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CHAPTER FIVE

Working Memory and Comprehension

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It seems intuitively obvious that the temporary retention of information would be important for complex cognitive behaviour such as listening and reading comprehension. In order to comprehend this chapter you must maintain representations of words, phrases, sentences, etc. However, traditional measures of short-term memory (STM) capacity, such as simple digit span, fail to reveal a strong relationship with measures of comprehension, such as the Verbal Scholastic Aptitude Test (VSAT). Baddeley and Hitch (1974) claimed that the lack of a relationship between STM capacity and complex cognition is due to the fact that STM is a passive storage buffer that is not involved in the processing of information. Instead, they proposed a working-memory (WM) system that is responsible not only for the storage of information, but also for the simultaneous processing of information. Working memory, not short-term memory, is the system that will play a role in complex cognitive behaviour, and working-memory capacity, not short-term memory capacity, is the critical constraint on behaviour.

The question we address in this chapter is where and when working memory and working-memory capacity are important for comprehension. Which processes involve WM, and how are these processes constrained by WM capacity? In the case of reading and listening comprehension, the answer is complex. There is clearly a relationship between measures of WM capacity and complex measures of comprehension, such as the VSAT, but why does this relationship occur? Which specific reading processes

require WM resources and which do not? Furthermore, what does a WM task measure that is also reflected in complex tests of comprehension?

Before we address the role of WM in comprehension, consider what is meant by the term comprehension. Are you comprehending right now? You are moving your eyes over a page of printed text and, one hopes, deriving some level of understanding or meaning from the process. As a skilled adult reader you can almost certainly "read" without comprehending. You can, for example, read aloud the sentence "'Twas brillig, and the slithy toves did gyre and gimble in the wabe; all mimsy were the borogoves and the mome raths outgrabe" without having any idea what Lewis Carroll meant when he wrote these so-called words.

Comprehension can be thought of as making sense of what we hear or read. But "making sense" has been defined differently by the various researchers who have studied comprehension. As Steven Schwartz (1984) said about comprehension in his book on reading competency, "For some, it means being able to extract the main idea of a passage. For others, making sense of a passage means being able to answer simple questions about it; and for still others, drawing inferences from what is read is the hallmark of comprehension" (p. 99). It is quite likely that you, as the reader, would process a passage differently if you knew you were going to be asked to retain a simple gist of the passage than if you knew you were going to be asked questions requiring the retention of specific facts and details or if you were reading for the simple pleasure of reading with no goal necessarily to recall the material later. What does it say about comprehension if you cannot recall that Schwartz was the author of the last quote but could tell me what the quote means or, conversely, if you could recall that Schwartz was the author but have no idea what he meant by the quote? Thus, comprehension can mean different things at different times, depending on the goal of the reader. As such, the role of WM in comprehension will also vary as a function of the goals of the reader.

We will tell you now some of our ultimate conclusions. It is probably the case that WM would not be important to comprehension if we were only speaking about adults, skilled in comprehending the language being presented to them, and if all spoken and written language were: (1) simple, active, affirmative sentences of relatively few words; (2) there was never a need to retain the specific words spoken previously in order to understand the specific meaning of a currently spoken word; (3) there was never any ambiguity in words or phrases that might lead to misinterpretation, which would hurt comprehension of words spoken or read later; (4) the structure of the "story" we were reading or hearing occurred in a linear fashion with no twists or turns; (5) the structure of the story could be built in a straightforward linear way, with each new element or proposition added to the gist of the story without the need to retain elements that

might later have to be discarded; and (6) when seeing or hearing this language, we are not distracted by other events happening in our environment. Of course, much of the language that we process in the modern world is not of the simple and boring type just described. It is for all those other language situations that WM will likely be important.

We will discuss comprehension in the context of the three elements of Baddeley and Hitch's (1974) model of WM: the visuo-spatial sketch-pad, the phonological loop, and the central executive. We have chosen this approach more for convenience than for theoretical motivation. This approach is convenient because most research on working memory, and subsequently, on working memory and comprehension, has been conducted in the context of the Baddeley and Hitch model. Therefore, following this format provides a context for the reader. However, we do not want our approach to suggest that we necessarily agree with the structural distinctions between slave systems, such as the phonological loop and the visuo-spatial sketch-pad. On the contrary, we tend to favour a view in which the structure of the slave systems is consistent, but what varies is the nature of the representation maintained by the system (cf. Cowan, 1995; Engle & Oransky, 1997). Representations can be maintained in many different formats; acoustic, phonological, articulatory, visual, spatial, orthographic, lexical, semantic, etc. We would speculate that there are myriad possible formats that can be maintained by the same structure, and that structure will have the same properties regardless of what type of format is maintained. Thus, "the distinctness and noninterchangeability of phonetic and spatial information occurs because different types of features are being activated, not because of distinctly different storage modules" (Cowan, 1995, p. 36).

THE VISUO-SPATIAL SKETCH-PAD AND COMPREHENSION

We will discuss the role of the visuo-spatial sketch-pad in comprehension first. This type of representation is typically thought of as coding the visual and spatial features of an event—what you might think of as a mental image. In answering the question "Is a pencil longer than a cigarette?" you might form a visual image of the two objects and base your answer to the question on the mental picture. Or suppose you read the following passage: "Nantoo leaned perilously over the edge of the rock and looked out over the huge lake. As his eyes scanned the horizon of diamonds shimmering on the water, he saw the revered eagle. It flew as an arrow to the jewelled surface, then rose with food for its young. An early spring breeze chilled him as he thought of his own efforts to feed his family." It is hard to read a passage such as this without thinking of what the scene

"looks" like and "feels" like. In your mind's eye, you can probably see what Nantoo is wearing and what the lake looks like and how far away the eagle is from where Nantoo is standing even though none of that is conveyed in the words. In your mind's heart, you can probably feel what Nantoo feels about feeding his family. Writers of poetry and prose are often judged by how well they can make us "see" and "feel".

