INVESTIGATING THE EPISODIC BUFFER

Alan BADDELEY[1], Richard J. ALLEN[2], & Graham J. HITCH[1]
[1]*Department of Psychology, University of York*
[2]*Institute of Psychological Sciences, University of Leeds*

A brief account is presented of the three-component working memory model proposed by Baddeley and Hitch. This is followed by an account of some of the problems it encountered in explaining how information from different subsystems with different codes could be combined, and how it was capable of communicating with long-term memory. In order to account for these, a fourth component was proposed, the episodic buffer. This was assumed to be a multidimensional store of limited capacity that can be accessed through conscious awareness. In an attempt to test and develop the concept, a series of experiments have explored the role of working memory in the binding of visual features into objects and verbal sequences into remembered sentences. The experiments use a dual task paradigm to investigate the role of the various subcomponents of working memory in binding. In contrast to our initial assumption, the episodic buffer appears to be a passive store, capable of storing bound features and making them available to conscious awareness, but not itself responsible for the process of binding.

Like André, I regard executive control as being at the heart of working memory (Vandierendonck, De Vooght & Van der Goten, 1998). I have however, always regarded analysing it as presenting a very tough problem. For many years I attempted to tackle the problem, by postulating a central executive that was capable of performing all of the many functions required by our multi-component model, apart from those that could be assigned to the phonological loop or the visuo-spatial sketchpad. In short, the central executive was an all-powerful homunculus, a little man who ran the whole working memory show.

This served the function of allowing us to concentrate on the more tractable questions of understanding the visuo-spatial and phonological subsystems, but was clearly not satisfactory. This became abundantly clear when, in writing my 1986 monograph, I reached the end of the first draft and realised that I had completely left out the central executive. Rather than starting again from scratch, I decided to borrow an attentional control model from elsewhere. But which model? This turned out not to be a problem since, although there were a number of models concerned with the attentional control of perception, we needed an action control mechanism. Choosing a suitable model proved easy, as there only appeared to be one, that proposed by Norman and Shallice (1986).

The Norman and Shallice model of executive control

The model was developed jointly by Tim Shallice and Don Norman for two somewhat divergent purposes. Norman was interested in understanding slips of action, everyday lapses that were often trivial, but could sometimes lead to major accidents. Shallice was interested in understanding the effects of frontal lobe damage on attention and the control of action. The model they proposed assumes that actions can be controlled in either of two ways. Routine actions such as driving a car on a familiar road were controlled principally by habits, based on schemas in long-term memory. Such control is relatively automatic and places only a light demand on attention. However, when routine behaviour is not feasible, then a second control mechanism the *supervisory attentional system* (SAS) needs to intervene. This system is capable of considering alternative plans of action and biasing behaviour in favour of whatever action appears most promising. In the driving case, an accident might have blocked the road; the SAS would then be involved in considering alternative routes, or if necessary abandoning the trip.

The SAS appears to depend upon the activity of the frontal lobes of the brain, with bilateral damage leading to what has subsequently become known as the dysexecutive syndrome (Baddeley & Wilson, 1998). This is reflected in disruption of attentional control. One feature of this is the tendency to perseverate. For example patient RJ, in describing a road traffic accident that had led to his brain damage, became locked into a descriptive loop describing a conversation between himself and the driver of the truck who he had driven in to. He described how he "apologised, whereupon the driver apologised, whereupon I apologised, whereupon the drive apologised etc etc". Exactly the opposite to perseveration can also occur within the same patient. Instead of being locked onto a single action, the patient may be multiply distracted by features of the environment. One aspect of this is utilisation behaviour (L'hermitte, 1983), whereby the patient responds inappropriately to features in the environment for example, reaching over and drinking someone else's cup of tea.

Fractionating the central executive

I adopted the SAS model, linking it into the original framework as providing a preliminary account of the central executive. In attempting to develop the model further however, I diverged from the neuropsychologically-based approach that Tim Shallice has continued to use, attempting instead to fractionate attentional control into a number of separate capacities, concentrating mainly on using normal participants and studying aspects of attention that I

assumed would be essential for the operation of working memory (Baddeley, 1996). These involved the capacity to focus attention, to divide attention between two or more sources, to switch attention from one task to another and finally to provide an attentional link between working memory and long-term memory.

Exploring this range of attentional capacities was clearly a very ambitious program, but proved useful in the attempt to turn my all-powerful homunculus into a method of tackling an important conceptual problem. I proposed first to specify the capacities that the homunculus would need if it were to function as an executive, then attempting, one-by-one to explain each, eventually making the homunculus redundant, when all his capacities had been explained.

The capacity to focus attention is clearly needed by our homunculus, is of course central to virtually any attentional model, and has been studied extensively (Norman & Shallice, 1986; Stuss & Knight, 2002). Our study of the division of attention proved more complex and benefited from applying the working memory model to the analysis of Alzheimer's Disease (AD). A series of studies involving colleagues in Milan and subsequently Aberdeen and Edinburgh, suggested that the capacity to divide attention was highly vulnerable to AD, whereas in normal aging, provided level of difficulty was titrated so as to be matched between the elderly and young participants, the capacity to divide attention per se appeared not be impaired (Baddeley, Bressi, Della Sala, Logie & Spinnler, 1991). This has continued to be a fruitful line of investigation, and provides strong support for a separable capacity to divide attention (Logie, Cocchini, Della Sala & Baddeley, 2004).

