where the backpack was placed, perhaps a check as to
10 whether the name is on the homework and so on. Miller and colleagues proposed that informa-
11 tion about the overall plan (getting to school) and about subplans as they are enacted (loading the
12 backpack or eating breakfast) are kept in a working memory as needed. One would test to see
13 if the task was completed, at which point the details could be released from working memory,
14 freeing it up for other parts of the overall plan. In this discussion, working memory was not
15 considered a certain area in the brain or very specific mechanism, but rather the ensemble of
16 whatever mental devices one can use to hold the information as needed for success in planning
17 and carrying out daily activities.

18 In subsequent years, the concept of working memory was developed further. Atkinson and
19 Shiffrin (1968) did not use that exact term, but they provided a seminal discussion of a short-term
20 memory resembling James' (1890) primary memory. One important contribution they made was
21 a careful consideration of how strategies might be used to enhance the limited amount of informa-
22 tion in short-term memory. They suggested that the individual largely controls his or her brain's
23 own flow of information from sensory memory to short-term memory to long-term memory, and
24 back again (e.g. when long-term information is used to enrich the encoding of information in
25 short-term memory). They modelled strategic processes such as *covert maintenance rehearsal*, in
26 which an item is mentally re-entered into short-term or primary memory repeatedly to keep its
27 representation from decaying. Also, *covert elaborative rehearsal*, the mental imposition of order
28 and meaning to the materials in primary memory, helps with the retention of information in
29 primary or working memory and also is a major way in which high-quality learning occurs.
30 People using different strategies can often perform the same task in very different ways, leading to
31 different patterns of results (Logie, Della Sala, Laiacona, Chalmers & Wynn, 1996).

32 Baddeley and Hitch (1974) wrote a book chapter entitled 'Working memory' that changed the
33 field dramatically. They showed that it is an untenable oversimplification to think of working
34 memory as a single entity as in James's (1890) primary memory or Atkinson and Shiffrin's (1968)
35 short-term memory. Instead, they argued, different kinds of materials are stored separately. Verbal
36 materials are stored in a faculty that is sensitive to phonological properties; for example, it is
37 difficult to remember the order of words in a random list if the words all rhyme, as in *cat, bat, hat,*
38 *mat . . .* etc. Visual, non-verbal materials, similarly, are stored in a faculty that is sensitive to visual
39 or spatial properties. Therefore the interference between two stimuli in working memory depends
40 to a large extent on whether they are encoded using similar features (both verbal or both visual-
41 spatial) or different features (one verbal and one visual-spatial). These working memory stores,
42 now called the *phonological loop* and the *visuo-spatial sketchpad*, were thought to preserve infor-
43 mation automatically. It was thought that these stores hold information automatically, but only for
44 a short time, about 2 seconds, unless it is rehearsed. (Lists of long words were not retained as well as
45 lists of shorter words, suggesting that slowing down the rehearsal process allowed the information
46 to decay from working memory before it could be rehearsed.)

47 Baddeley and Hitch suggested that there also would be a central working memory store that
48 could hold ideas with the help of attention, but Baddeley (1986) later omitted that kind of storage

1 until he later was convinced of a definite need for it. Then he essentially re-introduced it as the
 2 *episodic buffer*, a kind of storage in which disparate components could be held, bound together, to
 3 form ideas in working memory (Baddeley, 2000). This is the kind of working memory most
 4 closely aligned with information retrieved from long-term memory.

5 Cowan (1988, 1999, 2001) raised the possibility that information is held in a manner that is less
 6 modular than in Baddeley's conception. There may be many types of working memory store
 7 (memory for the spatial locations of tones, memory for the body locations of touches and so on).
 8 For the time being, not knowing the true taxonomy, Cowan considered them to be myriad
 9 instances of a temporarily activated portion of long-term memory. Similar items interfere with
 10 one another more than different items do, as a general principle within this type of memory. In
 11 this conceptualization, instead of the episodic buffer, it is said that the focus of attention holds
 12 only a small number of items in an integrated form, whereas many features in long-term memory
 13 outside of the focus of attention can be temporarily activated at the same time, but in a less-
 14 integrated form. According to this view, working memory is a composite that is centred on the
 15 few items or chunks of information currently in the focus of attention, plus a great deal more
 16 information that is readily accessible but is not at present within the person's focus of attention
 17 and awareness (recently spoken ideas, events within the last few seconds, etc.).

18 Given that learning depends heavily on working memory, it is important to know what aspect
 19 of working memory changes with childhood development and to incorporate this information to
 20 formulate the best educational practices. Recent work suggests that more items can be held in
 21 something like the focus of attention, and other recent work suggests that the process of rehears-
 22 ing or refreshing information to keep its representations active increases in speed and efficiency
 23 with age. Before we get into all that, let us discuss in greater depth the limitations of working
 24 memory and how they can be overcome.

25 9.3 Limitations in working memory and how they are overcome

26 Item limits

27 The scientific understanding of working memory depends a great deal on finding the laws by
 28 which its capabilities are limited. How do we know that there exists a working memory in the
 29 brain that functions separately from long-term or secondary memory? We can establish this, it
 30 seems, only by showing that there is a temporary quality of working memory that is subject to
 31 some limits that can be specified. Miller (1956) pointed to an item limit, in particular about seven
 32 items. However, the work of Baddeley and Hitch (1974) showed that this limit was not so absolute,
 33 but varied with properties of the items to be remembered, such as how similar they were to one
 34 another and how long it took to pronounce each one. The inability to state fixed limits of working
 35 memory even has provided a space for some investigators to suggest that there is no separate work-
 36 ing memory mechanism per se, just memory with a general set of principles and the attention
 37 processes that operate upon memory (e.g. Nairne, 2002).

38 In a way, too, Miller's (1956) paper consumes itself, in that the chunking principle casts doubt
 39 on the meaning of the capacity limit. On one hand, it is suggested that people can remember about
 40 seven items. On the other hand, it is suggested that people can combine items to come up with
 41 larger chunks, which allows more items to be recalled. When people recall about seven items, how
 42 do we know that they are not rapidly forming chunks to assist in their performance? This would,
 43 for example, explain why it is helpful that telephone numbers are presented with a dash between
 44 the first three and the remaining four digits. Perhaps this is accomplished mentally for lists that
 45 are presented without grouping. The experimenter may present to the research participant the

1 digits 3452168, and the participant may think something like, 34–52–168. Indeed, Broadbent (1975)
 2 suggested that when one looks for lists that elicit perfect performance rather than performance that
 3 is correct only some of the time, one finds that lists of three items usually fit the bill. Cowan (2001)
 4 greatly extended this reasoning, suggesting that when grouping and rehearsal strategies are not
 5 possible, adults usually recall only three to five items, not the five to nine that Miller suggested.

