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Working memory and language: an overview

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Abstract

Working memory involves the temporary storage and manipulation of information that is assumed to be necessary for a wide range of complex cognitive activities. In 1974, Baddeley and Hitch proposed that it could be divided into three subsystems, one concerned with verbal and acoustic information, the phonological loop, a second, the visuospatial sketchpad providing its visual equivalent, while both are dependent upon a third attentionally-limited control system, the central executive. A fourth subsystem, the episodic buffer, has recently been proposed. These are described in turn, with particular reference to implications for both the normal processing of language, and its potential disorders.

Learning outcomes: The reader will be introduced to the concept of a multi-component working memory. Particular emphasis will be placed on the phonological loop component, and (a) its fractionation into a storage and processing component, (b) the neuropsychological evidence for this distinction, and (c) its implication for both native and second language learning. This will be followed by (d) a brief overview of the visuospatial sketchpad and its possible role in language, culminating in (e) discussion of the higher-level control functions of working memory which include (f) the central executive and its multidimensional storage system, the episodic buffer. An attempt throughout is made to link the model to its role in both normal and disordered language functions.

Keywords: Working memory; Phonological loop; Visuospatial sketchpad; Central executive; Nonword repetition; Specific language impairment

In his classic book, *The Organization of Behavior*, Hebb (1949) suggested a distinction between long-term memory, which involved durable changes in the

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nervous system, and short-term memory, which he attributed to temporary electrical activity. Some 10 years later, empirical research by Brown (1958) in Cambridge and the Petersons in Indiana (Peterson & Peterson, 1959) presented evidence of the rapid loss of material over a few seconds if rehearsal is prevented; both studies attributed their results to a temporary short-term memory (STM) system which they contrasted with long-term memory (LTM). The 1960s saw considerable controversy over this issue, with the evidence appearing to support at least two separate types of memory. The most influential two-component model was that of Atkinson and Shiffrin (1968), who proposed that information came in from the environment into a temporary short-term storage system which served as an antechamber to the more durable LTM. In their model, the temporary system also served as a working memory, a workspace necessary not only for long-term learning, but also for many other complex activities such as reasoning and comprehension.

Perhaps the most striking evidence in favor of such a two-component system came from the study of neuropsychological patients. It was shown that damage to the medial temporal lobes could lead to grossly impaired capacity for new learning, while leaving performance on STM tasks unaffected (Baddeley & Warrington, 1970; Milner, 1966). This fitted the two-component model very well, since it clearly reflected damage to the LTM system, together with preserved STM. An exactly opposite pattern was found by Shallice and Warrington (1970), testing patients who had previously been diagnosed as suffering from conduction aphasia. Shallice and Warrington showed that such cases could be fitted into the existing literature very neatly by assuming they had a specific deficit in STM. However, this left a paradox. If the STM system functioned as a working memory, then such patients ought to have problems not only in LTM, but also in a wide range of other complex cognitive tasks. They did not do so; one was a very efficient secretary, another a taxi driver, while a third ran a shop.

Baddeley and Hitch (1974) attempted to tackle this paradox by disrupting the operation of STM in normal subjects. They required subjects to hold sequences of digits ranging in length from zero to eight items, while at the same time performing a range of tasks that were assumed to depend on working memory. Their data indicated that there was indeed progressive impairment as the concurrent digit load was increased, but the effect was far from dramatic. In response to this and a wide range of other data, they proposed to divide the unitary STM into three separable components, which were assumed to work together as part of a unified working memory system that served the function of facilitating the performance of a range of complex tasks. The three components are shown in Fig. 1. They comprise a temporary verbal–acoustic storage system which is assumed to be necessary, for example, for the immediate retention of sequences of digits, and which was hence proposed to be the locus of the deficit in the STM patients described by Shallice and Warrington (1970). A parallel visual subsystem for storage and manipulation was proposed, and was termed the visuospatial

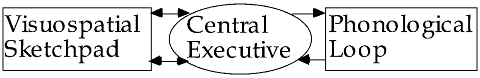

Fig. 1. The three component model of working memory proposed by Baddeley and Hitch (1974). An attentional control system, the central executive, is supported by subsidiary storage systems for phonological and visuospatial information.

sketchpad. Finally, and most importantly, behavior was assumed to be controlled by a limited capacity attentional system, the central executive (Baddeley, 2001).