The case of attentional switching proved more complex. We adapted the classic attentional switching paradigm developed originally by Jersild (1927) by presenting our participants with a column of digits. We then required them, in the non-switching condition, to add one to each digit, or to subtract one, while in the switching condition, they were required to alternate, adding one to the first digit subtracting one from the second and so forth. We obtained the expected substantial cost when switching between adding and subtracting was required. However, when the task was subjected to analysis using a concurrent task paradigm, we found to our surprise that the most dramatic deficit came from simple articulatory suppression. What we had discovered or rather rediscovered, was the role of the phonological loop in action control, something that was of course already well known to Luria (1959). There was indeed an additional attentional cost, reflected in further slowing with a more demanding concurrent task, but this effect was by no means substantial, suggesting that the central executive played a rather modest role. Furthermore, subsequent developments in the area cast some doubt on the question of whether there is a single specific executive capacity de-

voted to task switching (Monsell, 2005). My own current view is that task switching may be performed in a number of different ways, depending on the specific tasks, and the cognitive capacities available.

The fourth hypothetical component concerned the capacity to link working memory with LTM. The evidence here was mixed. It is certainly the case that a concurrent attentional load will reduce long-term learning capacity, as shown in the original Baddeley and Hitch (1974) paper. A concurrent load of six digits disrupted the free recall of lists of unrelated words, and also interfered with retention of prose passages. On the other hand, the concurrent task appeared to have little effect on retrieval capacity (Baddeley, Lewis, Eldridge & Thomson, 1984), although the process of retrieval from LTM <u>was</u> found to interfere with concurrent task performance (Craik, Govoni, Naveh Benjamin & Anderson, 1996; Naveh-Benjamin, Craik & Peratta, 2000).

Problems with the three-component model

A puzzle was generated however, by an attempt to use random generation as a measure of concurrent load, an approach used with success by Andre Vandierendonck and colleagues who developed an ingenious task requiring the generation of random time intervals (Vandierendonck, De Vooght & Van der Goten, 1998; De Rammelaere, Stuyen & Vandierendonck, 1999). Our own earlier work used the more conventional random generation of letter or number sequences, while our later research investigated the possibility of using the random pressing of an array of keys (Baddeley, Emslie, Kolodny & Duncan, 1998). We did indeed find that the randomness of key pressing decreased when it was accompanied by a demanding concurrent task such as solving the type of problem involved in intelligence test performance. A later study attempted to use random generation as a measure of comprehension, comparing performance on a range of texts that were read, or heard while the participant pressed keys as randomly as possible. We compared three passages, a simple fairy story, a piece of descriptive prose describing a tropical disease, and a paragraph from a philosophy text. The three differed markedly in readability as measured by standard procedures. We confidently expected that key pressing would be much more random when listening to or reading the fairy story, than the more demanding disease description, which in turn would be more random than performance while attempting to understand the philosophy. To our surprise, we found no differences, comprehension was indeed impaired, but to an equivalent extent for each of the three passages, despite major differences in readability. This was also the case for a series of replications in which we eventually moved away from random generation to the more conventional approach of using concurrent reaction time.

We contrasted performance on the three passages when performing a simple reaction time task with that found with a much more demanding eight choice concurrent measure. The results are shown in Figure 1a; as with the random generation, we found that the more demanding concurrent task did impair performance but that it did so equally for all three passages. Could that reflect a speed-error trade off? If so, then we would expect to find our predicted differential pattern in recall performance. As Figure 1b shows this was not the case; although the philosophy passage was harder, there was no interaction with concurrent load.
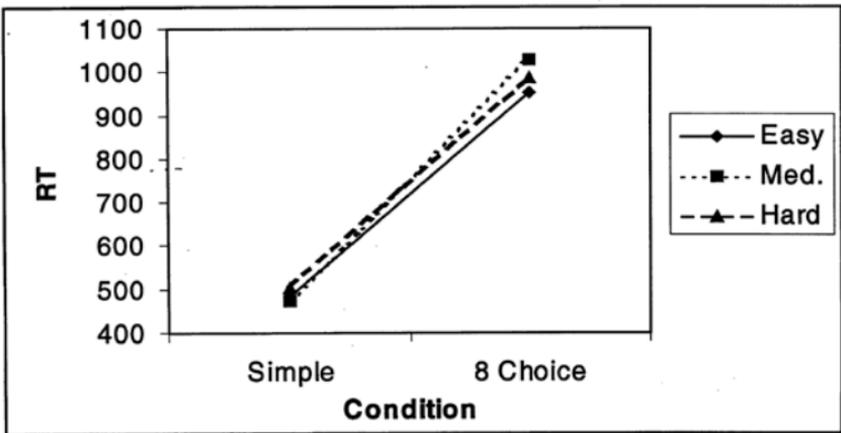