The visual and spatial representation is almost certainly a consequence of much of the language we read and hear, but is this type of coding *necessary* for comprehension? Again, the answer probably depends on how we define comprehension. For example, Levin (1973) had 10- to 11-year-old children, who were classified as poor readers, read a 12-sentence story. The children were then asked questions about the details of the passage. Children in one group were trained to form a mental image of the events in each sentence as the passage was read, and other children were simply told to remember what they read because they would be asked questions about it later. The group that was trained to think about the passage using the visuo-spatial code performed better on the test of details. The finding that at least some types of poor readers can be helped if they are trained to use mental imagery is a reliable finding (Pressley, 1976). There is also a relationship between the comprehensibility of prose passages and the ease with which they elicit mental images. Goetz, Sadoski, Fatemi, and Bush (1994) found, for example, that newspaper articles that were rated most comprehensible and understandable were also rated as most likely to lead to a mental image.

But is the visuo-spatial code necessary for comprehension at the level of the individual sentence? An elegant set of studies by Glass, Millen, Beck, and Eddy (1985) addressed this question. They had subjects read, or listen to, high- and low-imagery sentences like "The stars on the American flag are white" and "Biology is the study of living matter". The subjects' task was to verify whether or not the sentence was true. A typical finding on this task is that high-imagery sentences take longer to verify than low-imagery sentences if they are read, but *not* if they are heard. One theory for why this interaction occurs is that comprehension of the high-imagery sentences requires the construction of a visuo-spatial image and that reading, an act requiring visual processing, interferes with this process, thus slowing the construction of the image. Listening, the theory argues, does not interfere with the construction of the visual image. Glass and his colleagues attempted to determine the conditions under which the "high–low imagery by modality" interaction in verification times occurred and when it did not. The interaction was found regardless of whether visual presentation was a word at a time or in normal left-to-right fashion and regardless of the rate of presentation. This suggests that the interference occurred because the necessary visual processing in reading

interfered with constructing the visual representation. Two other studies demonstrated that the interaction also occurred with sentences rated high in imagery for location in space such as the following sentence about baseball: "A right-handed hitter places his right side towards the pitcher." This and the earlier findings suggest that the representation used to verify the sentences is a visual and spatial code much like the type of representation maintained by what Baddeley and his colleagues refer to as the visuo-spatial sketch-pad (Baddeley, 1986). But the findings thus far do not say whether the visuo-spatial code is necessary for the comprehension of the sentences *or* for the verification of the truth value of the sentence.

In a crucial experiment to answer this question Glass et al. had subjects judge whether high- and low-visual-imagery sentences were meaningful or not. The sentences were either meaningful, such as "His shirt looked like a giant checkerboard", or not meaningful, such as "A baseball team has nine flavors' and the subject was to rapidly judge the meaningfulness of each sentence. The critical finding was that the high–low imagery by presentation modality interaction was not significant, showing that reading did not hurt comprehension of the high-imagery sentences, at least if comprehension is defined as the ability to say that a string of words makes sense. Thus, Glass et al. concluded that the visuo-spatial code was necessary to judge the truthfulness of a sentence like "Is a pencil longer than a cigarette?" but not to comprehend the sentence.

On the basis of the meagre research on the role of the visuo-spatial representation and comprehension, we would conclude that the type of coding we call the visuo-spatial sketch-pad is useful in many forms of reading and language comprehension, that it is certainly necessary for making comparisons about the objects described by the language, that it even adds to our enjoyment of the language. However, if we define comprehension as whether the language makes sense, then the sketch-pad is probably not necessary for comprehension.

ROLE OF THE PHONOLOGICAL LOOP

In the following section we will use the term "phonological loop" to refer to the slave system of WM responsible for the storage of verbal information. In Baddeley's (1986) model, the phonological loop refers to a system that includes a phonological store coupled with an articulatory loop (Vallar & Baddeley, 1984; 1987). The phonological store maintains short-lived representations resulting from speech-based coding and appears to be particularly important in the retention of order information. The articulatory loop is required to refresh the quickly decaying representations maintained in the phonological store. The loop is also required to

transform non-phonological input such as printed words or pictures into a phonological form to be maintained in the store.

That said, we should note the distinction between spoken and written language comprehension. Comprehension of written language has the added dimension of transforming printed words into a form of representation that can be manipulated by a WM system (i.e., phonological store). As such, comprehension of written language makes an added demand on the articulatory-loop component of WM. This is not to say that the articulatory loop is not necessary for comprehension of spoken language. We will argue that the loop is required for maintenance of phonological information during comprehension. Thus, when we refer to "comprehension" we assume both spoken-language and written-language comprehension.

When we read, we often have the intuition that we can hear our inner voice saying the words as we progress through the text. Our intuition suggests that we translate language into some form of memory representation, be it echoic, phonological, or articulatory. Our intuition also tells us that this memory trace is very short-lived. If this book was taken from you right now and you were asked to recall the words of this sentence, you could probably do so without much difficulty. However, if you were asked to recall the words from the first sentence of this paragraph, you would have a problem and would probably make errors. Support for this intuition was provided in a series of experiments by Jarvella (1970, 1971). Subjects listened to passages and were periodically asked to recall the portion of text just presented. The syntactic structure of the passages was manipulated such that the to-be-recalled information was either from the most recent sentence or from an earlier sentence. For example, in the passage, "With this possibility, Taylor left the capital. After he had returned to Manhattan, he explained the offer to his wife." The subject was instructed to recall all the information after the word "After". In this condition all of the to-be-recalled information is included in the last sentence. However, in the passage, "Taylor did not reach a decision until after he had returned to Manhattan. He explained the offer to his wife", the to-be-recalled information "after he had returned from Manhattan" is not included in the most recent sentence. Jarvella (1971) found that retention of the phrase "after he had returned to Manhattan" was poorer if it occurred prior to the sentence boundary. This finding suggests that verbatim information about language is temporarily maintained in an active, readily accessible form, that some form of removal of (or failure to maintain) the information occurs at the sentence boundary, and thus, this information is more difficult to retrieve after the sentence boundary. Jarvella's (1970; 1971) work demonstrated that when readers are asked to do a verbatim recall of what they are reading, they do, in fact, maintain a short-term memory trace of the material they are reading, at least up to the sentence boundary. But it

did not demonstrate that the memory trace is phonological or that the phonological loop is necessary to maintain that trace. More importantly, it did not demonstrate that the phonological loop is necessary for comprehension or understanding of what is being read.