6 Chen and Cowan (2009) recently have had considerable success in showing that this line of
 7 reasoning from Broadbent (1975) is correct. Chen and Cowan taught individuals novel written-
 8 word pairings (like *brick–dog*) to a 100% correct criterion, so that these word pairings could be
 9 considered two-item chunks. Other words were introduced as one-item chunks for a fair
 10 comparison. Then the words were presented in lists, which varied in several ways. They could
 11 comprise four, six, eight, or 12 singletons. They also could comprise four or six learned pairs. This
 12 study showed that it is necessary to remove rehearsal in order to see the chunk capacity limit.
 13 When nothing was done to remove rehearsal, the number recalled was somewhat variable from
 14 one condition to the next. Participants in a different group, though, were required to recite a sim-
 15 ple word repeatedly, twice per second (*the, the, the. . .*) while reading the stimuli. What was
 16 observed in this group was that almost exactly three chunks were recalled, disregarding the
 17 correctness of the order of words in recall. This was the case no matter whether these three chunks
 18 were singletons or learned pairs. This finding is exactly what Broadbent (1975) would have pre-
 19 dicted. The review of Cowan (2001) may have overestimated the limit just slightly, by including
 20 procedures in which strategies were not completely eliminated.

21 Cowan and colleagues (2005) showed that measures of the capacity limit are fairly well correlated
 22 with indices of successful learning, such as high school class rank and achievement scores, as well
 23 as with more basic tests of intelligence.

24 It is probably not be only the number of items in working memory that is limited, but also the
 25 number of relationships between items. Suppose I tell you that in Spain, cookies have more flour
 26 than sugar whereas in Italy, cookies have more sugar than flour. (It is a completely fabricated
 27 example.) Understanding this two-way interaction of country with the ratio of ingredients is dif-
 28 ficult, as it requires the mental coordination of two of these variables: the relation between sugar
 29 and flour, and the dependence of that relation on the country. Halford, Baker, McCredden and
 30 Bain (2005) demonstrated that there is a strict limit in the human ability to understand higher-
 31 level interactions, even when all of the elements appear together on a printed page so that only the
 32 relationships have to be held in memory. Perhaps the basic limit in the understanding of complex
 33 ideas depends on the same memory faculty as the limit in chunks (Halford, Cowan & Andrews,
 34 2007). Regardless, the important point is that the complexity of thought is highly dependent in
 35 some way on working memory capacity.

36 **Goal maintenance limits**

37 Adults' ability to hold in working memory only about three chunks of information seems rather
 38 restrictive. Making matters worse, it is not a foregone conclusion that working memory will
 39 always be filled with the most relevant information. A child in the classroom is often supposed to
 40 be using working memory to form new long-term knowledge. For example, in a history class, the
 41 various details are supposed to be used to paint a mental picture of an era, a series of events, or a
 42 movement over time. But here the child's motivation and ability to concentrate is critical. To the
 43 extent that irrelevant thoughts such as goings-on outside of the classroom, a classmate's whisper-
 44 ing, or daydreams are allowed to enter the focus of attention and dominate working memory, the
 45 effort to acquire a new concept or idea will be sabotaged as some of the needed information is
 46 edged out of the focus of attention.

1 Two studies of individual differences illustrate well this principle of the potentially damaging
 2 effects of irrelevant information. One study (Kane & Engle, 2003) made use of the Stroop effect,
 3 based on a task in which participants are to name the colour in which colour words are written.
 4 If, say, the word *red* is written in blue on the computer screen, the assigned task is to say 'blue' but
 5 the tendency in adults is to want to say 'red' because word reading has become more automatic
 6 and faster than colour naming. The task is especially difficult if the word and colour match for
 7 most of the stimuli, which can lull the participant into reading words instead of maintaining the
 8 goal of naming the actual colours in which those words are printed. The task was administered to
 9 individuals with high and low working memory spans, as tested on a standard *operation span* task
 10 that requires concurrent storage and processing of information (words and mathematics prob-
 11 lems, respectively). Low spans did poorly on the Stroop task compared to high-span individuals
 12 because low spans failed to maintain the goal as consistently. They more often were swayed by the
 13 word in place of its printed colour.

14 In another study on inhibition with a very different experimental technique (Vogel, McCollough
 15 and Machizawa, 2005), arrays of bars were presented and the task was to keep in mind the orienta-
 16 tion of each bar. Actually, some bars were presented on the left and others on the right, and a cue
 17 indicated which side was to be retained in memory (without actually moving the eyes away from
 18 a centre fixation). This arrangement allowed the measurement of an electrical brain response, or
 19 event-related potential, to the task of holding the information in working memory. The more
 20 items held in working memory, the larger the magnitude of an event-related response component
 21 called *contralateral delay activity* (CDA). On the side of the display to be remembered, moreover,
 22 there were often some bars that could be neglected (perhaps the red ones) and other bars that had
 23 to be remembered (perhaps the green ones). The CDA magnitudes indicated that low-span indi-
 24 viduals kept in mind both the relevant and the irrelevant items, whereas the high-span individuals
 25 excluded the irrelevant items from memory and therefore kept more of their working memory
 26 capacity free. In other situations, this freed-up working memory in the high spans presumably
 27 could be put to use for the sake of learning more.

28 Kane et al. (2007) showed that this ability to exclude irrelevant information plays an important
 29 role in actual life. Participants carried around small devices on which they were cued to respond
 30 from time to time regarding whether they were paying attention to what they were doing or their
 31 minds were wandering. Low-span individuals reported their minds wandering, against their will,
 32 more often than did high spans. There was no difference between the two when they deliberately
 33 were allowing their minds to wander; in low spans, it was involuntary mind-wandering that was
 34 in excess.

35 Time limits

36 The press towards the belief that there are time limits in addition to, or instead of, item limits
 37 started early within the field of cognitive psychology. Peterson and Peterson (1959) found that
 38 even something as simple as a consonant trigram was forgotten precipitously across 18 seconds
 39 filled with a demanding distracting task to prevent rehearsal, counting backwards. Some recent
 40 studies, though, would attribute this loss to the presence of interference from the digits presented
 41 in the backward-counting task. Lewandowsky, Duncan and Brown (2004) have presented lists to
 42 be recalled, in conditions in which the participant was to repeat one word once (*super*) or several
 43 times in a row (*super, super, super*) before recalling each word. This was done to vary the time
 44 before recall without introducing new interference in the more delayed recall condition. No effect
 45 of the time before recall was obtained. Even when a third, attention-demanding task was added
 46 (Oberauer & Lewandowsky, 2008), little difference was seen in the loss of memory from one word

1 to the next; the recall results did not show a fan-shaped pattern, which would have indicated more
2 forgetting for slower recall.