Figure 1a

Performance on concurrent simple and choice reaction time tasks while processing prose at three levels of difficulty
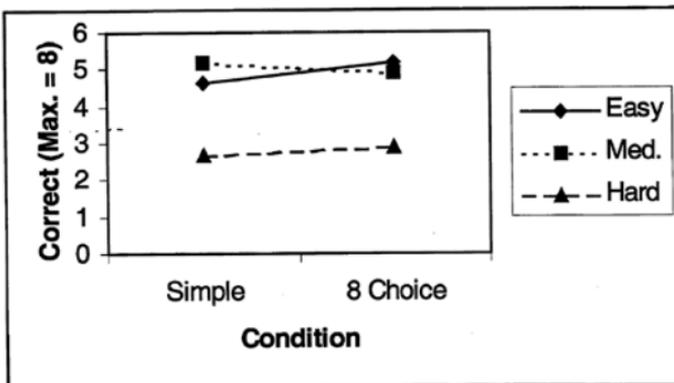

Figure 1b

Means comprehension test score, as a function of concurrent task and level of prose readability

We seemed to get more encouraging results from a study of the retention of prose by amnesic patients (Baddeley & Wilson, 2002). When asked to recall a paragraph of prose such as the Anna Thompson story from the Wechsler Memory Scale, most amnesic patients performed very poorly, both on immediate and delayed recall. However, a small number showed good immediate recall, coupled with grossly impaired recall after a delay. We argued that such patients were probably using their central executive to hold together the idea units comprising the story. In support of this, those successful on immediate test tended to be patients with high and well preserved intellectual capacity. However, although one could argue that these particular patients appear to be able to use attentional capacity in order to enhance memory, this did not prove to be at all typical of other potentially less intelligent patients, suggesting that the capacity to use executive resources to maintain prose passages was not a viable strategy for most people (Gooding, Isaac & Hayes, 2005).

Where does that leave the working memory model? When invited to summarise the model as part of a symposium on working memory organised by Miyake and Shah (1999), Robert Logie and I still presented the executive as a purely attentional subsystem, excluding the idea of the executive as a memory store on the grounds of parsimony (Baddeley & Logie, 1999). I was however beginning to worry about the increasing number of skeletons locked in the working memory cupboard.

One such problem concerned the way in which the visuo-spatial and phonological systems might interact, given that they were assumed to rely on quite different coding systems. This is typically not noticeable since we tend to design our experiments specifically to focus on either visuo-spatial or verbal processing. However, when both options are possible, they appear both to be used and integrated to optimise performance. One example of this comes from the study by Logie, Della Sala, Wynn and Baddeley (2000) in which participants were visually presented with a sequence of letters in mixed upper and lower case, and required to recall them immediately in the correct order. They were instructed that in order to be correct, they must also reproduce the case. There was clear evidence of verbal coding, but also of visual memory, reflected in the higher error rate for letters in which the upper and lower case forms were similar (e.g. <u>Vv</u> and <u>Ss</u> versus <u>Bb</u> and <u>Hh</u>), forcing reliance on memory for size rather than size and/or shape.

Further evidence for the interaction of the visuo-spatial and verbal system comes from the study of sign languages of the deaf in which visuo-spatial information supports verbal processing (Rudner, Fransson, Ingvar, Nyberg & Rönnberg, 2007), producing results that are interpreted in terms of the episodic buffer, which is then elaborated into a working memory model for the ease of language understanding (Rönnberg, Rudner & Foo, 2010).

In the example just described, visual and verbal codes appear to be combined in order to optimise performance. The capacity to combine codes is, however, much more dramatically shown in the recall of meaningful material; immediate memory span for unrelated words is around five or six, whereas when those words form part of a sentence, span is somewhere between 12 and 20 (Brener, 1940). Could that simply reflect five words from the phonological loop and another 10 from LTM? If that were the case, then one might expect patients with a pure deficit of the phonological loop to have a sentence span of around 10, whereas their sentence span is around five or six, substantially more than their unrelated items, but far below the 10 or 12 one might otherwise expect (Baddeley, Vallar & Wilson, 1987). How is such verbal information maintained during the process of combining it with information from phonological and semantic sources?

A particularly striking limitation of the three component model, was its difficulty in explaining the predictive power of the apparently simple measure of working memory span developed initially by Daneman and Carpenter (1980). This involved presenting participants with a sequence of sentences which they must process, subsequently recalling the final word of each. Daneman and Carpenter showed that this was highly correlated with measures of comprehension of the type used for student selection by US universities. This finding has subsequently been replicated many times (Daneman & Merikle, 1996) with a similar predictive capacity found across a wide range of other cognitive tasks ranging from note taking to learning about logic gates, and from acquiring computer programming skills to performance on intelligence tests (see Engle & Kane, 2004 for a review).

