Reading and Working Memory

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The concept of working memory is outlined, with particular reference to a hypothetical subcomponent, the articulatory loop. Research on the possible involvement of the articulatory loop in fluent adult reading is discussed in connection with the effects of phonological similarity within the material to be read, and the effects of articulatory suppression. Evidence from written and spoken puns is also considered. The model is then used to investigate the comprehension and reading performance of a patient with defective STM attributable to an impairment in the phonological short-term store. The evidence combines to suggest that the articulatory loop is not essential for most fluent reading, but is important for the accurate processing of complex text. The final section considers the possible involvement of the articulatory loop in learning to read, presents evidence for its importance, and suggests possible strategies for optimizing its use.

The Concept of Working Memory

During the 1960's there was a dramatic increase in the amount of both experimental and theoretical work devoted to the topic of short-term memory. By the early 1970's the field had become enormously complicated, with a wide range of experimental techniques, all claiming to tap short-term memory, and a bewilderingly large range of models. In an attempt to clarify this increasingly complex picture, Graham Hitch and I decided to ask the simple question "What is short-term memory for?". The answer assumed by most theorists was that short-term memory (STM) acts as a temporary working memory. A wide range of cognitive tasks require the manipulation of information, and this in itself demands temporary storage; STM was assumed to provide the storage, and hence to play a central role in such important cognitive skills as reading, understanding, and reasoning. There was however virtually no direct evidence in support of this widely held view. We therefore decided to collect such evidence.

We required our subjects to perform a range of tasks including reasoning, learning, and prose comprehension while remembering sequences of digits such as might be involved in remembering a telephone number. The assumption was that the greater the number of digits held in immediate memory the more of the limited capacity of the working memory would be occupied, and the less would be left for

Visible Language, XVIII 4 (Autumn 1984), pp. 311-322.
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reasoning or comprehending. Our results indicated that such memory tasks do impair performance, but that the effect is considerably less dramatic than might have been expected. Impairment in performance on a complex reasoning task, for example, occurred only when the subject was required to hold six or more digits, a load approaching the limit of his memory span (Baddeley and Hitch, 1974). As a result of this and other studies, we suggested that instead of a single unitary short-term memory system, working memory should be regarded as a set of inter-related subsystems. A given task such as digit span might load heavily on some of these, but relatively lightly on others.

We began by dividing working memory into three subsystems. The first of these we termed the central executive. It was assumed to be responsible for running the whole system, and to be limited in attentional capacity, but able to offload some of its demands onto a series of subsidiary slave systems. Two of these have been explored in detail, namely *the articulatory loop* and *the visuo-spatial sketch or scratch pad.* The sketch pad was regarded as a temporary spatial memory system, and was shown to be involved in manipulating visuo-spatial imagery (Baddeley and Lieberman, 1980). The articulatory loop is a system based on inner speech that is regarded as responsible for the many speech-like characteristics of short-term memory. In the case of reading, our research has largely concentrated on the role of the articulatory loop, and only this component will be described in any detail.

The Articulatory Loop

This is the most widely explored subcomponent. It was originally formulated to account for a cluster of results that seem to suggest a strong association between verbal coding and STM. These include:

1 The phonological similarity effect: If a subject is required to repeat back a sequence of consonants or words, then the more similar in sound or articulation the items comprising the sequence are, the greater the probability of error, hence a sequence of letters with similar names such as *BTGVPD* will be harder than a dissimilar sequence such as *KYWXFR* (Conrad and Hull, 1964).

2 The word length effect: Memory span for words is a simple function of their spoken duration; hence most subjects would probably manage to repeat back a sequence such as *sum wit harm bond day*, but would have difficulty with a sequence like *organisation university tuberculosis aluminum hippopotamus*. It proves to be the case that the crucial variable is spoken duration rather than number of syllables. Hence disyllabic words with long vowel sounds such as *Friday* and *harpoon* are less well recalled in a memory span situation than words that have short rapidly spoken vowels, such as *bishop* and *topic* (Baddeley, Thomson, and Buchanan, 1975).