If maintaining prior sentence information does, in fact, require use of the phonological loop, then disrupting the function of the loop through articulatory suppression should hurt comprehension. Baddeley, Eldridge, and Lewis (1981) had subjects read sentences and verify whether each sentence was semantically acceptable. For half of the sentences the subjects were instructed to count repeatedly from one to six at a rate of four digits per second while reading. This procedure, called articulatory suppression, has been shown to disrupt the articulatory loop. Baddeley et al. (1981) found that articulatory suppression interfered with comprehension such that subjects were less accurate at judging sentences when they were simultaneously articulating (also see Waters, Caplan, & Hildebrandt, 1987). Thus, it does appear that the phonological loop is necessary for comprehension.

Developmental investigations of children's comprehension also illustrate the importance of the role of the articulatory loop in language comprehension. Donald Shankweiler and his colleagues have argued that children who are classified as good readers perform better than poor readers because they have superior verbal-memory abilities. Importantly, Shankweiler and his colleagues have ruled out alternative hypotheses that differences in reading and listening comprehension are due to differences in knowledge structure, such as different syntactic or phonological knowledge (Mann, Shankweiler, & Smith, 1984; Shankweiler & Crain, 1986; Shankweiler, Smith, & Mann, 1984; Smith, Mann, & Shankweiler, 1986). For example, Mann et al. (1984) classified children as either good or poor readers, based on their performance on the reading subtest of the Iowa Test of Basic Skills, and then compared their listening-comprehension ability on a range of sentence types. The sentences varied in syntactic structure but did not differ in length. The four sentence types were as follows:

1. The sheep pushed the cat that jumped over the cow.
2. The sheep that pushed the cat jumped over the cow.
3. The sheep pushed the cat that the cow jumped over.
4. The sheep that the cat pushed jumped over the cow.

The children were presented with toy actors (i.e. a sheep, a cat, and a cow) and instructed to demonstrate what they heard in each sentence. The dependent variable was comprehension accuracy, which was based on the child's ability to demonstrate correctly the events described in the sentence.

There was a main effect for sentence type, such that sentences of type 1 and 4 caused the most errors. There was also a main effect for reading group, such that the poor readers performed worse than the good readers. More importantly, there was not an interaction between reading group and sentence type. The lack of interaction suggests that the poor readers did not have a deficit specific to one type of syntactic structure. They were simply worse on all types of sentences. Poor readers were also inferior to the good readers in immediate recall of the sentences and on other tests of short-term recall. Thus, it appears that the difference between the good and poor readers was due to differences in short-term or WM. It is not clear whether the differences in performance can be attributed to the phonological loop or to the central executive or to both. However, we should note that the children in the good and poor reading groups were equated for IQ. Given the relationship between central executive processes and IQ (Engle, Tuholski, Laughlin, Conway, 1997), it seems plausible to attribute the differences in these children to differences in phonological processing.

Another way to investigate the specific role of the phonological loop in language comprehension is to study patients who have phonological processing deficits as a result of brain injury.[1] A number of case studies have been reported in the literature and the evidence is remarkably consistent (see Caplan & Waters, 1990, for a review). First, when sentences are short and do not contain complex syntactic structures, such as passive constructions or centre-embedded clauses, patients comprehend as well as normal controls. Patients do have trouble when the syntax becomes more complex, as with passive constructions (e.g. "The boy was pushed by the girl") or centre-embedded clauses ("The man the boy hit carried the box") (Friedrich, Martin, & Kemper, 1985; Saffran & Marin, 1975). Patients also have trouble with sentences that are semantically reversible such as "The cat is chased by the dog" (Caramazza, Basili, Koller, & Berndt, 1981; Caramazza, Berndt, Basili, & Koller, 1981). Another widely reported finding is that patients have difficulty performing the Token Test (Caplan & Waters, 1990), which requires the manipulation of geometrically shaped coloured objects in response to verbal demands. The test varies from simple commands such as "Touch the large white circle" to more difficult commands such as "Put the red circle between the yellow square and the green square." Patients with damage leading to a disturbance of the phonological loop typically perform well when the commands are short and simple but do badly when the commands are long and complex. This

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[1] For the sake of simplicity and brevity, we will gloss over the distinction between patients with disturbances to the phonological store and those with disturbances to the articulatory loop. For a discussion of this distinction the reader is referred to Caplan and Waters (1990).

suggests that the phonological loop is only required for comprehension when sentences are long or when they contain complex syntactic structures. The problem with the Token Test is that syntactic complexity and sentence length are confounded. Thus, it is impossible to distinguish whether difficulty is due to a deficit in syntactic processing or simply the number of words necessarily retained in WM.

Baddeley, Vallar, and Wilson (1987) recognised this confusion and manipulated sentence length while controlling for syntactic complexity. Two patients with brain damage resulting in phonological-loop disturbances read a number of short sentences that contained a range of syntactic structures. The patients had no trouble comprehending any of the short sentences. However, Baddeley et al. (1981) found that when they increased the length of the sentences by adding syntactically simple components such as adjectives and adverbs, comprehension performance was reduced to chance levels. They concluded that the phonological loop is used as a "mnemonic window" storing and maintaining sentence information as it is processed. Sentence information is entered into and remains in the phonological store until syntactic processing is complete and the discourse representation is updated. Thus, when propositions and sentences are lengthy, the phonological loop is critical for comprehension.