1. The phonological loop

It was proposed that this could be broken into two subcomponents, a temporary storage system which held memory traces over a matter of seconds, during which they decayed, unless refreshed by the second component. This involved a subvocal rehearsal system that not only maintained information within the store, but also served the function of registering visual information within the store, provided the items can be named. Hence, if a subject is shown a sequence of letters for immediate recall, then despite their visual presentation, subjects will subvocalize them, and hence their retention will depend crucially on their acoustic or phonological characteristics. Thus, while subjects can readily recall a sequence of letters such as *B*, *W*, *Y*, *K*, *R*, *X*, they are likely to have considerable difficulty in retaining sequences of letters with similar sounding names, such as *T*, *C*, *V*, *D*, *B*, *G* (Conrad & Hull, 1964). A similar phenomenon occurs when words are used, with a word sequence such as *man*, *cat*, *map*, *cab*, *can* being correctly recalled on less than 20% of occasions, whereas subjects will have a score above 80% on a dissimilar sequence such as *pit*, *day*, *cow*, *sup*, *pen* (Baddeley, 1966a). The same study showed that immediate recall was not equivalently influenced by similarity of meaning, with a sequence such as *huge*, *big*, *long*, *tall*, *large* being almost as easy to remember as a string of adjectives with dissimilar meanings, such as *old*, *wet*, *thin*, *soft*, *dark*. The fact that this is characteristic of the STM rather than LTM systems was shown in a further study in which subjects were presented with lists of 10 words from each set, and required to learn the sequence across a series of trials. Under these circumstances, similarity of meaning becomes important, and phonological similarity loses its effect (Baddeley, 1966b).

Evidence for the rehearsal system is provided by the word length effect, which again involves presenting subjects with a sequence of items and requiring immediate serial recall. Here, memory for a five-word sequence drops from 90% when these are monosyllables to about 50% when five syllable words are used, such as *university*, *opportunity*, *international*, *constitutional*, *auditorium* (Baddeley, Thomson, & Buchanan, 1975).

The word length effect can be abolished by simply requiring the subject to utter a sequence of irrelevant sounds, such as repeating the word “the.” This process impairs performance, because it both blocks the maintenance of the memory trace through rehearsal, and, when visual presentation is used, also prevents the subject using subvocalization to register the items in the phonological store.

While the word length effect is robust, its interpretation remains somewhat controversial. There is no doubt that some of the effect occurs because long words take longer to recall, leading to more forgetting (Cowan et al., 1992). Indeed, it has been suggested that this may be the only factor (Dosher & Ma, 1998). However, the fact that a word length effect occurs when output delay is held constant, either by using a probe procedure (Henry, 1991), or by recognition (Baddeley, Chincotta, Stafford, & Turk, 2002), indicates that the effect operates at both the on-going rehearsal level and through forgetting during responding.

Our simple model of phonological storage accounted for the results of Shallice and Warrington (1970) by assuming that STM patients do not take advantage of the phonological loop, presumably because one or more components is defective. This view received support from Vallar and Baddeley (1984a), who studied a patient, PV, with a very pure phonological immediate memory deficit. She, like other such patients, had normal language production, and normal comprehension, provided that the material did not involve particularly complex sentences in which comprehension depended upon retaining the surface structure of the sentence beginning, in order to allow subsequent disambiguation (Vallar & Baddeley, 1984b; Vallar & Shallice, 1990).

The process of subvocal rehearsal does not appear to depend on the capacity for overt articulation. Baddeley and Wilson (1985) showed that dysarthric patients who have lost the capacity to articulate can show clear evidence of subvocal rehearsal as reflected in the word length effect, or an effect of acoustic similarity with visually presented items. In contrast, dyspraxic patients whose problems stem from a loss of capacity to assemble speech-motor control programs show no sign of rehearsal (Caplan & Waters, 1995). This implies that it is the capacity to set up speech-motor programs that underpins rehearsal, rather than overt articulation.

1.1. Neuroanatomical basis of the phonological loop

Both the study of patients with lesions resulting in phonological loop deficits, and neuroimaging studies support the hypothesis of separable storage and rehearsal systems, with Brodmann area 44 being the cortical area associated with storage, while subvocal rehearsal appears to be associated with Broca's area (Brodmann areas 6 and 40). In both cases, activation is principally in the left hemisphere, although there are occasionally suggestions of homologous activity in the right hemisphere under particularly demanding conditions.

Fig. 2, based on an excellent review of data from patients with deficits in phonological STM by Vallar and Papagno (2002), gives a somewhat more detailed specification of the phonological loop model. With auditory presentation, the speech stream is analyzed and then fed into a phonological storage system. It may