The episodic buffer

To summarise, the problems with the three component model can be seen as reflecting two separate but related questions. The first concerns the way in which the various components of working memory, each using a different code, could be integrated. The second concerns the relationship between working memory and long-term memory. I attempted to tackle the problem by proposing a fourth component, the episodic buffer. The episodic buffer is a buffer in the sense that it is a limited capacity temporary store that forms an interface between a range of systems all having different basic memory codes. It is assumed to do so by having a multi-dimensional coding system. It is assumed to be episodic in the sense that it is capable of holding episodes, integrated chunks of information that then became accessible to conscious awareness (see Figure 2).
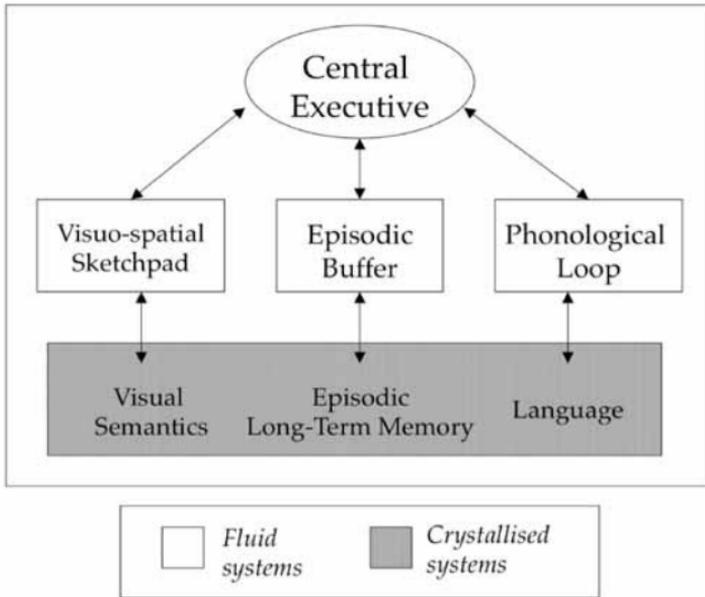
Figure 2

The working memory model proposed by Baddeley (2000) in which the episodic buffer is assumed to depend purely upon access from the central executive. Later evidence suggests that this is not the case

I introduced the new concept with trepidation; did the world need yet another approach to consciousness? It seems however to have been very successful, at least when judged by citations which, sadly, appears to be the principal measure of success these days. While this is gratifying, I suspect that much of its use may reflect its lack of specificity. Psychology journals, all too frequently, seem to require a theoretical explanation of every feature of even the most atheoretical experimental paper. I suspect that the possibility of attributing any puzzling results to the operation of the episodic buffer may be providing a godsend to the frustrated experimenter.

However, while I am always happy to help my fellow man/woman, I had hoped for more. My view of theory is that it should not only capture what we know, but also stimulate new and tractable questions that will expand our area of knowledge, potentially challenging the theory and requiring it to be further developed, or if appropriate replaced by a better theory. Unlike the early views of scientific method proposed by Karl Popper (1959), I do not think a theory needs to be directly testable through critical experiments that "prove" or "disprove" it. Although I began my scientific career with this view, I gradually began to notice that what seemed to work empirically, bore little relationship to Popperian theory. It was indeed possible to draw up precise models, but only by choosing areas that were very much simpler than the

ones that interested me, or by making multiple assumptions about specific variables. If these were made in advance, then the chance of guessing the right value was negligible and hence the chance of disproving your theory extremely high. If on the other hand, you left the variables unspecified, then there is a danger that your model is simply a form of complex post hoc curve fitting, evoking the complaint that "given enough parameters you can fit an elephant".

My approach to science has been closer to Popper's later views, and those of Feuerabend (1991). This approach is much less concerned with testability, preferring instead to evaluate theories according to their <u>productiveness</u>, the extent to which they generate new research and new ideas that are themselves productive. The classic example of the greater importance of productiveness than simple testability is provided by the theory of evolution, and I would argue that in biological sciences at least, successful theories are much more likely to be those that are productive, rather than those that are precisely and elegantly formulated, and clearly testable. I recommend Francis Crick's (1988) book "What mad pursuit" as very stimulating discussion of the differences between theories in physics, where he started his career, and those in biology, to which he made such a dramatic contribution.

So has the concept of an episodic buffer been productive? I was fortunate enough to obtain a four year research grant supporting a post doctoral fellow that allowed me to attempt to tackle that question, despite the scepticism of some referees as to just how practicable this enterprise might be. Happily, times were a little less tough than they are now. The postdoctoral fellow on the grant was Richard Allen, and after a year we moved from Bristol to York, with Graham Hitch then becoming a co-grant holder. We decided to tackle a question that was central to the operation of the hypothetical episodic buffer, and indeed to the general study of consciousness, namely the capacity to bind information from several sources into a unitary object, concept or episode. The revised model (see Figure 2) had proposed that information could be fed into the episodic buffer either from long-term memory (LTM) or through the central executive, but not directly from the visuo-spatial and phonological subsystems. I had intentionally omitted any arrows suggesting such a direct link, on the grounds of parsimony, anticipating that it should prove possible experimentally to decide whether or not such links were necessary. When I formulated the concept of a buffer, I envisaged it as an active processor, which came relatively close to our initial hypothesis of an all-powerful central executive, attributing the main source of attentional control to the executive, but leaving a substantial but unspecified degree of processing capacity within the episodic buffer.