This conclusion assumes that comprehension does not proceed, on-line, as each word occurs. It assumes that, instead, each word is processed at a superficial level and the phonological representation of each word is maintained until the occurrence of syntactic boundary markers in the form of articles or punctuation marks. The markers lead to syntactic parsing of the words, and, at that point, comprehension of the set of parsed words occurs. In other words, syntactic parsing is not immediate. Rather, it is delayed until sufficient information is encountered to achieve the correct syntactic structure and the information is represented in the phonological loop until parsing is complete. Then comprehension of the words in the recently parsed set occurs. By syntactic parsing we mean the process of converting a string of words into a mental representation that contains information about the syntactic class of individual words in the sentence. Parsing is the process by which the reader determines which word is the subject, object, verb, etc., and the syntactic qualities of groups of words such as noun and verb phrases. Obviously, the correct syntactic structure of a phrase or sentence cannot be made immediately when the first word of a sentence is encountered. However, many researchers have argued that parsing occurs very early in the first pass through a sentence. This leads to cognitive structures being built early in the processing of a phrase or sentence. The particular structure is based on the frequency of and bias for the structure. For example, we typically assume a subject–verb–object structure such as "girl-hit-ball".

The question of how syntactic information is extracted from words and sentences is complex, and currently there is not a single model of syntactic parsing that can account for all the phenomena that have been observed. However, Mitchell (1994), in his extensive review of the parsing literature, concluded in favour of early parsing, meaning that this syntactic representation is constructed on the initial pass through a sentence. Thus, the notion proposed by Baddeley et al. (1987) that parsing is delayed and depends on the phonological loop is questionable. There is considerable evidence that word meaning, for instance, occurs as a result of relatively automatic activation of long-term memory when the word is read (cf. Balota, 1983). Studies on the time that we gaze at a word while reading (cf. Just & Carpenter, 1987) suggest that we spend more time looking at more meaningful and lower-frequency words, which suggests that the words are being processed for meaning at the time the word is being read. The studies do suggest that we pause at the end of the sentence, probably to do final wrap-up and integration processes (Just & Carpenter, 1987).

Martin and Feher (1990) employed a strategy similar to that of Baddeley et al. (1987) and found similar results. However, they came to very different conclusions about the role of the phonological loop in language comprehension. They investigated sentence comprehension in aphasic patients and varied both syntactic complexity and sentence length. They also manipulated the presentation mode, with sentences being presented either auditorily or visually. There were two visual conditions, either limited—a word at a time, or unlimited—all words of the sentence presented at one time. In the visual condition, subjects performed better in the unlimited than limited condition, suggesting that the unlimited condition was less memory demanding than the limited condition. Therefore, the difference between performance in the unlimited and limited modes was used as an index of the memory requirements for each sentence type.

Martin and Feher (1990) found that sentence length interacted with presentation mode. In the limited visual condition, there was a decrement in performance for long sentences but not for short sentences. Furthermore, syntactic complexity did *not* interact with presentation mode, meaning that complexity had the same effect with limited and unlimited presentation. They concluded that the phonological loop *is* necessary for the processing of sentences with a large number of content words, but *is not* necessary for processing of sentence syntax, even complex syntax. They argued that the phonological loop is not necessary for initial parsing into syntactic constituents. The loop is necessary AFTER syntactic analysis has taken place but before the sentence has been fully interpreted. This view differs from that of Baddeley et al. (1987) in that it assumes syntactic parsing occurs immediately at input for all sentence types. This conclusion

would fit with the idea that the phonological loop is necessary for the wrap-up and integration processes occurring at the end of the sentence.

Waters, Caplan, and Hildebrandt (1987) used healthy adult subjects to address the issue of whether the phonological loop plays a role in initial syntactic parsing or if it plays a role at a post-syntactic level. In one experiment, subjects were asked to make semantic-acceptability judgements about sentences of four different types. The four types were as follows:

1. It was the gangsters that broke into the warehouse.
2. It was the broken clock that the jeweller adjusted.
3. The man hit the landlord that requested the money.
4. The meat that the butcher cut delighted the customer.

These sentences vary along two dimensions: number of propositions and syntactic complexity. The first two types have one proposition and the second two have two. The second and fourth types are more syntactically complex than the others.

Waters et al. (1987) found that subjects were both slower and less accurate to respond to syntactically complex sentences. They also found an effect for number of propositions. However, there was not an interaction between complexity and number of propositions. Waters et al. argued that the absence of an interaction suggests that these variables affect different stages of processing.

In a second experiment, subjects performed a concurrent memory task while reading the same sentences as in the first experiment. The memory task was similar to the reading-span task (Daneman & Carpenter, 1980). The subject was required to make a semantic-correctness judgement about each sentence in a series and then, at the end of the series of sentences, recall the final word of each sentence. There were from two to six sentences in each series. The purpose of this experiment was to determine if those sentence types that were more difficult to process place greater demands on WM. Three dependent measures were recorded: Number of words recalled, judgement accuracy, and judgement latency. For all three dependent variables there were main effects for syntactic complexity and number of propositions, but the interaction was not significant. Waters et al. concluded that the syntactically complex and the two-proposition sentences placed greater demands on WM than the less complex and shorter sentences. Again, the absence of an interaction suggests that these variables affected different stages of processing.

In a third study, subjects performed a semantic judgement task while concurrently performing an articulatory suppression task of repeatedly saying aloud the digits 1–6. Recall that the suppression task has the purpose

of eliminating use of the articulatory loop. In addition, there was a no interference condition and a concurrent tapping condition.

The authors found that articulatory suppression interacted with number of propositions, such that suppression had a larger effect on the time to make a judgement for two-proposition sentences than for one-proposition sentences. However, suppression did NOT interact with syntactic complexity. Therefore, they concluded that the phonological loop does NOT play a role at the initial stages of comprehension, that is, syntactic parsing, but does play a role in later stages of analysis. Thus, the loop would be used to represent or to hold already parsed information for later stages of comprehension, such as resolving ambiguities and finalising the interpretation.