3 The unattended speech effect: If a subject is required to remember a sequence of visually presented items, then his performance will be markedly impaired if irrele-

vant material is spoken at the same time (Colle and Welsh, 1976). The important feature of the irrelevant material is its speech-like character. Irrelevant white noise does not produce the effect, but provided the material is spoken, its meaning is unimportant, with nonsense syllables being just as disruptive of performance as words (Salame and Baddeley, 1982).

4 Articulatory suppression: If subjects are prevented from subvocally rehearsing material by requiring them to utter some irrelevant speech sound such as the word "the", then their immediate memory span is impaired. Furthermore, provided material is presented visually, then the suppression of subvocal rehearsal abolishes the phonological similarity effect (Murray, 1968), the word-length effect (Baddeley, Thomson, and Buchanan, 1975) and the effect of irrelevant unattended speech on memory (Salame and Baddeley, 1982).

All these phenomena can be explained relatively simply by assuming a separate articulatory loop that is capable of holding spoken material. In the case of visually presented items, registration in this system will occur only if the subject subvocally articulates the material. In the case of auditory presentation, however, registration in the store is obligatory, hence irrelevant spoken material will disrupt performance even though the subject is attempting to ignore it. The process of subvocal rehearsal allows the subject to take advantage of this store in two ways. First, by subvocal rehearsal he is able to revive fading memory traces within the store. Second, by articulating visually presented items, he can supplement the visual store with a more durable phonological memory trace.

The Articulatory Loop and Fluent Reading

A perennial problem in discussions of reading is that of the role of subvocal speech. We attempted to tackle this question using some of the techniques and concepts developed in studying the articulatory loop. One of these was to attempt to study speech coding by manipulating the phonological similarity within the material to be read. We did indeed find that subjects took longer to decide on the grammaticality of a sentence such as *Rude Jude chewed crude stewed food*, as opposed to *Rude chewed Jude crude stewed food*. However, we were not able to rule out the possibility that this effect might stem from visual similarity within such sentences. Although one can get occasional words in which sound and spelling are sufficiently divergent to allow them to be studied separately, the structure of English simply does not allow one to produce sentences of such words (Baddeley and Lewis, 1981).

A more straightforward set of results was obtained from a series of experiements studying the effects of articulatory suppression on fluent reading (Baddeley, Eldridge, and Lewis, 1981). In one experiment we required our subjects to read silently passages of prose taken from a travel book. Their task was to detect occasional errors, an error being the reversal of the order of two words hence *he was very rich* might be transformed to *he very was rich*. In one condition, subvocal articulation was suppressed by requiring the subject to repeat the word *the* at a rate of about 3-4 per second. Performance was compared with a control condition in which subjects were free to indulge in whatever subvocal activity they wished. Finally, in order to control for the possibility that performing any supplementary task will impair performance, we included a tapping condition in which the subject was required to tap with a pencil, again at a rate of 3-4 times per second.

The results of this experiment are shown in Table I, from which it is clear that suppressing articulation substantially impairs performance ($p > .01$) while tapping led to no significant decrement ($p > .10$). In contrast to the clear effects of suppression on errors, however, we obtained no effect on speed. Other results indicated that articulatory suppression had no detectable influence on the processing of brief and simple sentences for which the error rate was universally low, but had a marked effect on the accuracy but not the speed of performing more complex comprehension tasks. This suggests that being free to subvocalize may be important for complex comprehension tasks. Furthermore, since speed of processing is unaffected by suppression, our results suggest that this subvocalization operates in parallel with other aspects of comprehension, providing a supplementary backup, probably one that is particularly useful when it is important to process order information accurately.

While trying the task ourselves we noted that it was still possible to "hear" the passage one was reading. We checked out this observation in a series of experiments where subjects were required to make judgements on the sound of words or nonwords. For example, subjects might have to decide whether *cayoss* sounded like a real word, or whether a word and nonword (e.g. *brude - brewed*) sounded alike. Table II shows the effect of articulatory suppression on both the speed and accuracy of performing a range of tasks involving the judgement of the sound of words or pseudowords.