In tackling the problem, we fell back on our well-tried dual task approach, a method that others, notably including André Vandierendonck have

found productive (Vandierendonck, Kemps, Fastame & Szmalek, 2004; Vandierendonck & De Vooght, 1997). We chose to study in parallel, two very different forms of binding, one involved the binding of visual features into perceived and remembered objects, while the other involved verbal binding, as reflected in the role of chunking in immediate memory for sentences. I will discuss these two areas in turn.

Binding in visual working memory

The development of the original Baddeley and Hitch (1974) model of working memory was far from uniform across the proposed subsystems. As mentioned above, the central executive proved to be the most demanding, and least extensively investigated component, in contrast to the phonological loop which presented a much more tractable problem, given its comparative simplicity and the extensive existing data on verbal STM. Visual working memory lay somewhere between these; considerable progress had been made, but much of this work involved relatively complex activities such as the use of visual imagery, with rather less focus on the more basic aspects of visual working memory that might correspond more closely to the extensive work on the phonological loop (see Logie 1995 for a good review of this earlier work). Things began to change in the study of visual working memory when it attracted a number of investigators with a background in the more basic aspects of visual attention. In particular, an influential paper by Luck and Vogel (1997) exploited the change detection paradigm (Phillips, 1974; Phillips & Baddeley, 1971) in a series of ingenious experiments that began to pick apart the processes involved in the retention of simple objects such as coloured shapes.

An elegant series of experiments (Luck & Vogel, 1997; Vogel, Woodman & Luck, 2001) developed a memory paradigm that has since been used very widely and productively. They were particularly interested in comparing the retention of individual features such as the colours red and green, and shapes square and circle, with the capacity to retain the binding between features, for example that the circle was red and the square green. A typical task would involve presenting a row of four colours, or four shapes or four coloured shapes, then presenting a single test item and asking whether it had occurred in the stimulus set. They found that people could retain about four items, with little difference between retention of individual features, and of features bound into objects. Somewhat surprisingly they found that the number of features had little effect on performance, providing they were bound into specific objects. The number of such objects that could be retained was limited to four or less, regardless of whether they comprised one or many features.

There was no evidence that performance depended on verbal coding.

About the same time, Wheeler and Triesman (2002) carried out a broadly similar study; they also found little cost to binding when tested by a single probe item, but observed that retention of bound objects was less than that of features when the test involved searching for a target in array of objects comprising other feature bindings. They attributed this latter result to the attentional demand of maintaining bindings over time.

We ourselves were interested in the question of whether the central executive was necessary for binding, as was assumed within our initial version of the episodic buffer. The Wheeler and Triesman attentional interpretation of their multiple test item result might be regarded as supporting this view. However, it is equally plausible to argue that their result reflected forgetting due to interference from the items scanned in searching for a target match. We attempted to test this in a series of studies using the single probe technique. We aimed to disrupt the central executive component of working memory by means of attentionally demanding concurrent tasks, which included counting backwards in one study and maintaining a concurrent load of six digits in another (Allen, Baddeley & Hitch, 2006). These demanding concurrent tasks consistently impaired overall performance, but had no greater impact on the condition requiring binding than on those that only required retention of a single feature. Our initial interpretation was that the binding process operated automatically, and hence was not influenced by an attentionally demanding concurrent task, whereas the overall task of retaining four objects was far from automatic.

We went on to test this hypothesis using a series of manipulations in which it was less and less plausible to assume that the act of binding was automatic. In one study, we spatially separated the colour and shape, having an array of four colours above an array of four shapes. Participants were required to bind the adjacent colour and shape, and were tested by being presented with a coloured shape; if that colour and shape had been adjacent, they were to respond "yes", whereas if the two were non-adjacent they should respond "no". This was compared to a condition in which the colours and shapes were combined at presentation into four unitary objects (Karlson, Allen, Baddeley & Hitch, in press). Again we compared retention of individual features and of bound objects, and again, we found an overall effect of a demanding concurrent task, but no interaction. A further study within the same series separated the colour and shape in time, presenting an array of shapes followed by an array of colours, or vice versa. This was a difficult task that required us to reduce the number of test items presented, but the result was the same, namely a clear overall, decrement when compared to presentation of unitised stimuli, but regardless of whether we were testing retention of individual features, or of features bound into objects, the degree of decrement was the same.

Where does this leave our original interpretation, based on the assumption that the binding of features into objects was automatic? Any visual system that automatically bound features from adjacent locations into single objects would surely lead to visual chaos, as would the sequential binding of different features separated in time.