In summary, there are two opposing views regarding the role of the phonological loop in language comprehension. Both views agree that the phonological loop is only required when sentences are long and syntactically complex. The first view, proposed by Baddeley et al. (1987), is that the phonological loop maintains sentence information BEFORE syntactic parsing occurs. The second view is that the phonological loop comes into play AFTER parsing occurs and only when initial first-pass processing is not sufficient for comprehension (Caplan & Waters, 1990; Martin & Feher, 1990; Waters et al., 1987).

Either of these theories could be correct, depending on how parsing works. According to Baddeley et al., the phonological loop acts as a "mnemonic window" maintaining information until enough information is provided for a successful parse. The parser does not immediately commit itself to a single syntactic structure. Thus, when a reader encounters complex or ambiguous structures, syntactic analysis is suspended until enough information is provided as to which form is correct. Baddeley et al. would argue that the phonological loop is required to maintain sentence information during this delay. We will refer to this as the "late parsing" view.

The alternative position is that the phonological loop plays a role in comprehension only as a back-up store to be used when processing cannot proceed on-line. According to this view, syntactic parsing occurs automatically, but the parser chooses the structure that is most common or that is most biased by the previous language. However, sometimes the parser is "garden-pathed" or otherwise biased into choosing an incorrect structure. In this case, off-line, second-pass processes are necessary to correct the initial structure. When these second-pass processes are necessary, the phonological loop will be important for comprehension (Caplan & Waters, 1990; Martin & Feher, 1990; Waters et al., 1987). We will refer to this as the "early-parsing" view.

These two accounts make diametrically opposed assumptions with

regard to syntactic processing. According to the "late-parsing" view, parsing can be suspended or delayed until an ambiguity is resolved. According to the "early-parsing" view, parsing occurs automatically on-line, even in the face of syntactic ambiguity.

As of this writing, the data required to tease these positions apart are inconclusive, but the evidence seems to support the early-parsing view. According to the late-parsing view, some analyses must be suspended until a syntactic ambiguity is resolved. Therefore, there should be a cost associated with processing the subsequent region of the sentence containing the information that resolves the ambiguity. That is, there should be a slow-down in reading over the portion of the sentence that resolves an earlier-created ambiguity. Indeed, there is a vast amount of evidence to suggest that there is a cost associated with processing disambiguating text when the less common or subordinate interpretation of the ambiguity turns out to be correct (for a review, see Mitchell, 1994). However, there is less evidence with regard to processing disambiguating text when the dominant interpretation of the ambiguity turns out to be correct. This is the evidence needed to answer this question because BOTH early- and late-parsing theories would predict a cost associated with processing the less dominant interpretation of an ambiguity but only late-parsing theories would predict a cost associated with processing the dominant interpretation of an ambiguity.

One study reports no cost associated with processing the dominant interpretation of an ambiguity, relative to an unambiguous control (Mitchell & Cuetos, 1991). This supports the early parsing view. A different study did report an ambiguity effect consistent with the late-parsing view (MacDonald, Just, & Carpenter, 1992). However, the effect was only reported for high-WM-span subjects and other problems have been reported with that study (see Mitchell, 1994; Waters & Caplan, 1996). Furthermore, MacDonald et al. (1992) did not interpret their result as support for a delayed-parsing model. Instead, they suggested that high-span subjects have more central-executive resources than low-span subjects, and are therefore able to build and maintain multiple-syntactic representations while low-span subjects cannot. The maintenance of multiple-syntactic structures will cause high-span readers to read more slowly even after the ambiguity has been presented, and even when the dominant interpretation is correct.

MacDonald et al.'s (1992) claim raises the issue of whether multiple syntactic structures can be built when a syntactic ambiguity is encountered and maintained until the ambiguity is resolved. As an analogy, consider the case of lexical ambiguity.[2] Many authors have argued that multiple

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[2] We would like to thank Kathy Binder for suggesting this analogy.

meanings of a lexically ambiguous word are activated and maintained until the ambiguity is resolved (Onifer & Swinney, 1981; Swinney, 1979). This claim has been supported by an experimental manipulation called "cross-modal" priming. In a cross-modal priming task, subjects listen to sentences that contain a lexically ambiguous words, such as "There was a bug in the room." Immediately after the lexically ambiguous word (i.e. "bug") has been spoken, the subject is presented with a word on a computer screen and instructed to make a lexical decision. The word presented for lexical decision is either related to one interpretation of the ambiguous word (i.e. "ant"), another interpretation (i.e. "spy"), or neither interpretation (i.e. "sew"). Using these materials, Swinney (1979) found that both "ant" and "spy" were primed by the word "bug", suggesting that both meanings had been activated.

In the case of syntactic ambiguity, evidence of this kind has not been presented. The problem is that there has not been an experimental procedure developed, like cross-modal priming, that demonstrates that multiple syntactic representations are active as MacDonald et al. (1992) argue. Until such evidence is presented, it is not clear whether multiple representation can be formed or not. Therefore, on the basis of the evidence available with regard to syntactic parsing, we are inclined to favour the view that syntactic parsing occurs automatically, on-line, and that the structure that is most common, given the prior sentence information, is initially built.

In the context of our discussion of parsing, we agree with Caplan and Waters (1990), who argued that the phonological loop is not required for automatic, first-pass language comprehension, including syntactic parsing. The phonological loop is required, however, when the first-pass processing is insufficient for comprehension and second-pass processing is necessary for successful comprehension *and* when the number of content words necessary for comprehension of a structure is large. This view is consistent with our notion that WM is important in tasks that require effortful, controlled processing, but not in tasks that can be performed with automatic processing. It is also likely that the phonological-loop processes are harder to use and more attention-demanding with some types of materials. For example, a sentence that contains many rhyming words would make the phonological loop more attention-demanding. To the extent that controlled, limited-capacity attention is required for the coding formats, either phonological or visual/spatial, then the central executive would play a more prominent role in comprehension. The more attention-demanding the situation, the more the central executive would be involved and necessary for comprehension. Thus, those situations placing most burden on the phonological loop would also place most burden on the central executive.