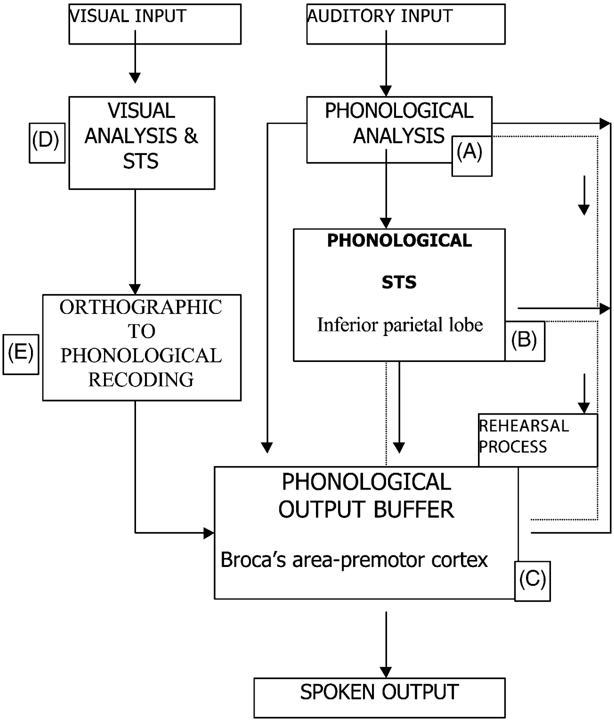

Fig. 2. A proposed structure for the phonological loop. Auditory information is analyzed (A) and fed into a short-term store (STS) (B). Information from this system can pass into a phonological output system (C) which can result in spoken output, or in rehearsal. This in turn may recycle information, both subvocally into the STS, and when rehearsal is overt, into the ears. Visually-presented material (D) may be transferred from an orthographic to a phonological code (E) and thereby registered within the phonological output buffer. Based on Vallar and Papagno (2002).

then be fed into the articulatory control system, either for direct recall, or rehearsal. If rehearsal is overt, then a further speech signal will be fed into the system. We will return to this model later.

1.2. Functional significance of the phonological loop

Although the simple phonological loop model gave a good account of a wide range of available data, it was still not clear what biological function, if any, was served by this system, given that patients with STM deficits appeared to have very few problems in coping with their everyday life. As mentioned earlier, they do have problems with particularly long and complex sentences (Vallar & Baddeley, 1987), suggesting that it might serve as a backup to comprehension, but this hardly seems a sufficiently dramatic advantage to have led such a system to evolve.

A second hypothesis was that the system might conceivably have evolved in order to facilitate the acquisition of language. Given that the patients studied were adult and had already acquired their native language, such a deficit would not be readily noticed clinically. We therefore decided to test the capacity of patient PV, who had a very pure phonological STM deficit, to acquire the vocabulary of an unfamiliar foreign language, Russian. We required her to attempt to learn eight items of Russian vocabulary (e.g., *rose-svieti*), comparing this with her capacity to learn to associate pairs of unrelated words in her native language (e.g., *horse-castle*). We found that such native language pairs were learned as rapidly by PV as by normal control subjects, whereas she failed to learn any of the eight Russian items (Baddeley, Papagno, & Vallar, 1988). It appears, then, that the phonological loop can be a useful aid in learning new words.

We went on to extend our findings, showing that variables that impair the performance of the phonological loop also disrupt foreign language learning, but not paired associate learning in one's native language, for which subjects typically rely on semantic coding. We found, for example, that requiring the subjects to suppress rehearsal by uttering an irrelevant sound disrupted foreign, but not native language learning (Papagno, Valentine, & Baddeley, 1991), and that phonological similarity among the items to be learned also disrupted the acquisition of novel vocabulary, as did increasing the length of the novel items (Papagno & Vallar, 1992). Both of these variables impair phonological loop performance.

These results fit neatly with the findings of Service (1992) who studied the acquisition of English as a second language by young Finnish children, finding that children with good immediate verbal memory proved to be better at language learning than those with short spans, not only when measured by vocabulary, but also by acquisition of syntax. Similar results have been found for adult learners of a second language, in the case of both vocabulary and syntax by both adults (Atkins & Baddeley, 1998; Gathercole, Service, Hitch, Adams, & Martin, 1999) and children (Service, 1992). The evidence we have reviewed so far has been confined to second language learning. Our argument would clearly carry much more weight were we to demonstrate similar effects in the acquisition of native language.

1.3. The phonological loop and native language acquisition

We began by investigating a group of children who had been identified as having a specific language impairment (SLI). They had a mean age of 8 years, with normal nonverbal intelligence, and a delay of 2 years in language development. We gave them a range of tests, including the Goldman, Fristo, and Woodcock (1974) test of verbal memory. This suggested a particular deficit in sound mimicry, the capacity to hear and repeat back nonwords. On the basis of this finding, we developed a nonword repetition test that went considerably beyond the original in incorporating words ranging up to five syllables (Gathercole & Baddeley, 1989). We compared our SLI children with a group of normal children matched for age and nonverbal intelligence, and also with a group of younger, language-matched children. Our SLI group performed substantially below, not only their age controls, but also their younger language controls, functioning at a level that subsequently proved to be that of 4 year olds, 4 years behind their chronological age, and 2 years behind their level of language development. They showed no evidence of articulatory or auditory difficulties, prompting us to attribute their deficit to an impairment in the phonological storage component of the loop (Gathercole & Baddeley, 1989).