At this point we should return to our earlier question concerning the explanation of Wheeler and Triesman's (2002) results. These indicated that bindings were less well retained than features, when tested within an array comprising one target and a number of non-targets, a result they interpreted as reflecting the greater attentional demand of maintaining the feature bindings. Our own results however, suggest that attention, viewed as the limited capacity operation of the central executive, is important for performance, but <u>not</u> for binding. That suggests an explanation of Wheeler and Triesman's data in terms of some form of <u>interference</u> between the remembered target and potentially distracting items in the test array. Supporting evidence for this interpretation was provided in the final experiment of the Allen et al. (2006) study. In this experiment, the items to be remembered were presented sequentially, rather than in a simultaneous array. They were tested as before, using a single probe item. The results are shown in Figure 3. Here at last, we do obtain a difference between the retention of individual features, and of features bound into coloured shapes, an effect that is present at all serial positions except for the last. We interpreted this as suggesting that, as each item appeared, it interfered with retention of the previous item, with this effect being greater for binding than for individual features. Only the last item presented escapes this, and shows the absence of a difference between features and bindings that has characterised all our earlier experiments.
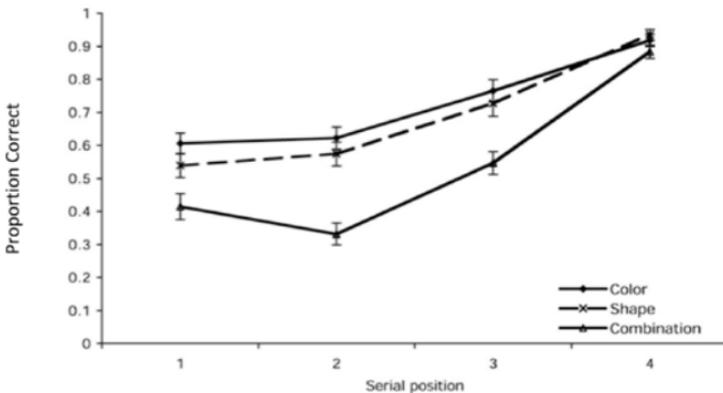

Figure 3

Probe recognition of sequentially presented items. Individual features are better retained than features bound into objects (Data from Allen et al., 2006)

While our sequential presentation experiment throws light on the Wheeler and Triesman results, it differs from their study in a number of respects. An important one concerns the fact that our participants were attempting to remember each of the potentially interfering items, whereas this was not the case with Wheeler and Triesman experiment, in which non-targets in the probe array did not need to be stored. We therefore moved on, in collaboration with our Japanese colleagues Taiji Ueno and Satoru Saito to devise a paradigm that would allow us to explore this issue in more detail (Ueno, Allen, Baddeley, Hitch & Saito, submitted). Instead of presenting a list of items to be remembered, we reverted to a parallel presentation of an array of items, but followed it with a single item suffix, that participants were asked to ignore, before testing by presentation of a probe item.

If our interpretation of the Wheeler and Triesman result were correct, we would expect the suffix to interfere with performance, having a particularly marked effect on the capacity to retain the binding of features into objects. Consistent with this view, we found a reliable impairment in recognition accuracy following a suffix that was slight in the case of retention of individual features, but more substantial in the case of retention of features bound into objects. There was however, a crucial further aspect of our results. Disruption was dependent upon the nature of the suffix, being substantially greater when the features making up the suffix were chosen from the set used to make up the targets. For example if the list of permissible colours included green and the permissible shapes included circle, then a green circle would disrupt performance, even though neither feature had appeared in the list of items to be remembered. Conversely, a pairing of novel features, for example a brown oval had little impact. We explained this by assuming that the suffix effect has two separate sources. The attentional demand of filtering out the irrelevant suffix was assumed to cause some disruption, regardless of the nature of the suffix. However, when the suffix has features in common with the target set, its exclusion is less reliable, allowing it to be encoded, and to disrupt retention of bound objects, which are assumed to be less robustly encoded than individual features.

A series of later studies (Ueno et al, in preparation) studied the effects of interposing a suffix that contained one permissible feature, combined with a second feature from outside the set, in the above case for example, a brown circle. Such mixed suffixes were just as disruptive as those in which both features came from the permissible set. We interpret this latter result as confirming our assumption of some form of attentional gating mechanism that is capable of excluding totally non-permissible items, but for which a single feature is enough to gain access to the memory store, despite the fact that the suffix occurs at a different time from the remembered stimuli.

The work described so far has focused on the capacity to bind the simple

features of colour and shape into perceived and remembered objects. Broadly similar studies have, however, been performed using a somewhat different principle of binding, namely that involved in linking a series of object locations into a pattern. An important factor in remembering such an array is that of symmetry, with patterns having vertical symmetry being more memorable. This effect was studied by Rossi-Arnaud, Pieroni and Baddeley (2006) using a sequential method of presentation such that the participants were required to observe and then reproduce a pattern of stimuli, each comprising a sequence of locations on a 5 by 5 matrix, after which the participant had to recall the array. Patterns could be symmetrical along a vertical, horizontal or diagonal axis, or could be asymmetric. There was a clear advantage to vertical symmetry, but not to horizontal or diagonal. The role of working memory was then studied using a concurrent task method to investigate the contribution of the central executive, the visuo-spatial sketchpad and the phonological loop to performance. Overall performance was unaffected by articulatory suppression, suggesting that verbal encoding was not involved. Performance was however impaired by a visuo-spatial task, and even more substantially by a task involving executive processing. However, neither of these effects interacted with the presence or absence of symmetry. This is consistent with the assumption that the capacity to bind objects into a symmetrical and hence more memorable pattern is not dependent on working memory per se, although the overall retention process does appear to be dependent on both executive and visuo-spatial components of the system.