ROLE OF THE CENTRAL EXECUTIVE

Of the three elements of the Baddeley and Hitch (1974) model, the central executive has, until recently, received the least conceptual and empirical development. There is considerable overlap among the ideas referred to as central-executive, controlled-effortful attention (Kahneman, 1973; Posner & Snyder, 1975), supervisory-attentional system (Shallice & Burgess, 1993), working-memory capacity (Daneman & Carpenter, 1980; Conway & Engle, 1994; Engle, Cantor, & Carullo, 1992), and possibly even general fluid intelligence (Kyllonen & Christal, 1990; Engle et al., 1997). It is too early to say whether all of these concepts reflect a common mechanism or are simply related, but recent work from our lab suggests that WM capacity is akin to controlled attention. Thus, before we discuss the role of the central executive in comprehension, we will clarify our view of the central executive (Conway & Engle, 1994; Engle, 1996).

The contents of WM can be conceived of as those memory representations in long-term memory (LTM) that are active beyond some critical threshold. Representations in LTM can become active either because an external event causes activation of the representation or an element of thought automatically spreads activation to the representation. As we wrote earlier, the meaning of a word will likely be activated automatically when the word is read. For the representation of that word to be maintained in an active state, over time, and in the face of subsequent interfering events, the individual must attend to the representation to keep it in the focus of attention (cf. Cowan, 1995). Thus, the amount of information that can be maintained in working memory is limited by the available attentional resources. Please note that this view of working-memory capacity sees the limitation as one of attention, not memory *per se.*

Much of what we consider to be comprehension in the skilled reader is accomplished via automatic spreading activation. For example, the simple occurrence of a printed word in the visual focus will lead to the activation of associations reflecting the meanings of that word. Further, as discussed in the previous section, reading a series of words will likely lead to those words automatically being parsed or given a syntactic structure. We contend that working-memory or central-executive capacity will be important to comprehension whenever the outputs of automatic language processes are insufficient for comprehension and there is confusion either: (1) because of the large number of words in the sentence; (2) because there is ambiguity about the meaning of individual words or phrases; (3) because language early in a passage is misleading about the ultimate meaning of the passage; or (4) because the syntactic structure of the language is unduly complex.

When the language becomes unduly complex, the reader must have the

ability to maintain information that is relevant to the passage and block out or suppress information that is irrelevant. Thus, we will focus on two aspects of language comprehension: maintenance of information over a period of time and the suppression of distracting or irrelevant information.

Daneman and Carpenter (1980; 1983) were the first to demonstrate the importance of individual differences in central-executive capacity to comprehension. They reasoned that individuals with large WM capacity should be able to maintain more information in an active state at any given time. This would be important to comprehension when sentences are particularly long or when the meaning of a word depends on the retention of information read much earlier. For example, consider the following passage:

> Fred and Bill went to the store to buy groceries. Fred bought a half gallon of ice cream and Bill bought some bread and a bottle of juice. On the way home they were involved in an accident but no one was hurt. After lengthy questioning by the authorities and exchanging insurance information with the driver of the other car, the two went home. When they arrived home, he quickly put the ice cream in the freezer.

When the reader encounters the word "he" in the last sentence, successful comprehension depends on whether the reader can quickly retrieve the information about *who* bought the ice cream. Daneman and Carpenter (1980) reasoned that individuals with larger WM capacity should be more likely to have that information still available when the word "he" is read. They developed a task called the reading-span task, mentioned earlier. In this task, the subject read a set of sentences aloud and then attempted to recall the last word of each sentence in the correct order. The sentence sets varied from two to seven and the maximum number of final words the person could recall correctly was called the reading span score. Those individuals who received a high reading span score were referred to as high working memory and those with a low score were referred to as low working memory.

Daneman and Carpenter (1980) found that high WM subjects correctly answered questions like "Who put the ice cream in the freezer?" better than did low WM subjects. The comprehension difference between low and high WM capacity subjects was even greater if more words separated the pronoun (he) from its noun referent (Fred). Reading span correlated with a variety of reading-comprehension measures including answering fact questions (r = 0.27), pronoun reference questions (r = 0.90), and even the VSAT (r = 0.40 − 0.59).

Clearly, individual differences on the reading-span task covary with important aspects of tests of comprehension. But what is the nature of that

covariation? What does the reading span task measure that is important to comprehension? Daneman and Carpenter (1980; 1983) argued that the reading-span score was really an indirect measure of the reading skills of the individual. If reading processes are very efficient and automatic, then more attentional resources are available to retain the final words. To the extent that reading processes are less efficient, there would be less capacity to allocate to retention of the words. By this view, which we have labelled the *task-specific view* of working-memory capacity, the reading span–comprehension correlation is quite specific to tasks involving reading.

An extensive series of studies from our lab has disputed this claim, and we have argued that complex tasks such as reading span reflect general, domain-free attentional resources that will be important in any cognitive task requiring controlled processing, an idea we call the *general-capacity view*. Turner and Engle (1989) used a measure of working-memory capacity called the operation span in which subjects performed sets of arithmetic strings with a word to be recalled later following each string. For example, the subject might see "IS (4/2) − 1 = 1? SNOW", followed by "IS (3 × 1) + 4 = 7? TABLE". The subject would answer "yes" or "no" to indicate whether the given answer is correct or incorrect, read the word aloud, and then do the next string, and so on. After a set of strings (which varied from two to seven strings), the subject would try to recall the words, in this case, SNOW and TABLE. If the task-specific view is correct, then the operation span should not correlate with reading comprehension, because the processes used in the span task are different than those used during reading. However, Turner and Engle (1989) showed that the relationship between reading comprehension and operation span was just as high as between comprehension and reading span. Engle, Cantor, and Carullo (1992) showed that factoring-out skill on the processing component of both the operation span and reading span did not reduce the correlation between the span score and comprehension. Conway and Engle (1996) showed that manipulating the difficulty of the processing component, so that subjects were equated on the difficulty of the processing, did not reduce the correlation between the span score and comprehension. Thus, there is considerable evidence for the idea that complex measures of working-memory capacity reflect general, domain-free attentional resources.