A subsequent series of studies investigated the role of the phonological loop in the acquisition of vocabulary within groups of normal children. We tested 4 year olds who were just starting school, measuring nonword repetition, the sound mimicry component of the Goldman et al. (1974) test, nonverbal intelligence using Raven's matrices, and receptive vocabulary. This used a procedure whereby the child was shown four pictures, the name of one was spoken, and the child was required to point to the appropriate item. On this and a subsequent test at age 5, the correlation between vocabulary and nonword repetition was substantial ($r = 0.525$); the link to the Goldman et al. measure was significant but substantially less ($r = 0.295$). Vocabulary was also predicted by nonverbal intelligence ($r = 0.388$), but even when this and other variables were statistically removed, the association between nonword repetition and vocabulary was clear (Gathercole & Baddeley, 1990; Gathercole, Willis, Emslie, & Baddeley, 1992).

We have since replicated our finding many times across age groups ranging from 4 to 13 years (Baddeley, Gathercole, & Papagno, 1998). Typically, the standard digit span measure also correlates with vocabulary, although less reliably. We believe that the advantage of our nonword repetition measure, in which the subject must repeat an unfamiliar sequence of phonemes, occurs because it is closer to the situation facing the language learner than is digit span, which involves sequencing highly familiar items.

Of course, correlation does not mean causation. It is as plausible to assume that children with a rich vocabulary can use it to help acquire new words, as is the reverse assumption that good phonological memory facilitates vocabulary acquisition. Support for the primacy of phonological storage came from a study in which cross-lagged correlation was used to relate vocabulary and nonword repetition between the ages of 4 and 5. We found that nonword repetition at 4 predicted vocabulary at 5, when allowing for vocabulary at 4, while attempting to predict nonword repetition at 5 from the vocabulary scores of 4 year olds proved unsuccessful, once nonword repetition at 4 was allowed for (Gathercole & Baddeley, 1989).

It should be pointed out, however, that as children get older, the relationship becomes much more reciprocal, with good phonological memory helping vocabulary learning, which in turn facilitates the repetition of unfamiliar nonwords. This reciprocal relationship between working memory and long-term memory is shown in Fig. 3, where the initial tripartite working memory model is modified to indicate its interaction with long-term memory, represented by the shaded area

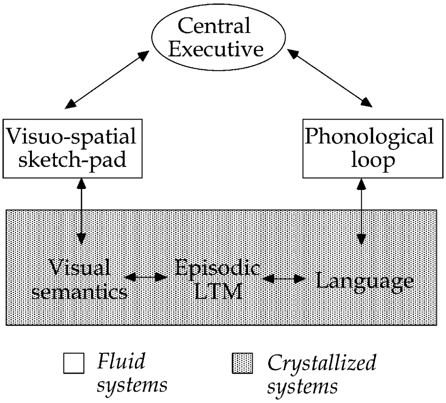

Fig. 3. The three component model of working memory in which visual and verbal subsystems are controlled by an attentional executive. The shaded areas refer to crystallized, or long-term systems, which involve stored information which is capable of interacting with the working memory system.

labeled "crystallized" in the figure to reflect its long-term character. We assume that a similar interactive learning process operates in the case of the visuospatial sketchpad, although this has yet to be investigated.

1.4. An alternative view

Although our results fit neatly into the phonological loop model, others have suggested that phonological storage itself is merely a reflection of deeper phonological processing problems (Snowling, Chiat, & Hulme, 1991). The way in which a variant of this model handles vocabulary acquisition is shown in Fig. 4. This model by Brown and Hulme (1996) differs from our own in placing the emphasis on the role of existing language habits in facilitating vocabulary learning.

Before discussing the pros and cons of this view, however, an important study by Gathercole (1995) should be outlined. She observed that for any given length of nonword, some sequences appeared to be harder than others, with the easier ones being ones that appeared to most closely resemble English words. She tested this hypothesis by dividing her nonwords into two groups, initially on the basis of subjective ratings, but subsequently based on phonotactic frequency measures; fortunately the two measures were very closely related. She found that those sequences closer to English (e.g., *stirple*; *blonterstaping*) were indeed consistently easier than less familiar phoneme sequences (e.g., *kipser*; *perplisteronk*). This strongly suggests the influence of existing language habits on current nonword repetition performance, exactly as the Brown and Hulme (1996) model would predict. Importantly, however, she went on to study the capacity of these two types of items to predict subsequent vocabulary development, finding that the performance of subjects on the unfamiliar phonotactic sequences was a good