A subsequent study (Pieroni, Rossi-Arnaud & Baddeley, in press) was equivalent, except that all the stimuli were presented simultaneously, making the presence of symmetry easier to detect. Under these conditions, an advantage accrued following horizontal, as well as vertical symmetry, but there was still no advantage to the diagonal version. Again there was an impact on overall performance of concurrent visuo-spatial and executive processing, but again this failed to interact with the presence of symmetry.

To summarise, our experiments on visual working memory have produced a very coherent picture. Binding, whether within the features of a visual object, or across the components of a symmetrical pattern, appears to operate independently of working memory. This is clearly not because our concurrent tasks are too simple since overall performance is consistently influenced by tasks impinging on the visuo-spatial sketchpad, and even more so by those involving executive processing. Binding per se however appears to operate outside working memory.

Binding in verbal working memory

While we found no evidence for the involvement of working memory in visual binding, it could be argued that perceptual processing operates outside working memory. Fortunately, in parallel with our visual experiments we had also studied the role of binding in verbal working memory, concentrating on the difference between recall of unrelated word sequences and that of sentence memory. As mentioned earlier, sentence span is very substantially longer than span for unrelated words, an advantage that is readily explained in terms of the concept of chunking, initially proposed by George Miller (1956). This assumes that memory span is capable of holding a limited number of chunks, regardless of the size of each chunk. Meaningful prose allows several words to be combined into a single chunk, hence increasing memory span.

Substantial evidence for a limited capacity working memory system is provided by Cowan (2005), although he argues for a limit of five, rather than Miller's seven chunks. The application of the concept of chunking to the retention of prose was elegantly investigated by Tulving and Patkau (1962). They presented their participants with sequences of words that varied in their approximation to English prose, ranging from random words to actual text. As expected, the closer the approximation to English prose, the greater number of words recalled. They then measured recall of chunks, with a chunk defined as a sequence of words that were recalled in the same order as they were presented. Hence, if the passage contained the sentence "The cat was a great hunter and often caught rats in the barn". A participant who recalled the whole sentence correctly would be scored as reproducing one chunk whereas "The cat……….. often caught rats in the barn" would count as two. Tulving and Patkau found that the greater recall of the material approximating to English reflected the recall of larger chunks, while the number of chunks recalled remained constant, regardless of level of approximation.

We decided to use the sentence chunking effect to study binding, comparing the immediate recall of sequences of unrelated words with recall of material that was presented in meaningful sentence form. One problem with this approach is the very large difference in span for these two types of material, approximately 5 versus 15 words. Making comparisons between material as divergent in length as this seemed to present serious methodological problems. We therefore set about trying to devise a method of limiting the advantage to be gained from sententiality, by trying to minimise the contribution of long-term memory. We did this by repeatedly using a small set of words to generate a set of simple active declarative sentences. We assumed that the repeated use of the same words in different combinations across sentences, would potentially produce substantial proactive interference from

prior use of those words, emphasising the need to focus each time on the new and most recent binding. This proved to be the case, with the result that our new constrained memory span was about seven to eight words, around two words longer than that random sequences of the same items. We confirmed this in another study in which we compared immediate memory for scrambled words, constrained sentences, and sentences taken from newspaper stories. As expected, more words were remembered from the newspapers than constrained sentences, which in turn led to better recall than of random word lists. In the case of both the constrained and news sentences, the advantage reflected better recall of order information.

We went on to study the role of the various components of our working memory model, again using a concurrent task procedure (Baddeley, Hitch & Allen, 2009). Our results were consistent across a number of studies, of which only one will be described. In this study we used the N-back method, as a basis for creating concurrent tasks with participants responding either to a digit sequence, providing a verbal interference task, or to locations within a matrix as a visuo-spatial equivalent. In one condition which we termed 0-back, participants pressed a button corresponding to the digit or location items that were identical to that immediately preceding it. We assumed that this would occupy the sketchpad or phonological loop, but put would minimal demands on the central executive. We contrasted these with the requirement to detect a match between the item presented earlier, either 1-back or 2-back; the longer the lag the greater the demand placed on the central executive (Owen, McMillan, Laird & Bullmore, 2005).