3 In contrast to this research finding, Barrouillet and colleagues (e.g. Barrouillet, Bernardin,
4 Portrat, Vergauwe & Camos, 2007; Portrat, Barrouillet & Camos, 2008) have findings that seem to
5 require that there is loss of memory over time; but that is indirect reasoning. They have manipu-
6 lated the time between items during their presentation and have shown that they can measure the
7 proportion of time between items that is taken up with a distracting task. In one task, for example,
8 letters are to be recalled but numbers between them are to be read. The time from the beginning
9 of the presentation of each number until it is pronounced by the participant is assumed to be
10 engaged in that task, and therefore unavailable for refreshing or rehearsing the letters to be
11 recalled. It turns out that it is not the amount of time between items to be recalled that is critical,
12 but rather the *cognitive load* defined as the proportion of time taken up by the distracting task.
13 The higher the cognitive load, the lower the span, in a close linear relation. This was taken to sug-
14 gest that information is lost over time unless it is refreshed, and that it cannot be refreshed during
15 the distracting task.

16 Tests are under way to adjudicate between these views on the presence versus absence of decay.
17 Meanwhile, though, it has become clear that there is some sort of memory loss over time in
18 certain other situations. Ricker and Cowan (2010) presented a concurrent array of three uncon-
19 ventional characters followed by a pattern mask to eliminate sensory memory and then, in one
20 condition, a blank interval of 1.5, 3, or 6 seconds. This was followed by a probe to test recognition
21 of one randomly-selected item from the three-item array. The basic finding was that memory
22 declined across retention intervals despite the absence of any interference. In contrast, though,
23 arrays of six English letters were not forgotten across a 6-second interval. Zhang and Luck (2009)
24 found that array memory loss over a number of seconds is not a loss of the precision of each item
25 but rather a loss of items, and that it occurs suddenly for items that are lost. It appears from these
26 studies that the loss over time may occur for items that are not easily categorized, and that cate-
27 gorical information such as letter arrays may persist longer over time.

28 A basic educational implication of these findings is that it is utterly important for the learner to
29 have good categories for the information that is being presented, or it may well tend to fade from
30 memory within a matter of seconds.

31 **Overcoming the limits**

32 What makes human cognition capable is its flexibility. We have already discussed the fact that
33 learning to chunk items together increases the amount of information that can be saved by increas-
34 ing the number of item per chunk, so that more information can be packed into the same limited
35 number of chunks (Chen & Cowan, 2009; Miller, 1956). In processing ordinary language, a struc-
36 ture is built up as one listens to or reads the sentence, which allows quite a bit of material to fit into
37 the limited number of chunks in working memory (see Tulving & Patkau, 1962). A dramatic dem-
38 onstration of this principle is the work of Ericsson, Chase and Faloon (1980). They taught a par-
39 ticipant to increase his digit memory span over the course of a year from six or seven items, a
40 normal ability, to more than 80 items. Subjective reports suggested that he was able to do this
41 because he started with knowledge of many athletic records. He was able to recode the digits into
42 chunks based on such records (e.g. 3:57.2, a former world record for running a mile). In this way,
43 he raised his span to about 20 items. After that, he learned how to make higher-level chunks out
44 of the primary chunks and, in that way, raised his span to about 80 items. Yet, this increase was
45 very specific and, when he was switched to letter materials, he again could recall only about six of
46 them. Further studies have indicated that, despite the fantastic performance, memory experts still

AU: Please provide detail of "Zhang and Luck (2009)" for ref. list

1 base their performance on a basic memory capacity that is around three or four chunks; it is just
 2 that each chunk is very densely packed with information (Ericsson, Delaney, Weaver & Mahadevan,
 3 2004; Wilding, 2001).

4 Another strategy for remembering information is to rehearse it covertly. If the information is in
 5 a verbal form and the serial order of the information has to be retained, this retention is aided
 6 considerably by rehearsal, provided that the items to be rehearsed are phonologically distinct (e.g.
 7 not composed of rhyming words) and can be recited in about 2 seconds (Baddeley, Thomson &
 8 Buchanan, 1975). This was attributed at the time to a phonological memory trace that decays in
 9 about 2 seconds unless it is refreshed through rehearsal, though others would now suggest that the
 10 basis of the effect is phonological interference (e.g. Neath & Nairne, 1995; Lewandowsky &
 11 Oberauer, 2008). If the order of items does not have to be retained, what is found is that the first
 12 few items receive special rehearsal that is carried on until the list ends; this has been observed in
 13 studies in which the participants must rehearse aloud (Rundus, 1971; Tan & Ward, 2000).

14 Perhaps grouping and rehearsal work together, or perhaps they are completely separate strategies.
 15 In any case, these strategies account for why memory span tests typically show people remember-
 16 ing about seven items, not three items as Chen and Cowan (2009) found with rehearsal prevented
 17 and grouping controlled.

18 It is possible to refresh items in memory without using a verbal form of rehearsal; not all mate-
 19 rials lend themselves to verbal rehearsal. Another mnemonic device is to use attention to refresh
 20 the information in working memory, presumably by re-entering the information into the focus of
 21 attention (Cowan, 1999; Raye, Johnson, Mitchell, Greene & Johnson, 2007).

22 As mentioned earlier, various kinds of thinking depend heavily on working memory. It is note-
 23 worthy that new or abstract problems make a higher demand on working memory than problems
 24 in which one's past knowledge can be applied, as the knowledge allows the problem to be repre-
 25 sented with fewer separate chunks of information. Take the famous example of the four-card task
 26 (Wason & Shapiro, 1971). An abstract example of this task might be as follows. You have four
 27 cards, each with a number on one side and a letter on the other side. The cards are displayed with
 28 4, 7, E and X showing. You wish to determine whether the following rule describes these four
 29 cards: *If a card has an even number on one side, it has a vowel on the other side.* Which cards need
 30 to be turned over to test the rule? This would be a good time to come up with an answer on your
 31 own before reading on.