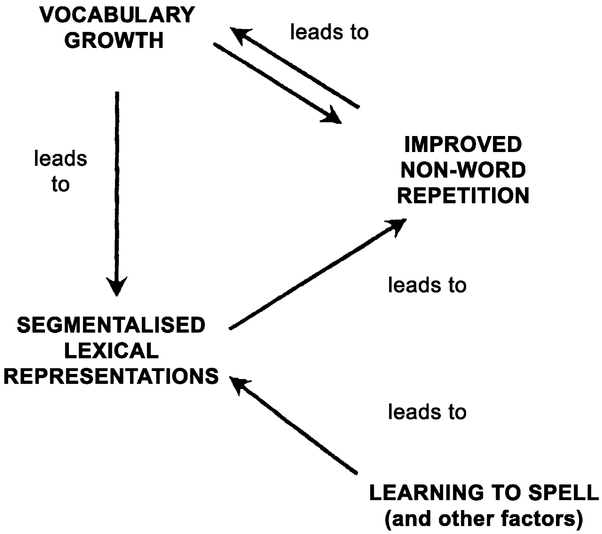

Fig. 4. The Brown and Hulme (1996) hypothesis of vocabulary growth. A reciprocal relationship between vocabulary growth and the capacity to repeat nonwords is assumed. The model differs from that proposed by Baddeley et al. (1998) in not specifying a role for phonological short-term memory.

predictor, while familiar sequences showed little correlation with subsequent vocabulary learning.

One way of explaining this pattern of results is in terms of the division of the phonological loop into separate storage and articulatory components. The nonword repetition task might demand both of these, whereas only the articulatory output system might depend on earlier language habits, leaving the phonological store relatively language-independent. In retrospect, such an arrangement could be seen to be highly appropriate. If the phonological store were dominated by earlier habits, new items would tend to be swamped by old knowledge, making new learning difficult because of the distorting effect of old habits. Such language habits could, however, contribute to repetition by impacting on the second articulatory output stage. In due course, via rehearsal, it would also influence long-term learning.

Unexpected support for this view came from a series of recent studies by Gathercole and colleagues which stemmed from the very practical aim of attempting to measure phonological STM in children who might have articulatory difficulties. Gathercole attempted to do this by using recognition. Hence, the child might hear a sequence of words, followed by a second sequence that was either identical, or had two of the items reversed, for example, *dog*, *pen*, *hat*, *tip*, followed by *dog*, *hat*, *pen*, *tip*. The child simply has to indicate whether the order is identical or changed. In one study, she compared recognition of sequences of words and of phonotactically matched nonwords, testing performance by both this recognition procedure, and by asking for recall of the sequence. Somewhat surprisingly, she found that despite finding the expected very robust difference between words and nonwords for recall, this lexicality effect virtually disappeared when tested by recognition (Gathercole, Pickering, Hall, & Peaker, 2001). Subsequent work has replicated this, and shown a similar phenomenon with bilingual subjects, who show a clear advantage for sequences in their first and dominant language when tested by recall, but no such difference with either recognition or re-ordering, a procedure whereby the items that were presented are given to the subject who must then assemble them in the correct order (Thorn, Gathercole, & Frankish, 2002).

I suggest, therefore, that existing language habits have a major effect on performance in tasks that resemble the acquisition of vocabulary through their impact on output and rehearsal, rather than by directly influencing phonological storage.

We are still left, however, with two possible models, that of Snowling et al. (1991) attributing differences in the capacity to acquire language to differences in basic phonological processing, and our own phonological loop hypothesis. We suggest two reasons for preferring our own view (discussed more extensively in Baddeley et al., 1998). The first concerns the lack of specificity of the general phonological processing hypothesis. We do not deny that impairments in phonological processing of one kind or another may have an impact on both the immediate and long-term phonological memory. However, unless the mechanisms are specified, this is unlikely to prove a productive hypothesis. Consider, for example, the concept of phonological awareness. A wide range of tests have been used to substantiate this some, such as rhyme judgment, being accessible to preliterate children, whereas others such as phoneme deletion and relocation appear to reflect processes that are developed during the acquisition of reading. Furthermore, while both nonword repetition and phonological awareness models are capable of predicting reading performance, they appear to account for separable variance (Baddeley et al., 1998; Gathercole, Willis, & Baddeley, 1991). We would argue therefore that the greater specificity of the phonological loop hypothesis presents a clear advantage over a general phonological processing interpretation.