We found that our subjects were quite capable of making such judgements while suppressing articulation, and that their performance was not significantly slower or less accurate. On the basis of these results we concluded that there probably exist at least two speech codes, one is involved in the articulatory loop, and helps to support short-term memory. The other, possibly analogous to an acoustic image, is sufficient to allow rhyme judgements, but does not appear to be used in short-term memory tasks (Baddeley and Lewis, 1981). A similar conclusion was reached independently by Besner on the basis of both studies of judgement of homophony under suppression (Besner, Davies, and Daniels, 1981) and by a demonstration that memory span is greater for pseudo-homophones (e.g. *frute, chane*) than for other non-words (e.g. *prute, chale*) even under conditions of articulatory suppression (Besner and Davelaar, 1982).

Our results seemed to suggest that phonological coding in reading was used sometimes, but was in fact optional. One implication of this would be that puns might be different when presented in the written and the spoken mode. A pun is essentially a play upon words in which two meanings are accessed by the same phonological pattern. They can be divided into identical puns, where the two meanings are spelt in the same way (e.g. *saw*) and others where the same sound is spelt in different ways (e.g. *cheap* and *cheep*). If reading is always accompanied by a phonological code, then it should not matter whether the spelling is or is not identical for either spoken or written puns. If on the other hand, a phonological code is optional, then one might expect to find that experienced written punsters would tend to favour identical spellings.

We therefore analysed headlines from two British daily newspapers, *The Guardian* and *The Daily Mail* for one week, categorising the large number of puns perpetrated by headline writers as either identical or non-identical. We compared these with the puns detected from a range of radio and TV programmes. Finally to obtain a baseline we analysed a set of truly awful puns published in *Famous Monsters* and perpetrated by the editorial board (Chairman D. R. Acula) in an attempt to en-

Table I. Influence of articulatory suppression and tapping on the detection of errors in prose. Data from Baddeley, Eldridge, and Lewis (1981, p. 448).

	Control	Suppression	Tapping
Misses (out of 5)	1.54	2.40	1.64
False alarms (%)	.05	.04	.07
Time/passage (s)	68.03	69.19	68.44

Table II. Effect of articulatory suppression on speed and accuracy of rhyme judgments of three types. Data from Baddeley and Lewis (1981).

	Speed (Sec/Item)		Errors (%)	
Task	Control	Suppression	Control	Suppression
Sounds like a real word, e.g. *yorn*	1.88	2.02	14.4	18.5
Word-nonword rhymes, e.g. *ocean-oshun*	1.88	1.92	6.4	6.6
Non-words rhyme, e.g. *kerm-curm*	2.34	2.34	8.4	13.3

Table III. Distribution of identical and nonidentical puns in different media[a,b]

	Identical	Nonidentical
Newspapers	68	18
Radio & TV	25	37
Monster panel	14	48

[a] $X^2 = 50.0$, d.f. = 2, p .001

[b] Excluding monster jokes: $X^2 = 23.3$, d.f. = 1, p .001

courage its readers to take part in a monster joke competition. The results of our profound and extensive research are shown in Table III, from which it appears that headline writers do appear to avoid non-identical puns, suggesting that they at least, operate on the assumption that the creation of a phonological representation in reading is by no means guaranteed (Baddeley and Lewis, 1981).

Our evidence suggests then that there are probably at least two phonological codes. Coding by articulation appears to operate in parallel with other reading processes since it does not slow down reading, and appears to increase accuracy but is probably not necessary for comprehension of gist. There is almost certainly a second phonological code which is sufficiently powerful to allow rhyme judgements, but does not appear to contribute to verbal memory.