32 This is actually a difficult problem for most people. Turning over the 4 card is important because
 33 the rule requires that it have a vowel on the other side. People generally get that. Turning over the
 34 7 card is unimportant because the rule says nothing about cards with an odd number on one side.
 35 Turning over the E card is unimportant because the rule does not state what is on the other side
 36 of cards with an odd number; therefore, neither an even nor an odd number on the other side
 37 would disconfirm the rule. Finally, turning over the X is important because an even number on
 38 the other side would disconfirm the rule. People often mistakenly think that it is the E, and not
 39 the X, that needs to be turned over.

40 It can be argued that working memory is really challenged by this problem. It strains working
 41 memory to retain the rule while figuring out what each possible outcome would indicate in rela-
 42 tion to the rule. This difficult problem becomes a lot easier, though, if common knowledge is
 43 used. Suppose, for example, that the problem is as follows. A certain car repair shop services
 44 Hondas and Buicks (as has been the case in Columbia, Missouri). A recall announcement indi-
 45 cates that the accelerator pedals on the Hondas can stick, potentially leading to accidents and
 46 therefore warranting repair. Four customer cards are sitting on the desk. Each one indicates the
 47 customer's name and the brand of car on one side and, on the other side, whether the accelerator
 48 pedal has been checked. The four cards as placed on the desk show *Honda, Buick, checked, and not*
 49 *checked.* Which cards need to be turned over?

1 It is obvious upon a moment's thought that the *Honda* and the *not-checked* cards need to be
 2 turned over. This would be obvious even if this problem were given before the abstract one.
 3 However, it is logically the same problem as the more abstract one. As Wason and Shapiro (1971)
 4 showed, a problem based in knowledge is much easier than the same problem expressed in an
 5 abstract manner. Making the best use of students' knowledge, as well as encouraging retention
 6 strategies, is critical for fostering learning and comprehension.

7 Often, abstract terms cannot be avoided because the domain of a problem is new. In fact, it
 8 could be argued that the point of a test of fluid intelligence is to examine how well an individual is
 9 able to cope with a problem that he or she has not encountered before (a working-memory-
 10 intensive enterprise). One reason that intelligence test scores appear to have increased over time
 11 worldwide, for example from the 1950s to the 1990s, may be that people these days have varied
 12 experiences that make the tests invalid inasmuch as the types of problems on the intelligence tests
 13 are not as unfamiliar as they once were in a previous generation (cf. Flynn, 2007).

14 When a problem is new or unfamiliar and working memory is insufficient to allow an individual
 15 to solve it easily, the individual may fall back upon several very common thinking strategies
 16 (albeit often unknowingly). These strategies often work but they also are fraught with danger. One
 17 strategy is to use a heuristic, a rule of thumb that yields the correct answer often, though certainly
 18 not always (Kahneman, 2003). For example, it can be effortful and working-memory-intensive to
 19 evaluate a political argument; less effortful to typecast the speaker based on political affiliation,
 20 emotional tone or the similarity of the speaker to oneself. Another strategy that is often used is to
 21 rely on social consensus. It may not give you the correct answer, but at least it gives you the answer
 22 that is easiest to obtain and that results in little friction with those around you. Even one's basic
 23 perceptual judgements (such as judging the length of a line) apparently can be influenced by what
 24 others say (Asch, 1956). One of the most important tasks of the educational system may be to
 25 make students aware of these cognitive pitfalls and train them to exert more effort so that their
 26 working memory can be put to best use in obtaining the most valid answers, rather than the
 27 answers that are simply easiest to obtain or are the most comfortable.

28 9.4 Development of working memory

29 It has been clear for a very long time that there is profound developmental growth in what is now
 30 called memory span (Bolton, 1892). It has, however, been much more difficult from an analytic
 31 point of view to figure out exactly which basic working memory mechanisms change with devel-
 32 opment (Cowan & Alloway, 2009). Nevertheless, some important progress has been made
 33 recently.

34 Growth of capacity

35 Neo-Piagetian psychologists have long believed that the fundamental basis of cognitive develop-
 36 ment is an increase in working memory ability, expressed either as increasing energy that allows
 37 more items to be held in the attention-based part of working memory as children develop (Pascual-
 38 Leone, 2005; Pascual-Leone & Smith, 1969) or in an increasing ability to keep in mind the rela-
 39 tions between elements and therefore comprehend information of greater complexity (Andrews,
 40 Halford, Bunch, Bowden & Jones, 2003).

41 One difficulty in supporting the premise that capacity, expressed as the number of chunks in
 42 memory, increases with age is that there are other explanations of basic performance increases
 43 over age. It could be that what increases with age is only the ability to build larger chunks, in order
 44 to use the same basic chunk capacity more efficiently. However, Gilchrist, Cowan and Naveh-
 45 Benjamin (2009) were able to show that, in one circumstance at least, this is not the case; there is
 46 true development of chunk capacity. They presented for verbatim, spoken recall lists of short,

1 simple spoken sentences that were unrelated to one another (e.g. take your paper and pencil; our
 2 neighbour sells vegetables; thieves took the painting; drink all of your milk). The length of the
 3 materials made it impractical to use verbal rehearsal to remember the items (Baddeley, 1986),
 4 which presumably forced participants to use a chunk-limited capacity. Presumably, each sentence
 5 forms a separate chunk of information, with strong links between words in a chunk and very weak
 6 links, if any, between chunks.

7 The beauty of this stimulus set-up is that it was possible to estimate not only the number of
 8 chunks, but also the integrity of chunks in memory. It turned out that the children from the first
 9 grade (aged 6–7 years), children from the sixth grade (aged 11–12 years) and adults all formed
 10 sentence chunks that were equally good. In particular, for participants of any age, if any substan-
 11 tive part of a short sentence was recalled, about 80% of the sentence was recalled. Yet, the number
 12 of such sentences recalled increased from an average of about 2.5 in first-grade children to about
 13 3.0 in adults. This reflects a small but probably rather important growth in basic working memory
 14 capacity. Of course, capacity may be smaller in children too young to test in this procedure.
 15 Increase in the basic capacity might account for developmental increase in the complexity of
 16 propositions and materials that can be retained and understood during development (e.g. Andrews
 17 et al., 2003; Halford, Wilson & Phillips, 1998; Pascual-Leone & Smith, 1969).