A second and potentially more powerful argument in favor of the phonological loop hypothesis comes from its capacity to account for a wide range of data from adults who appear to have quite normal phonological processing skills. In the case of STM patients, their language deficit appears to be limited to a major disruption of short-term phonological storage, while other phonological and linguistic skills appear to be preserved (Vallar & Shallice, 1990). The previously described studies on second language learning in adults typically use a within subject paradigm whereby varying the nature of the material of the concurrent task influences language learning in ways that are clearly predicted by the phonological loop model. Such subjects do not have general phonological processing problems. We therefore suggest that the phonological loop hypothesis gives both a more precise and a more widely applicable theory than is offered by a general phonological processing interpretation.

1.5. Implications for language deficits

The clearest implication of our results is for the importance of the phonological loop during native language learning. There is, of course, abundant evidence that children with SLI typically exhibit poor digit span, and show impairment on nonword repetition (Baddeley et al., 1998; Gathercole & Baddeley, 1990). Two single case studies show that the prediction is not simply from poor reading to impaired span, but also occurs in the reverse direction. In one population study, a child was identified as having an abnormally poor digit span. When further examined, he proved to show the standard pattern of phonological loop impairment, and to have been identified independently as requiring remedial reading instruction (Baddeley & Wilson, 1993). Another case (Baddeley, 1993) concerned a highly intelligent graduate student who was identified as having a much reduced digit span. He proved to perform normally on native language paired-associate learning, but extremely poorly on acquiring the vocabulary of a foreign language; it transpired that he had previously tried extremely hard to acquire a foreign language for university admission purposes, without any success.

A second implication of our model stems from the observation that patients with left hemisphere damage frequently, but not invariably, show phonological loop deficits (Vallar, Corno, & Basso, 1992). It seems probable that those with preserved phonological STM might benefit from rather different methods of speech therapy, although to the best of my knowledge, this has not, in fact, been investigated.

A third possible application of the phonological loop model stems from study of its detailed structure. It should help distinguish between dysarthria, where the speech deficit is relatively peripheral, and dyspraxia. The former deficit should leave rehearsal capacity relatively preserved, as reflected in both a word length and a phonological similarity effect with visually presented items (Baddeley & Wilson, 1985). Both should be abolished in dyspraxia (Caplan & Waters, 1995).

1.6. The phonological loop and the control of behavior

A recent attempt to study the capacity to switch from one cognitive operation to another (Baddeley, Chincotta, & Adlam, 2001) uncovered an important role for the phonological loop in action control. It prompted a re-examination of the influential earlier work by Vygotsky (1962) and Luria (1959) on the role of language in the control of behavior. They showed that overt verbal control can be particularly useful in helping young children and certain brain-damaged adults to develop the capacity to control their actions. Furthermore, in normal adults, I suspect that subvocalization may be a common mechanism for maintaining strategic control. For example, when driving along an unfamiliar route under stressful weather conditions, subvocally maintaining the number and direction of the next turn can be a simple but very effective strategy. As Miyake and Shah (1999) point out, it seems likely that the phonological loop is much more than a slave system used only in the acquisition of language, although we are as yet, only at the beginning of attempts to investigate its role in the control of action.

2. The visuospatial sketchpad

This subsystem of working memory serves the function of integrating spatial, visual, and possibly kinesthetic information into a unified representation which may be temporarily stored and manipulated. My own early involvement in the area stemmed from the experience of driving on a freeway at the same time as I was listening to, and vividly imagining a football game. I noticed that the car was drifting from lane to lane, and rapidly switched to music. In a laboratory version of this, our subjects were required to remember a sequence of instructions that in one case could be stored in terms of an elaborated visual image, while in the other relied on purely verbal coding. They performed this memory task either alone, or while performing a spatial tracking task in which they had to keep a stylus in contact with a moving light spot. The tracking disrupted performance based on imagery, but had no influence on the purely verbal task (Baddeley, Grant, Wight, & Thomson, 1973). Subsequent research has indicated that, depending on the memory task, storage may be primarily spatial (Baddeley & Lieberman, 1980), principally visual as represented by color and shape (Logie, 1986), or possibly motor or kinesthetic (Smyth & Pendleton, 1990). Both lesion and neuroimaging studies indicate that the system is principally, but not exclusively, dependent on the right hemisphere of the brain (for reviews, see Della Sala & Logie, 2002; Smith & Jonides, 1997).

The sketchpad clearly is of less central relevance to language disorders than is the phonological loop. However, it seems likely that the system will be involved in everyday reading tasks, where it may be involved in maintaining a representation of the page and its layout that will remain stable and facilitate tasks such as moving the eyes accurately from the end of one line to the beginning of the next.