Neuropsychology, reading, and the articulatory loop

We have recently begun to study the reading of a patient with a very pure deficit in auditory verbal STM (Vallar & Baddeley, 1984a). This patient, P.V., has impaired digit span for auditorily presented material, with relatively normal visual digit span. She shows no evidence of recoding visually presented material, with visually presented letters showing no phonological similarity effect, and her performance being unaffected by articulatory suppression. She shows no word-length effect, suggesting that she does not indulge in subvocal articulatory rehearsal, although her speech is unimpaired, and her ability to articulate is normal, as measured by her speed of counting or reciting the alphabet. When material is presented auditorily, memory span performance is poor, but she does show a phonological similarity effect. Her pattern of dysfunction is consistent with the view that the phonological storage component of the articulatory loop is present but impaired in capacity. For that reason, subvocal rehearsal ceases to be a profitable strategy, hence the lack of an effect of word length, or with visual presentation, of a phonological similarity or articulatory suppression effect.

In a subsequent study we have begun to investigate her capacity for comprehending both spoken and written language (Vallar & Baddeley, 1984b). Her phonological processing of spoken or written items proved to be well within the normal range as measured by phonological discrimination, assignment of stress to words and rhyme judgment. She was capable of understanding individual words and short sentences, but was poor at detecting errors in complex sentences for which preservation of the specific wording was necessary for understanding. The crucial factor proved not to be length since she found no difficulty in classifying as erroneous a sentence such as *It is true that physicians comprise a profession that is manufactured in factories, from time to time.* However, she was performing virtually at chance in detecting errors in sentences of the following kind: *The world divides the equator into two hemispheres, the northern and the southern* or *One could reasonably claim that sailors are often lived on by ships of various kinds.*

The sentences which she can handle can typically be verified by checking the extent to which the subject and the predicate are plausibly semantically related whereas for sentences of the second kind, retention of specific wording is necessary. Further experiments are currently planned to investigate in greater detail the nature of her impairment.

An as yet unpublished study (Baddeley & Wilson, in press) has explored the role of articulation in inner speech by studying the phonological judgment and STM performance of patients who are unable to speak following brain damage, but whose capacity to comprehend and to generate language is unimpaired. Such anarthric and dysarthric patients typically show an excellent capacity for understanding and producing language. Since most have severe motor problems, language production tends to involve either a rather laborious process of pointing to letters on a letter board, or a rather more convenient device whereby a keyboard is used to produce a printed output on ticker tape. We observed excellent reading, writing, and spelling in such patients, together with clear evidence for the use of the articulatory loop. Our patients showed an effect of phonological similarity in retaining visually presented letter sequences, a word length effect, and a well preserved ability to judge whether two words or nonwords would be homophonous if pronounced. Our results therefore suggest that a capacity to articulate is not necessary for the effective functioning of the articulatory loop, indicating that in mature adults, at least, it probably depends on central rather than peripheral processes.

Working Memory and Learning to Read

We are at present in the process of attempting to use the concepts of working memory to study the process of normal and dyslexic reading. We were encouraged in this by the observation that one of the most striking features of dyslexic children is their impaired digit span (Ellis and Miles, 1981). We argued that in learning to read, a child must decode a series of visually presented letters, store the outcome of his decoding in some temporary system, and subsequently blend the contents of his store to produce a word. We suggested that the articulatory loop system would be ideally designed to assist in this (Baddeley, 1979). We suggested that as each letter is decoded by the beginning reader, it is stored in the articulatory loop, hence freeing the central executive to decode the next item. Subsequently the loop is used to help blend the decoded letter sounds and to map the blend onto a real word. We were encouraged in this suggestion by the results of Liberman, Shankweiler, Liberman, Fowler, and Fischer (1977) who report that poor readers show much less evidence of the influence of phonemic similarity than do good readers, suggesting that they are not fully utilising the articulatory loop.

In an attempt to explore this further, Ellis, Miles, Lewis, Logie, and myself have studied the memory and reading characteristics of a range of dyslexic boys. We asked first, whether they showed normal signs of utilising the articulatory loop. If they were failing to do so, then there should be no evidence of the phonological similarity, word length, or articulatory suppression effects.