18 **Growth of goal maintenance**

19 One of the most important aspects of the development of working memory is the increasing
 20 ability to ignore irrelevant information and focus on more relevant information. For example,
 21 Elliott (2002) visually presented lists of digits for recall, either in silence or in the presence of
 22 various speech backgrounds. When the background consisted of a variety of spoken words (red,
 23 blue, green, yellow, white, tall, big, short, long) this background had an effect that was quite dev-
 24 astating in second-grade (age 7–8) children, reducing their proportion correct on the digit recall
 25 task from about 70% to about 30% (Elliott, 2002, figure 1). Each participant was tested with lists
 26 of a length based on his or her own pre-determined span. Despite that adjustment, the effect of
 27 irrelevant speech diminished with development so that, in adults, the effect of irrelevant speech
 28 was less than a 10% reduction.

29 There are two slightly different interpretations of this finding by Elliott (2002), and other
 30 findings like it. For the young children was the distracting speech just intrusive? Or did the dis-
 31 tracting speech actually make the children lose sight of the goal, which was to remember the
 32 printed digits and not the spoken words? That is not clear but, at least in some circumstances at
 33 least, young children actually do lose the goal. Zelazo (2003) has summarized a series of studies in
 34 which children must sort a deck of cards according to some rule (e.g. rabbits here, whether red or
 35 blue; cars over there, whether red or blue). After a while, the task switches to sorting on a different
 36 basis (e.g. red things here, whether cars or rabbits; blue things over there, whether cars or rabbits).
 37 The striking finding is that 3-year-old children can explain the new sorting rule, but nevertheless
 38 continue to sort according to the old rule. The old rule has become a too-compelling habit to
 39 overcome, given the apparently relatively weak support from the new rule, which may temporarily
 40 drop out of working memory.

41 Given these results, and many others on children's difficulty in inhibiting irrelevant information
 42 to focus on the most relevant information and task goals (e.g. Bjorklund & Harnishfeger, 1990;
 43 Williams, Ponesse, Schachar, Logan & Tannock, 1999), one might wonder if we really know that
 44 chunk capacity also increases with age. Perhaps young children have just as much capacity, but fill
 45 it with irrelevant materials. A study by Cowan, Morey, AuBuchon, Zwilling and Gilchrist (2010)
 46 argues against that as a general interpretation; a growth of the inhibition or filtering out of irrelevant

1 information cannot be the entire explanation of developmental change. Cowan et al. presented
 2 arrays with both more-relevant and less-relevant items to be remembered. Participants were
 3 sometimes, for example, to remember the colours of the circles and ignore the colours of the
 4 triangles. Occasionally, however, they were tested on the less-relevant shape. With two more-
 5 relevant and two less-relevant items in the array, children in first and second grades (6–8-year-
 6 olds) allocated their attention as efficiently as older children and adults. All groups favoured the
 7 more-relevant items by very similar amounts. However, the younger children simply remembered
 8 fewer items than did older children or adults, which held true for both the better-remembered,
 9 more-relevant items and the poorly-remembered, less-relevant items. Just as Gilchrist et al. (2009)
 10 showed that chunking ability could not explain away an apparent growth in basic capacity, Cowan
 11 et al. showed that the allocation of attention to filter out irrelevant items cannot explain away this
 12 growth in basic capacity.

13 The smaller capacity and poorer goal maintenance of younger children together have profound
 14 implications for education. Gathercole (2008) describes applied studies in the classroom in which
 15 she and her colleagues have found that what appeared on the surface to be cases of children's diso-
 16 bedience, rebellion or incomprehension often must be attributed instead to working-memory-
 17 based failures, such as forgetting the instructions, not keeping in mind the task goal or not recalling
 18 information critical to the successful completion of an assigned task or academic activity.

19 Despite the poignant observations and anecdotes contributing to this connection between
 20 working memory and school performance, one might wonder whether the contribution of work-
 21 ing memory is specific. After all, various kinds of working memory tests are highly correlated
 22 with the intelligence quotient (IQ) and other aptitude and achievement tests in children (e.g.
 23 Cowan et al., 2005). The contributions of working memory and general intelligence can be disen-
 24 tangled, however, using regression techniques. Alloway and Alloway (2010) examined children at
 25 5 years of age and again at 11 years. They found that literacy and numeracy at 11 years were pre-
 26 dicted by working memory even after taking into account IQ. It was also the case that literacy and
 27 numeracy were predicted by IQ even after taking into account working memory, but the contribu-
 28 tion of IQ was smaller than that of working memory. Alloway (2009) tested children between 7
 29 and 11 years of age who were identified as having learning difficulties, and found even more strik-
 30 ing results. The children were tested at intervals 2 years apart. In this sample, Alloway found that
 31 working memory at the first test accounted for subsequent learning even after taking into account
 32 IQ, but the reverse was not true: after taking into account working memory, IQ made no further
 33 contribution. It seems safe to say that educators must attend to issues involving working memory
 34 in order to understand academic performance in children.

35 **Growth of memory persistence over time**

36 There are a few studies indicating that memory for acoustic sensation, exactly how a noise or word
 37 sounds, may persist longer in older children than in young children. Keller and Cowan (1994)
 38 found that the duration of tone pitch memory increased from first grade (6–7-years-olds) to
 39 adulthood. Cowan, Nugent, Elliott and Saults (2000) presented lists of spoken digits to be ignored
 40 while a silent rhyming game was carried out and occasionally presented a cue to switch from the
 41 game to recall of the last spoken list, which had ended 1, 5, or 10 seconds before the cue. Lists were
 42 adjusted for the child's memory span for attended digits. It was found that forgetting of ignored
 43 digits across the retention intervals was equivalent for all ages, for most of the list; but that forget-
 44 ting of the very last digit in the list across the retention intervals was much more severe for
 45 younger children than for older participants. This suggests that the sensory memory, which is
 46 uninterrupted only for the final list item, fades more quickly in younger children. More research

1 is still needed to provide an understanding of the implications of such findings for education
 2 but it does provide one more reason why younger children have more trouble following spoken
 3 directions. These instructions may remain vivid in sensory memory for a shorter time in younger
 4 children.

5 **Growth of strategies**

6 Finally, there has been a great deal of research showing that the ability to use mnemonic strategies
 7 to overcome the limitations increases markedly across age groups in childhood. It is not fully clear
 8 exactly why this growth occurs but there are leads. Many studies have shown that young children
 9 are unable to engage in covert verbal rehearsal in a sophisticated manner (Flavell, Beach &
 10 Chinsky, 1966; Ornstein & Naus, 1978). One possibility is that they are just unaware that rehearsal
 11 would help performance. Against that interpretation, attempts to train children to rehearse, or to
 12 recite items more quickly, have not been very successful (e.g. Cowan, Saults, Winterowd & Sherk,
 13 1991; Hulme & Muir, 1985).