An unexpected role for the visuospatial system in comprehension was recently revealed as part of a study of the grammatical capacity of people with Williams syndrome. This genetic condition is characterized by elf-like facial features, typically associated with an unusual pattern of learning difficulties. The pattern includes relatively preserved verbal skills, together with impaired visuospatial processing (Bellugi, Wang, & Jernigan, 1994; Jarrold, Baddeley, & Hewes, 1999; Vicari & Carlesimo, 2002). We tested a group of people with Williams syndrome, comparing them with two matched control groups, one involving younger normal subjects, and the other comprising people with mild general learning disability. All three groups were tested on Bishop's (1979) test for the reception of grammar (TROG). This involves presenting subjects with sentences incorporating grammatical forms of gradually increasing complexity. In each case the subject must point to one of four pictures that corresponds to the sentence. Our Williams group was approximately equal to the controls, but with one or two items that appeared

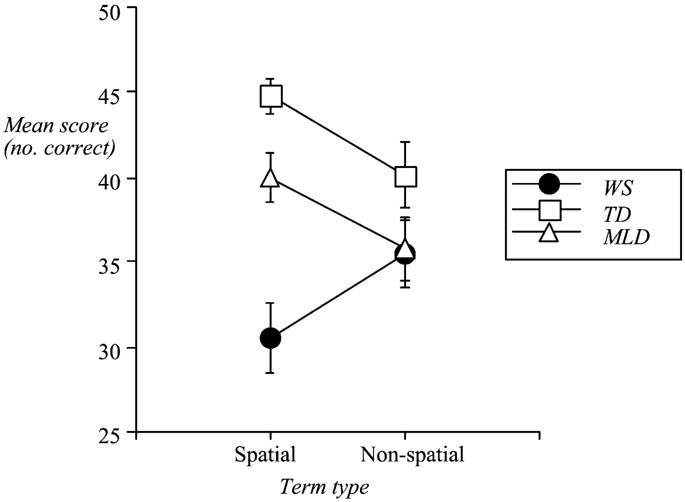

Fig. 5. Williams syndrome (WS) is associated with impaired spatial working memory. As it is also associated with difficulty in processing spatially-based syntax, when compared to typically developing normal children (TD) or to people with minimal learning disability (MLD). The difference is not present for nonspatial syntactic forms.

to be performed at a somewhat lower level. As these appeared to be items involving a spatial construction, we went on to test this directly, comparing a series of grammatical structures that involved spatial terms (e.g., above, below, in, shorter, etc.), together with a similar number of nonspatial constructions (e.g., neither/nor, X is but Y is not, etc.).

The results are shown in Fig. 5, from which it is clear that the Williams group were grossly impaired on the spatial items, in contrast to the nonspatial equivalents, on which the two groups were broadly equivalent, with the exception of one item, which, though not spatial, was visual (lighter/darker). Detailed analysis of error patterns indicated that the deficit did not represent a total failure to master the spatial syntactic forms, but rather to a greater tendency to make mistakes when using them (Phillips, Jarrold, Baddeley, Grant, & Karmiloff-Smith, in press). The visuospatial problems of Williams syndrome are not limited to STM, and hence may represent factors that extend beyond the sketchpad. What they suggest, however, is that cognitive capacities and the ability to maintain and manipulate information of a visuospatial nature is likely to play an important role in language comprehension, at least in the case of certain types of material.

3. The central executive

This system is assumed to be responsible for the attentional control of working memory. It relies heavily, but not exclusively, on the frontal lobes (Stuss &

Knight, 2002), and can almost certainly be fractionated into a number of executive subprocesses (Baddeley, 2002; Shallice, 2002).

Executive processes are probably one of the principal factors determining individual differences in working memory span (Daneman & Carpenter, 1980). In working memory span studies, subjects are typically required to combine simultaneous processing and storage, for example, reading out a series of sentences while being required to remember the last word in each sentence for subsequent immediate recall. Other studies have used mental arithmetic with interpolated words, with comparable results (Turner & Engle, 1989). Working memory span has proved to be a robust predictor of a wide range of complex cognitive skills, ranging from reading comprehension to learning electronics. It is highly correlated with performance on the type of reasoning test that underpins standard measures of intelligence (see Daneman & Merikle, 1996 for a review). However, while differences in working memory span certainly do influence comprehension capacity, it is likely that degree of relevant semantic knowledge is also a major factor. A recent study by Hambrick and Engle (2002) studied the retention of passages about baseball by participants who varied in age, their knowledge of the topic, and in working memory span. All three variables influenced performance, but level of expertise was the principal influence on recall.