We tested three groups of boys aged approximately 14 years, one from a school for dyslexics, one sample of children of the same chronological age from a normal school, and a third sample comprising children who were matched for reading age with the dyslexic boys, and hence who were somewhat younger (Ellis, Baddeley,

Table IV. Memory span performance of dyslexic and control subjects. Data from Ellis, Baddeley, Miles, and Lewis (Unpublished).

	Dyslexic group	Reading Age control group	Chronological Age Control group
N	20	20	20
Mean chronological age (yrs:months)	11:11	9:5	12:0
Mean reading age (Schonell)	9:1	9:5	12:10
Digit span	5:37	5:48	6.70
Digit span with suppression	3.70	4.27	5.17
Dissimilar word span	4.25	—	4.70
Similar word span	3.25	—	3.42
Short word span	3.88	—	4.28
Long word span	3.33	—	3.65

Miles, and Lewis, unpublished). We measured memory span for visually presented digit sequences, both with and without articulatory suppression, and auditory span for phonologically similar and dissimilar words and for long and short words. The results of these three tests are shown in Table IV.

Comparing the dyslexic group with their chronological age controls, it is clear first of all that their span is impaired, a characteristic result in the case of developmental dyslexia. Is this then because they failed to use the articulatory loop system? Surely not, since they show at least as clear an effect of articulatory suppression and phonological similarity as do either the chronological age or reading age controls. This result would seem to be at variance with reports by Liberman, Shankweiler, Liberman, Fowler, and Fischer (1977) of an absence of phonological coding in memory span performance by poor readers. It is, however, consistent with results obtained by Johnston (1982) who also found that dyslexic children exhibited apparently normal phonological coding.

A possible resolution to this paradox is offered by the work of Siegel and Linder (1984) who note that poor readers show evidence of impaired phonological coding, provided they are tested at a sufficiently early age, after which they appear to use the articulatory loop system in a normal way. Our dyslexic subjects were several years older than those studied by Lieberman et al. This suggests a developmental lag in the use of the articulatory loop for visually presented material. It is perhaps worth noting at this point that Hitch and Halliday (1983) report that young children show evidence of using the articulatory loop from a very early age when material is presented auditorily, but that with visual presentation, the use of a subvocal rehearsal strategy does not occur for 6 and 8 year olds, but is clearly present by the age of 10. This result suggests that it might have been wiser in our own study to have used visual presentation to study the phonological and word length effects, as well as the effects of articulatory suppression. Nevertheless, the fact that the effect of suppression remains strong in this group indicates that our subjects had, by the time we tested them at least, reached a point at which they were using the articulatory loop system in a relatively normal manner.

Does this then rule out an articulatory loop deficit as a possible explanation of developmental dyslexia? Clearly not, for two reasons. First, the children that we tested had all been attempting to learn to read for several years; it is therefore possible that during a critical earlier period, their failure to use the articulatory loop adequately may have handicapped them, producing a lag from which they have not yet recovered. This view would imply that once the articulatory loop had become functional, the difference between dyslexics and controls would begin to diminish, a reassuring but unfortunately not altogether convincing view. In fact, there was clear evidence that our subjects were continuing to have considerable difficulty in reading although they were obviously making progress, and in general the evidence suggests that severe developmental dyslexics continue to be somewhat handicapped into adulthood; although reading itself tends to improve particularly with remedial training, some problems of spelling and composition often persist (Zangwill, personal communication).

Further evidence to suggest a continuing impairment comes from two aspects of our data. First of all, the overall memory span of our subjects continued to be impaired, despite the fact that they were clearly using the articulatory loop. In fact their level of performance was approximately that of the younger children having a comparable reading age. A second source of evidence comes from a detailed correlation analysis of the various characteristics of our dyslexic sample and their reading age controls (Logie, Baddeley, and Ellis, in preparation). This correlated accuracy of reading with a number of other variables. The two best predictors of reading performance were memory span for visually presented digits under nonsuppression conditions, the one situation in which articulatory rehearsal of nonauditory material is crucial, and speed of articulation. This was measured by requiring the subject to count from one to ten five successive times as rapidly as possible ($r = -.43$, $p > .02$ and $r = .40$, $p > .05$ respectively). It remains plausible then that although our subjects had begun to use the articulatory loop in a normal way for retention of verbal material, its efficiency of operation may still have been impaired.