14 Instead, it could be that a certain working memory capacity is necessary in order to make these
 15 strategies work effectively. Two different findings in extremely different age groups support this
 16 hypothesis. First, in memory span tasks, young children recite items more slowly than young
 17 adults, and it was possible that this slower recitation could be allowing time for decay. Against that
 18 possibility, Cowan, Elliott et al. (2006) were able to get children to speed up so that they recalled
 19 digits in a list at an adult-like rate, but still their memory span did not improve. Second, at the
 20 other end of the age spectrum, Kynette, Kemper, Norman and Cheung (1990) found that older
 21 adults cannot rehearse as quickly and do not remember as much as young adults, even though
 22 there is no reason to assume that aging causes a loss of knowledge about the efficacy of particular
 23 mnemonic strategies. It seems reasonable to conclude that the growth of working memory capac-
 24 ity in children and its decline in old age both may affect the ability to use certain mnemonic
 25 strategies effectively, in opposite directions; and that the effects of age cannot be explained by the
 26 appreciation of the potential use of such a mnemonic strategy.

27 Barrouillet et al. (2007) found that memory in young adults depended on the cognitive load
 28 imposed by items in a secondary task between the items to be recalled. They suggested that this
 29 occurs because free time is used to attentionally refresh items in memory (Raye et al., 2007). This
 30 leaves open several potential bases of developmental growth. The basis may depend on the age
 31 range in childhood. Barrouillet, Gavens, Vergauwe, Gaillard and Camos (2009) found that 5-year-
 32 old children were sensitive to the presence or the absence of any distraction between items to be
 33 recalled, but were not sensitive to the cognitive load. This would be expected if these young
 34 children do not use the attentional-refreshing process (or any kind of rehearsal) that would be
 35 interrupted by the cognitive load. In contrast, 7-year-olds were sensitive to cognitive load.
 36 Moreover, the quality of attentional refreshing activities apparently continued to improve with age
 37 inasmuch as 14-year-olds' spans increased with increasing free time to refresh items more quickly
 38 than did younger children's spans. Moreover, some factor other than cognitive load appears to
 39 have contributed to age differences in recall, as well. That other factor may be the basic working
 40 memory capacity.

41 Finally, Cowan, Saults and Morey (2006) found that the simple strategy of verbal rehearsal
 42 sometimes can be put to good use in sophisticated ways to enhance performance in a complex
 43 task. Illustrating their procedure, suppose you need to remember temporarily the names and loca-
 44 tions of five cities in the eastern United States. That is a lot of name-place associations to hold in
 45 working memory. Sometimes, however, adults use a simpler strategy. It is not difficult for them to
 46 form a mental route from one location to the next; and it is not difficult for them to rehearse five

1 city names. Then it is possible for them to use these two relatively effortless forms of working
 2 memory together; the first name goes with the first map location, and so on. That memorization
 3 strategy, breaking up a complex situation into simpler, verbal and spatial sub-problems, of course
 4 is unavailable to children too young to use rehearsal well.

5 9.5 Working memory and maximized education

6 The lessons from this review of working memory and its development are fairly clear. It is neces-
 7 sary to pitch any kind of education to a level that the student can comprehend, and the ability to
 8 assess this comprehension is improved by an appreciation of how closely it may depend on work-
 9 ing memory abilities. Failure of working memory must be kept in mind as a possible explanation
 10 of any cognitive shortcoming in the classroom or as a basis, at least in part, for learning disabili-
 11 ties. A student's existing knowledge can be used to overcome working memory limits in many
 12 situations. One also can try to teach better learning skills and mnemonic strategies, all the while
 13 keeping in mind that the successful implementation of a strategy itself may depend on a certain
 14 working memory capacity.

15 In recent studies, there has been a suggestion that challenging working memory tasks, carried
 16 out repeatedly and with the challenges increasing as the participant improves, can be used to train
 17 working memory and attention. It is also said to have positive benefits for other aspects of per-
 18 formance, raising intelligence tests and helping to overcome attention deficit disorders (e.g.
 19 Klingberg, 2010; Tang et al., 2007). This has been in contrast to most prior studies in cognitive
 20 psychology, in which the benefits of training and practice have been found to be somewhat nar-
 21 row (e.g. Boron, Willis & Schaie, 2007; Ericsson et al., 1980). Perhaps what is learned in the newer
 22 training studies is that, by applying effort and attention repeatedly and persistently, one can
 23 improve one's performance on just about any task. It is thought, for example, that a difference in
 24 attitude helps to explain why Asian children learn mathematics with much more proficiency on
 25 average than children in the United States. They learn that if one does not do well in mathematics,
 26 one must work harder; US children, generally, tend to believe that some people are just not good
 27 at math (Chen & Stevenson, 1995).

28 If working memory training or some other challenging training in a game-like form can help to
 29 overcome biases such as the belief that one is just not good at certain tasks, such training will be
 30 well worth while. Perhaps it might even help children to become citizens who are willing to use
 31 their effort and working memory to formulate and carry out the best possible decisions for our
 32 society, without an over-reliance on simplistic heuristics, biases or prejudices, and social convention
 33 or popular approval.

34 References

- 35 Alloway, T. P. (2009). Working memory, but not IQ, predicts subsequent learning in children with learning
 36 difficulties. *European Journal of Psychological Assessment*, 25, 92–98.
- 37 Alloway, T. P. & Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in
 38 academic attainment. *Journal of Experimental Child Psychology*, 106, 20–29.
- 39 Andrews, G., Halford, G.S., Bunch, K. M., Bowden, D., & Jones, T. (2003). Theory of mind and relational
 40 complexity. *Child Development*, 74, 1476–99.
- 41 Asch, S. E. (1956). Studies of independence and conformity: A minority of one against a unanimous
 42 majority. *Psychological Monographs*, 70, (Whole no. 416).
- 43 Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes.
 44 In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation: Advances in research
 45 and theory* (Vol. 2, pp. 89–195). New York: Academic Press.