4. The episodic buffer

By the late 1990s, we had attempted to specify more clearly the role of the central executive by proposing that its functions were entirely that of an attentionally-based control system, and abandoning the idea that it also had a capacity for storage (Baddeley & Logie, 1999). This had the advantage of focusing attention on the fractionation of executive processes (Baddeley, 1996, 2002), but was then challenged by the identification of a range of phenomena that did not fit neatly into the Baddeley and Logie (1999) model. These typically reflected two deficits within the model. The first was a need for a system that would allow visual and verbal codes to be combined and linked to multi-dimensional representations in LTM. The second comprised the need for the temporary storage of material in quantities that seemed clearly to exceed the capacity of either the verbal or visuospatial peripheral subsystems. This shows up particularly clearly in the retention of prose passages. Immediate recall of prose was initially attributed to LTM, but this interpretation was challenged by a small number of densely amnesic patients who, despite grossly impaired LTM, nevertheless could perform at a normal level on immediate recall of a prose passage containing some 20 or more idea units, and hence considerably beyond verbal or spatial span (Baddeley & Wilson, 2002). An even more dramatic instance was described by Endel Tulving (personal communication). An exceptionally densely amnesic patient claimed nevertheless to be a good bridge player. Tulving asked to have this demonstrated, and was intrigued to discover that not only was the patient

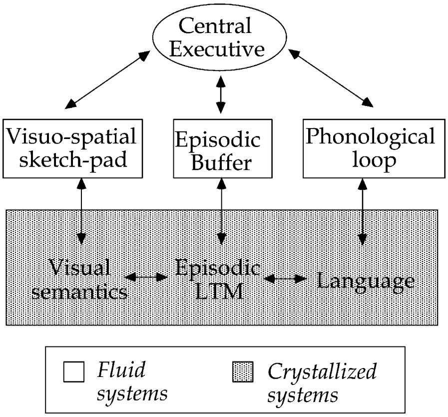

Fig. 6. The current multi-component model of working memory. The episodic buffer is assumed to form a temporary storage system that allows information from the subsystems to be combined with that from long-term memory into integrated chunks. The system is assumed to form a basis for conscious awareness.

able to remember the contract and the cards played, but was also able to carry information across games to the extent of winning the rubber. How could this be achieved by someone with grossly defective LTM?

Such evidence, together with the need to provide an account of working memory span, and of such fundamental features of STM as the capacity to chunk information (Miller, 1956), resulted in the proposal of a fourth component of the working memory system, namely the "episodic buffer" (Baddeley, 2000). This is assumed to be a limited capacity system that depends heavily on executive processing, but which differs from the central executive in being principally concerned with the storage of information rather than with attentional control. It is capable of binding together information from a number of different sources into chunks or episodes, hence the term "episodic"; it is a buffer in the sense of providing a way of combining information from different modalities into a single multi-faceted code (Fig. 6). Finally, it is assumed to underpin the capacity for conscious awareness (Baddeley, 2000).

If the new concept is to be useful, then it is clearly necessary to develop methods of investigating it. This process has already begun, using highly constrained prose recall tasks as the first of what we hope will be a range of measures of episodic buffer capacity.

5. Conclusions

If, as suggested, working memory is a temporary storage system that underpins our capacity for thinking, it is clearly the case that it should have implications for language processing, and that disorders in working memory may impact on language processes. While a huge amount of such language processing is relatively automatic, deficits within the phonological loop, and to a lesser extent, within other aspects of working memory, may seriously impair language processing. It seems likely that the interface between working memory and language will continue to be a fruitful one.

Appendix A. Continuing education

1. Which of the following refers to components of the multi-component working memory model described?
   A. Phonological loop.
   B. Levels of processing.
   C. Central executive.
   D. Echoic memory.
   E. Episodic buffer.
2. Which of the following phenomena have been used to argue for a two component phonological loop?
   A. The tendency for memory span to be reduced for phonologically similar material.
   B. The tendency for a negative correlation between word-length and verbal span.
   C. Removal of the phonological similarity effect when articulation is suppressed for visual but not auditorily presented items.
   D. All of the above.
   E. None of the above.
3. Which of the following *DOES NOT* provide evidence of the link between working memory and language?
   A. Dyspraxia.
   B. Autism.
   C. Williams syndrome.
   D. Dysarthria.
   E. Specific language impairment.
4. Which of the following is presented as an argument for rejecting a general phonological processing interpretation of SLI in favor of an account in terms of the phonological loop?
   A. The loop account is more specific.
   B. The phonological loop hypothesis has a broader scope, applying to developmental, acquired, and temporarily induced language acquisition deficits.
   C. Studies have conclusively disproved the general phonological hypothesis.

D. Neuroimaging studies clearly favor the phonological loop interpretation.
E. A. and B.

5. Which of the following statements is *INCORRECT*?
   A. Language processing is entirely preserved in Williams syndrome.
   B. It has been proposed that the episodic buffer plays a role in complex prose comprehension.
   C. Much on-line language processing is probably relatively automatic.
   D. Executive processes tend to rely heavily on the frontal lobes.
   E. Spatial processing tends to be impaired in Williams syndrome.

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