Thus, the resources of the central executive are important for maintaining information over time and in the face of distracting, misleading, or interfering information. A good example of this is when there is ambiguity in the meaning of words or phrases. For example, in the passage below:

> The lights in the concert hall were dimmed. The audience watched intently

as the famous violinist appeared on the stage. He stepped onto the podium and turned majestically to face the audience. He took a bow. It was very gracefully propped on the music stand. The enthusiastic applause resounded throughout the hall.

Such passages are called "garden path" passages, because the word "bow" has two different pronunciations and two different meanings. If the reader is led to select the incorrect meaning and fails to maintain the correct meaning, comprehension will break down when the reader encounters the sentence that implies that the protagonist grasped a violin bow that was propped on the music stand. Daneman and Carpenter (1983) argued that high WM subjects would be more likely to maintain the original meanings and pronunciation information available when they need to resolve the ambiguity, and they would be better than low WM subjects at answering a question such as "What did the violinist take?" They found that, indeed, high-span subjects were better than low spans at disambiguating the sentence. Further, this difference between WM groups was even greater if a sentence boundary occurred between the ambiguous word and the phrase that resolved the ambiguity. Daneman and Carpenter argued that the low WM subjects were more likely to lose the additional meaning of the ambiguous word in the wrap-up and integration processing that occurs at the end of each sentence.

A more detailed analysis of individual differences in the resolution of lexical ambiguity supports these results. Miyake, Just, and Carpenter (1994) had high- and low-WM span subjects read sentences that contained lexical ambiguities. Previous research suggested that when a lexical ambiguity is encountered, multiple meanings are automatically activated (Onifer & Swinnery, 1981; Swinney, 1979), and remain active until the ambiguity is resolved, at which point the correct interpretation of the ambiguous word is integrated into the discourse structure and the inappropriate meaning either decays or is actively suppressed (Simpson, 1984). Miyake et al. (1994) proposed that individual differences in WM capacity will not play a role in accessing the meanings of the ambiguous word because activating multiple meanings occurs automatically (Onifer & Swinney, 1981; Swinney, 1979). However, individual differences in WM capacity will play a role if multiple meanings need to be maintained over a period of time. Therefore, if the ambiguity remains unresolved for a period of time, low-span subjects will not abe able to maintain multiple meanings, which will cause confusion when the ambiguity is finally resolved.

Miyake et al. (1994) presented subjects with sentences such as the following, "Since Ken really liked the boxer, he took a bus to the nearest pet store to buy the animal.' Note that the word "boxer" is ambiguous and the ambiguity is not resolved until the phrase "pet store". The word

"boxer" is considered a "biased" ambiguous word because one interpretation (fighter) is more common than the other interpretation (dog). We will refer to the common interpretation as the dominant interpretation and the less common interpretation as the subordinate interpretation. According to Miyake et al., high- and low-span subjects activate both the dominant and the subordinate meanings when they encounter an ambiguous word. High-span subjects are then able to maintain both meanings until the ambiguity is resolved. By contrast, low-span subjects are only able to maintain the dominant meaning. Thus, when the subordinate meaning of the ambiguous word turns out to be the correct interpretation, as in the sentence, "Since Ken really liked the boxer, he took a bus to the nearest pet store to buy the animal", high-span subjects will not be adversely affected when the ambiguity is resolved because they will have the subordinate meaning active. By contrast, low-span subjects will be affected when the ambiguity is resolved because they will no longer have the subordinate meaning active.

Consistent with their predictions, Miyake et al. (1994) found that when the subordinate meaning turned out to be the correct interpretation, low-span subjects showed increased reading times in the disambiguating region of the sentence, while high-span subjects did not. Their conclusion was that both high- and low-span subjects activate multiple meanings of an ambiguous word, but that only high-span subjects are able to maintain both representations. Low-span subjects only maintain the dominant meaning.

An implicit assumption of this analysis is that both low and high working-memory subjects activated both meanings of the ambiguous word. Miyake et al. (1994) did not test this assumption. It is therefore possible that low-span subjects never activated the subordinate meaning of the ambiguous words. Low-WM subjects almost certainly have less word knowledge than high-WM subjects (Dixon, LeFevre, & Twilley, 1988; Engle, Nations, & Cantor, 1990), and so might have less access to the low-dominance meanings of homographs. Thus, the low WM subjects may not have activated the lower-frequency meanings. In fact, Deaton, Gernsbacher, Robertson, and Miyake (1995) presented evidence to suggest that low-span subjects do not activate the subordinate meaning of lexically ambiguous words. If so, then the results of the Miyake, et al. (1994) study occurred because of an effect at the stage of lexical access, not in the maintenance of information, and the effect was not really a result of differences in working memory.

Therefore, just as we ended our discussion of syntactic ambiguity, we will end here with a word of caution. Although it is possible that Miyake et al.'s (1994) interpretation is correct, more research is needed to establish whether low-span subjects do in fact activate multiple meanings of ambiguous words. Insofar as activation of meaning is automatic, we would

argue that they do activate multiple meanings. However, if the subordinate meaning of an ambiguous word is not well known, then the process of activating that meaning may not be automatic, which means that WM capacity may then play a role in lexical access. As an analogy, consider a child learning to read. When the child encounters a relatively novel word, accessing the meaning of that word may involve a conscious, effortful process that would demand attention. However, as the child becomes more familiar with that word, accessing the meaning will no longer require a controlled effortful process. Given the fact that low-WM span subjects have weaker vocabulary knowledge than high-span readers (Engle et al., 1990), it is possible that for low-span readers the activation of the subordinate meaning of an ambiguous word is not entirely automatic, and therefore may not occur when attention is directed elsewhere.