- 1 Baddeley, A. D. (1986). *Working memory*. Oxford: Clarendon Press.
- 2 Baddeley, A. D. (2000). The episodic buffer: a new component of working memory? *Trends in cognitive*
3 *sciences*, 4, 417–23.
- 4 Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nature Reviews: Neuroscience*,
5 4, 829–39.
- 6 Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and*
7 *motivation* (Vol. 8, pp. 47–89). New York: Academic Press.
- 8 Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in
9 working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 33, 570–85.
- 10 Barrouillet, P., Gavens, N., Vergauwe, E., Gaillard, V., & Camos, V. (2009). Working memory span
11 development: A time-based resource-sharing model account. *Developmental Psychology*, 45, 477–90.
- 12 Bjorklund, D. F., & Harnishfeger, K. K. (1990). The resources construct in cognitive development: Diverse
13 sources of evidence and a theory of inefficient inhibition. *Developmental Review*, 10, 48–71.
- 14 Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term
15 memory. *Journal of Verbal Learning and Verbal Behavior*, 14, 575–89.
- 16 Bolton, T. L. (1892). The growth of memory in school children. *American Journal of Psychology*, 4, 362–80.
- 17 Boron, J. B., Willis, S. L., & Schaie, K. W. (2007). Cognitive training gain as a predictor of mental status. *The*
18 *Journals of Gerontology: Series B: Psychological Sciences and Social Sciences*, 62B, 45–52.
- 19 Broadbent, D. E. (1975). The magic number seven after fifteen years. In A. Kennedy & A. Wilkes (Eds.),
20 *Studies in long-term memory* (pp. 3–18). Oxford: John Wiley & Sons.
- 21 Chein, J. M., & Fiez, J. A. (2010). Evaluating models of working memory through the effects of concurrent
22 irrelevant information. *Journal of Experimental Psychology: General*, 139, 117–37.
- 23 Chen, C., & Stevenson, H. W. (1995). Motivation and mathematics achievement: A comparative study of
24 Asian-American, Caucasian-American, and East Asian high school students. *Child Development*, 66,
25 1215–34.
- 26 Chen, Z., & Cowan, N. (2009). Core verbal working memory capacity: The limit in words retained without
27 covert articulation. *Quarterly Journal of Experimental Psychology*, 62, 1420–29.
- 28 Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual
29 constraints within the human information processing system. *Psychological Bulletin*, 104, 163–91.
- 30 Cowan, N. (1995). *Attention and memory: An integrated framework* (Oxford Psychology Series, No. 26).
31 New York: Oxford University Press.
- 32 Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.),
33 *Models of Working Memory: Mechanisms of active maintenance and executive control* (pp. 62–101).
34 Cambridge: Cambridge University Press.
- 35 Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage
36 capacity. *Behavioral and Brain Sciences*, 24, 87–185.
- 37 Cowan, N. (2009). Working memory from the trailing edge of consciousness to neurons. *Neuron*, 62,
38 13–16.
- 39 Cowan, N., & Alloway, T. (2009). Development of working memory in childhood. In M. L. Courage &
40 N. Cowan (Eds.), *The development of memory in infancy and childhood* (pp. 303–42). Hove: Psychology
41 Press.
- 42 Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. A. (2005).
43 On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes.
44 *Cognitive Psychology*, 51, 42–100.
- 45 Cowan, N., Elliott, E. M., Saults, J. S., Nugent, L. D., Bomb, P., & Hismjatullina, A. (2006). Rethinking speed
46 theories of cognitive development: Increasing the rate of recall without affecting accuracy. *Psychological*
47 *Science*, 17, 67–73.
- 48 Cowan, N., Morey, C. C., AuBuchon, A. M., Zwilling, C. E., & Gilchrist, A. L. (2010). Seven-year-olds
49 allocate attention like adults unless working memory is overloaded. *Developmental Science*, 13, 120–33.

- 1 Cowan, N., Nugent, L. D., Elliott, E. M., & Saults, J. S. (2000). Persistence of memory for ignored lists of
 2 digits: Areas of developmental constancy and change. *Journal of Experimental Child Psychology*, 76,
 3 151–72.
- 4 Cowan, N., Saults, J. S., & Morey, C. C. (2006). Development of working memory for verbal-spatial
 5 associations. *Journal of Memory and Language*, 55, 274–89.
- 6 Cowan, N., Saults, J. S., Winterowd, C., & Sherk, M. (1991). Enhancement of 4-year-old children's memory
 7 span for phonologically similar and dissimilar word lists. *Journal of Experimental Child Psychology*, 51,
 8 30–52.
- 9 D'Esposito, M., Postle, B. R., Jonides, J., & Smith, E. E. (1999). The neural substrate and temporal dynamics
 10 of interference effects in working memory as revealed by event-related functional MRI. *Proceedings of*
 11 *the National Academy of Sciences USA*, 96, 7514–7519.
- 12 Elliott, E. M. (2002). The irrelevant-speech effect and children: Theoretical implications of developmental
 13 change. *Memory & Cognition*, 30, 478–87.
- 14 Ericsson, K. A., Chase, W. G., & Faloon, S. (1980). Acquisition of a memory skill. *Science*, 208, 1181–82.
- 15 Ericsson, K. A., Delaney, P. F., Weaver, G., & Mahadevan, R. (2004). Uncovering the structure of a
 16 memorist's superior 'basic' memory capacity. *Cognitive Psychology*, 49, 191–237.
- 17 Flavell, J. H., Beach, D. H., & Chinsky, J. M. (1966). Spontaneous verbal rehearsal in a memory task as a
 18 function of age. *Child Development*, 37, 283–99.
- 19 Flynn, J. R. (2007). *What is Intelligence?: Beyond the Flynn Effect*. Cambridge: Cambridge University Press.
- 20 Gardner, H. (1985). *The mind's new science: A history of the cognitive revolution*. New York: Basic Books.
- 21 Gathercole, S. E. (2008). Working memory in the classroom. *The Psychologist*, 21, 382–85.
- 22 Gilchrist, A. L., Cowan, N., & Naveh-Benjamin, M. (2009). Investigating the childhood development of
 23 working memory using sentences: New evidence for the growth of chunk capacity. *Journal of*
 24 *Experimental Child Psychology*, 104, 252–65.
- 25 Halford, G. S., Baker, R., McCredden, J. E., & Bain, J. D. (2005). How many variables can humans process?
 26 *Psychological Science*, 16, 70–76.
- 27 Halford, G. S., Cowan, N., & Andrews, G. (2007). Separating cognitive capacity from knowledge: A new
 28 hypothesis. *Trends in Cognitive Sciences*, 11, 236–42.
- 29 Halford, G. S., Wilson, W. H., & Phillips, S. (1998). Processing capacity defined by relational complexity:
 30 Implications for comparative, developmental, and cognitive psychology. *Behavioral and Brain Sciences*,
 31 21, 803–65.
- 32 Hecht, S. A., Vagi, K. J., Torgesen, J. K. (2007). Fractional skills and proportional reasoning. In D. B. Berch &
 33 M. M. Mazzocco (Eds.), *Why is math so hard for some children? The nature and origins of mathematical*
 34 *learning difficulties and disabilities* (pp. 121–32). Baltimore, MD: Paul H Brookes Publishing.
- 35 Hulme, C., & Muir, C. (1985). Developmental changes in speech rate and memory span: A causal
 36 relationship? *British Journal of Developmental Psychology*, 3, 175–81.
- 37 James, W. (1890). *The principles of psychology*. New York: Henry Holt.
- 38 Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., & Moore, K. S. (2008). The mind and brain
 39 of short-term memory. *Annual Review of Psychology*, 59, 193–224.
- 40 Kahneman, D. (2003). A perspective on judgment and choice: Mapping bounded rationality. *American*
 41 *Psychologist*, 58(9), 697–720.
- 42 Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The
 43 contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of*
 44 *Experimental Psychology: General*, 132, 47–70.
- 45 Kane, M. J., Brown, L. H., McVay, J. C., Silvia, P. J., Myin-Germeys, I., & Kwapil, T. R. (2007). For whom the
 46 mind wanders, and when: An experience-sampling study of working memory and executive control in
 47 daily life. *Psychological Science*, 18, 614–21.
- 48 Keller, T. A., & Cowan, N. (1994). Developmental increase in the duration of memory for tone pitch.
 49 *Developmental Psychology*, 30, 855–63.