While testing these children, it became clear that immediate memory is indeed a major factor, at least in reading words that are at the limit of the child's capability. One could often hear the child subvocalising, and adopting a strategy whereby each individual letter is sounded out and stored sequentially. When the child comes to the end of the word, he attempts to recall the letter sounds and blend them into a single sequence. He then attempts to map this onto a known word. For instance the word *mad* might be sounded out "muh"-"ah"-"duh", with the three sounds blended to produce "muahd", followed by an apparent recognition of the word and an appropriate pronunciation. A particularly clear example of this occurred in the case of one subject, a 12-year-old boy of normal intelligence with a memory span of only three items. One could often hear him spell out the individual letters of a four- or five-letter word, often getting each sound correct, only to find that by the time he had read the last letter, the first letter had been forgotten, requiring him to enter the cycle once more. He was a persistent child, and would often continue for 90 seconds or more before giving up and attempting to produce something approximating some combination of the sounds he had generated.

However, given a child with a reasonable memory span and simple regular words this can be a highly effective strategy. Even for a normal child, however, it is open to two major problems.

The first problem stems from the irregularity of English, and in particular cases where later letters determine the pronunciation of earlier. Terminal *e*'s are a good example of this, since they may present the child with the problem of back-tracking in order to change the encoding of an earlier vowel, before going on to blend (e.g. the *a* in *mad* versus *made*). This backtracking process is clearly likely to cause forgetting of both the sounds and their order which in turn will make accurate reading difficult.

A second problem stems from the fact that it is difficult to encode the sound of an isolated consonant. The strategy here is usually to append a dummy *uh* sound, so that *bring* becomes *buh ruh i nuh guh*. As we know from the phonological similarity effect, a string of items that sound alike is very hard to remember correctly. Adding 'uh' to each consonant will thus make it hard for the child to remember the letters he has read. It is therefore not surprising that our children often appeared to decode the letters correctly but subsequently left letters out or changed their order in coming up with their final blend (e.g. *sing* for *sting*). The resulting errors might seem like visual misperceptions, and we suspect that many errors that are classified in subsequent analysis as visual errors are in fact a result of short-term forgetting.

If our observations prove to be correct, then it suggests that the teaching of reading could be improved by adopting two simple strategies. The first of these is to encourage the child to scan each new word looking for irregularities such as terminal *e*'s, before starting to decode it in detail. This will avoid the problem of having to backtrack and change the previous vowel sound. The second strategy suggests that children should be strongly discouraged from decoding individual consonants. Instead, they should decode consonant-vowel pairs or clusters; this should have two advantages. First it will reduce the number of chunks to be held in memory, hence a word like *clock* becomes two clusters rather than five separate letter sounds. Secondly, this strategy will minimise the phonological similarity effect by avoiding the production of sequences in which all the consonant names contain the same "uh" sound. Both of these should enhance the memory component substantially and would, we predict, lead to better reading in both normal and dyslexic children.

Conclusion

The concept of working memory represents an attempt to bridge the gap between the precise analysis of laboratory tasks, such as immediate memory span, and such important but more general cognitive skills as reading, understanding, and reasoning. I hope that in doing so, it will help us tackle these complex but important cognitive skills: I am sure that whether successful or not, the attempt will enrich our understanding of human memory.

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This was also the topic of an invited lecture given to The British Psychological Society at its annual conference at the University of York April 1982, on receipt of the Presidents' Award of the Society. An earlier abbreviated version has already appeared in *The Bulletin of the British Psychological Society*; permission to reproduce this component is gratefully acknowledged.