Not only is the central executive necessary for maintaining relevant information, it is also important for suppressing irrelevant information that is not needed for comprehension and would otherwise add confusion to the meaning of the passage. Gernsbacher and colleagues (Gernsbacher, 1990; Gernsbacher & Faust, 1991; Gernsbacher, Varner, & Faust, 1990) have studied the role of suppression in comprehension. They hypothesised that individuals who are poor comprehenders (who, given the correlation between WM capacity and reading comprehension, are likely to also be low-WM individuals) are less adept at suppressing contextually irrelevant information than are good comprehenders. Gernsbacher et al. (1990) had subjects read sentences such as "He dug with the spade." Notice that spade can be either an implement for digging or a card suit. Either immediately after, or one second after the sentence, the subjects were presented with a probe word, such as "car", "shovel", or "ace". The subject's task was quickly to respond "yes" or "no" to indicate whether the probe word was consistent with the meaning of the sentence. If both meanings of spade are activated when the sentence is read, then it should be more difficult for the subject to determine that the probe word "ace" is not consistent with the sentence than it would be for the subject to determine that "car" is not consistent with the sentence. Indeed, Gernsbacher et al. (1990) found that if the probe word was presented immediately after the sentence, both good and poor comprehenders were slower to say that "ace" was not related to the meaning of the sentence than they were to say that "car" was not related to the meaning of the sentence. If the probe was presented one second after the sentence, good comprehenders were no longer slowed, suggesting that they were able to suppress the irrelevant meaning of the ambiguous word. By contrast, poor comprehenders were slowed just as much after the one-second delay as they were when the probe was presented immediately after the sentence. This suggests that poor comprehenders did not suppress the irrelevant meaning of the

ambiguous word. Presumably, keeping irrelevant meanings active will ultimately interfere with comprehension because multiple-semantic structures will be possible and the simple presence of irrelevant information in WM will lead to interference and depletion of resources.

The work of Miyake et al. (1994) and Gernsbacher (1990) at first appear to suggest two contradictory characteristics of individuals with poor central-executive capacities. Miyake et al.'s results suggest that low-span subjects cannot maintain multiple meanings over a brief period of time, whereas Gernsbacher's results suggest that low-span subjects cannot suppress irrelevant meanings, which results in irrelevant meanings remaining active and causing confusion. We submit here that both of these proposals are, in fact, compatible with our notion (Conway & Engle, 1994; Engle, 1996) that both maintenance and suppression of information require attentional resources, and sentences can be constructed such that either suppression or maintenance will best serve comprehension. For example, in the sentence, "Since Ken really liked the boxer he took a bus to the nearest pet store to buy the animal", comprehension will be served better if both meanings of the ambiguous word are maintained until the ambiguity is resolved. However, once the ambiguity is resolved, the irrelevant meaning should be suppressed, so that it does not interfere with the correct interpretation of the sentence. Thus, in Gernsbacher's experiment, after reading, "He dug with the spade", the irrelevant meaning of "spade" (ace) should be suppressed immediately to avoid confusion and to clear working memory of irrelevant and potentially distracting information.

If the central executive is defined in terms of the ability to bring controlled attention to bear on the task at hand and individuals differ in that ability, then high-WM subjects can and will either maintain or suppress information, depending on which is deemed more appropriate for the task being performed at the moment. We submit that experiments could be designed in such a way as to encourage maintenance or suppression, and high-WM subjects would respond accordingly. Low-WM subjects, particularly if the comprehension task were already attention-demanding, would be less able to do the appropriate maintenance or suppression.

This hypothesis could be tested with regard to either syntactic ambiguity or lexical ambiguity. A number of variables could be manipulated in conjunction with ambiguity and WM span. For example, the time course of the ambiguity could be manipulated, such that the ambiguity is either immediately resolved or resolved after a number of words or phrases. Also, the local and global context surrounding the ambiguity could be manipulated to see if high- and low-WM-span subjects use contextual information differently. Experimenters could manipulate the type of ambiguity, with either equally biased ambiguities, where each meaning or

structure is equally likely given the preceding context, or biased ambiguities where one meaning or structure is the dominant interpretation and the other is subordinate. With this manipulation, one could test the possibility that high- and low-span subjects differ in their ability to activate multiple meanings or form multiple representations. This last point is especially important. That is, in order to test whether high- and low-span subjects differ in the maintenance or suppression of information, it must first be demonstrated that both high- and low-span subjects have the critical information active. Until that has been established, one cannot test for individual differences in maintenance or suppression.

Finally, we would submit that even high-WM-span subjects may sometimes perform like low-WM-span subjects, if they are burdened with a demanding workload. What would constitute a mental workload in real-life comprehension situations? Our intuition suggests that trying to read in a situation where there is much distraction, such as in a college dormitory or while trying to watch a television programme, would constitute a workload. A young man trying to listen to and comprehend what is said when he first meets his new girlfriend's father is under the added workload of the emotional pressure of worrying about making a good impression. We would argue that even high-WM subjects should not be able to suppress irrelevant meanings or maintain information for very long if they are trying to comprehend language under such circumstances.

CONCLUSION

Is working memory necessary for comprehension? If adults, skilled in reading and listening to speech, are asked to comprehend short, simple, active, affirmative, declarative sentences, and each sentence follows logically and inexorably from the previous one and no ambiguous words or phrases are used, then the collection of structures and processes we have referred to as working memory will not be necessary for comprehension. If there is never any need to retain a verbatim copy of the words we read or hear because those words are never referred to by pronouns, then working memory will not be necessary for comprehension. If we are never interrupted or distracted in the midst of reading or listening then it will not be necessary to maintain representations in an active state and working memory will not be necessary. If there is never a need to suppress or dump irrelevant information to avoid confusion, then working memory will not be necessary. However, it is for all those other situations that we can be grateful that we have the system of representational formats and controlled attention that we call working memory to aid our comprehension of complex language events.

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