- 1 Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences*, 14(7), 317–24.
- 2 Kynette, D., Kemper, S., Norman, S., & Cheung, H. (1990). Adults' word recall and word repetition.
3 *Experimental Aging Research*, 16, 117–21.
- 4 Lewandowsky, S., Duncan, M., & Brown, G.D.A. (2004). Time does not cause forgetting in short-term serial
5 recall. *Psychonomic Bulletin & Review*, 11, 771–90.
- 6 Lewandowsky, S., & Oberauer, K. (2008). The word-length effect provides no evidence for decay in short-
7 term memory. *Psychonomic Bulletin & Review*, 15, 875–88.
- 8 Logie, R. H., Della Sala, S., Laiacina, M., Chalmers, P., & Wynn, V. (1996). Group aggregates and individual
9 variability: The case of verbal short-term memory. *Memory & Cognition*, 24, 305–21.
- 10 Majerus, S., Argembeau, A. D., Perez, T. M., Belayachi, S., Van der Linden, M., Collette, F., Salmon, E.,
11 Seurinck, R., Fias, W., and Maquet, P. (in press). The commonality of neural networks for verbal and
12 visual short-term memory. *Journal of Cognitive Neuroscience*, 22(11), 2570–93.
- 13 McNab, F., & Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access to working memory.
14 *Nature Neuroscience*, 11, 103–107.
- 15 Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for
16 processing information. *Psychological Review*, 63, 81–97.
- 17 Miller, G. A., Galanter, E., and Pribram, K. H. (1960). *Plans and the structure of behavior*. New York: Holt,
18 Rinehart and Winston, Inc.
- 19 Nairne, J. S. (2002). Remembering over the short-term: The case against the standard model. *Annual Review*
20 *of Psychology*, 53, 53–81.
- 21 Neath, I., & Nairne, J. S. (1995). Word-length effects in immediate memory: Overwriting trace decay.
22 *Psychonomic Bulletin & Review*, 2, 429–41.
- 23 Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: decay, temporal
24 distinctiveness, or interference? *Psychological Review*, 115, 544–76.
- 25 Ornstein, P. A., & Naus, M. J. (1978). Rehearsal processes in children's memory. In P. A. Ornstein (Ed.),
26 *Memory development in children* (pp. 69–99). Hillsdale, NJ: Erlbaum.
- 27 Pascual-Leone, J. (2005). A neoPiagetian view of developmental intelligence. In O. Wilhelm & R. W. Engle
28 (Eds.), *Understanding and measuring intelligence* (pp. 177–201). London: Sage.
- 29 Pascual-Leone, J., & Smith, J. (1969). The encoding and decoding of symbols by children: A new
30 experimental paradigm and a neo-Piagetian model. *Journal of Experimental Child Psychology*, 8, 328–55.
- 31 Peterson, L. R. & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of*
32 *Experimental Psychology*, 58, 193–98.
- 33 Portrat, S., Barrouillet, P., & Camos, V. (2008). Time-related decay or interference-based forgetting in
34 working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34, 1561–64.
- 35 Raye, C. L., Johnson, M. K., Mitchell, K. J., Greene, E. J., & Johnson, M. R. (2007). Refreshing: A minimal
36 executive function. *Cortex*, 43, 135–45.
- 37 Ricker, T. J., & Cowan, N. (2010). Loss of visual working memory within seconds: The combined use of
38 refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and*
39 *Cognition*, 36(6), 1355–68.
- 40 Rundus, D. (1971). Analysis of rehearsal processes in free recall. *Journal of Experimental Psychology*, 89, 63–77.
- 41 Tan, L., & Ward, G. (2000). A recency-based account of the primacy effect in free recall. *Journal of*
42 *Experimental Psychology: Learning, Memory, and Cognition*, 26, 1589–625.
- 43 Tang, Y. -Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., Yu, Q., Sui, D., Rothbart, M. K., Fan, M., &
44 Posner, M. I. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings*
45 *of the National Academy of Science USA*, 104, 17152–56.
- 46 Todd, J. J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal
47 cortex. *Nature*, 428, 751–54.
- 48 Tulving, E., & Patkau, J. E. (1962). Concurrent effects of contextual constraint and word frequency on
49 immediate recall and learning of verbal material. *Canadian Journal of Psychology*, 16, 83–95.

- 1 Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for
2 objects. *Nature*, 440, 91–95.
- 3 Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences
4 in controlling access to working memory. *Nature*, 438, 500–503.
- 5 Wason, P. C. & Shapiro, D. (1971). Natural and contrived experience in a reasoning problem. *Quarterly*
6 *Journal of Experimental Psychology*, 23, 63–71.
- 7 Watson, J. B. (1913). Psychology as the behaviorist views it. *Psychological Review*, 20, 158–77.
- 8 Wilding, J. (2001). Over the top: Are there exceptions to the basic capacity limit? *Behavioral and Brain*
9 *Sciences*, 24, 152–53.
- 10 Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of
11 inhibitory control across the life span. *Developmental Psychology*, 35, 205–213.
- 12 Zelazo, P. D. (2003). The development of executive function in early childhood. *Monographs of the Society*
13 *for Research on Child Development*, 68, Serial No. 274.