Our results are shown in Figure 4, which, although apparently rather complex, can be summarised relatively simply:

1. All four tasks had a significant impact on performance.
2. Verbal tasks had a greater effect than visuo-spatial, suggesting the involvement of the phonological loop.
3. The 0-back performance was substantially higher than 2-back, implicating the central executive, and crucially
4. There was no interaction between load and the type of sentence. The concurrent tasks had just as big an effect on recall of unrelated words as they did on sentences.
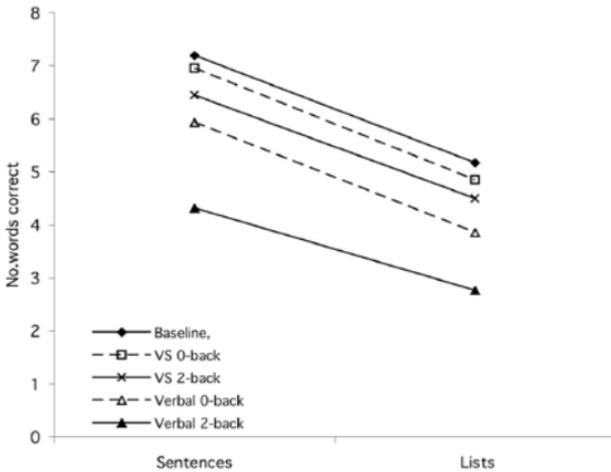
Figure 4
Mean recall of word sequences as a function of concurrent task.
Sentences are better recalled than random sequences, but this does not interact
with concurrent task (Data from Baddeley et al., 2009)

Once again we appear therefore to have found clear effects of concurrent working memory tasks on overall performance. In contrast to our visual binding studies, articulatory suppression has a much more substantial effect than does its visual equivalent, while the demand for concurrent phonological and executive processing proves particularly disruptive. However, as in the case of visual working memory, there is no interaction between the effects of any of the disruptive concurrent tasks and binding; they disrupt sentence recall just as much as recall of random sequences. Again therefore, we have no evidence for a major role of working memory in binding.

Implications

We found no evidence that binding per se depends on working memory for either visual or verbal materials. Interpreting negative results is of course, always problematic. Could it be that our experiments were simply lacking in power? If this were the case, we might expect to repeatedly find trends of marginal significance in favour of an interaction. This was simply not the case. Furthermore, it was not the case that our experiments failed to show effects; our concurrent tasks consistently impaired overall performance, with a pattern of deficits that is precisely that to be expected from the working memory literature, namely a substantial impact of executive disruption, with articulatory suppression disrupting the verbal but not the visual task, and

concurrent visual processing having a minimal effect on verbal recall, and a more substantial one on visual STM.

In the face of this substantial body of evidence, we abandoned our original idea of the episodic buffer as a system that <u>actively</u> binds information into chunks. Instead we propose that it acts as a passive store that is capable of holding multidimensional representations that are created elsewhere within the cognitive system. It seems likely that the source of bound chunks will vary depending on the material and the type of binding. Hence, the binding of features into perceived objects, of objects into arrays and of arrays into structured patterns presumably operates within the perceptual system, which in turn will drawn upon LTM in parsing these into meaningful scenes. In the case of verbal material, it seems likely that relatively low level prosodic processing systems will be involved in utilising pauses, while more complex syntactic and semantic factors are likely to contribute to the enhanced recall of sentences, or of the gist of longer passages.

Conclusions

Our current view of the episodic buffer is therefore that it operates as a multidimensional but essentially passive store, analogous to the screen of a computer, capable of holding a limited number of chunks, which are then available to conscious awareness. We assume that it can be fed from the sub-systems of working memory, from LTM or through perception. Although not the all-powerful processor I originally envisaged, it none-less provides a crucial link between the purely attentional central executive, and the rich array of multidimensional information that is necessary for the operation of working memory.

Does the episodic buffer depend upon a single anatomical structure, for example the hippocampus? This seems unlikely since a patient with substantial impairment to the structure and function of his hippocampus has proved to be absolutely normal in his capacity for binding (Baddeley, Allen & Vargha-Khadem, 2010) and in his complex working memory performance (Baddeley, Jarrold & Vargha-Khadem, in preparation). Clearly, the episodic buffer remains a somewhat shadowy concept, as indeed did the original multicomponent working memory model. I would argue however, that it has already proved itself theoretically useful and empirically productive in helping understand the crucially importance processes involved in the binding of more basic features into complex chunks.

References

Allen, R., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General, 135*, 298-313.

Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology, 49A*(1), 5-28.

Baddeley, A. D., Allen, R. J., & Vargha-Khadem, F. (2010). Is the hippocampus necessary for visual and verbal binding in working memory? *Neuropsychologia, 48*, 1089-1095.

Baddeley, A. D., Emslie, H., Kolodny, J., & Duncan, J. (1998). Random generation and the executive control of working memory. *Quarterly Journal of Experimental Psychology, 51A*(4), 819-852.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. A. Bower (Ed.), *Recent Advances in Learning and Motivation* (Vol. 8, pp. 47-89). New York: Academic Press.

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2009). Working memory and binding in sentence recall. *Journal of Memory & Language, 61*, 438-456.

Baddeley, A. D., Jarrold, C., & Vargha-Khadem, F. (in preparation). Working memory and the hippocampus.

Baddeley, A. D., & Wilson, B. A. (2002). Prose recall and amnesia: Implications for the structure of working memory. *Neuropsychologia, 40*, 1737-1743.

Brener, R. (1940). An experimental investigation of memory span. *Journal of Experimental Psychology, 26*, 467-483.

Cowan, N. (2005). *Working memory capacity.* Hove: Psychology Press.

Craik, F. I. M., Govoni, R., Naveh Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology - General, 125*(2), 159-180.

Crick, F. (1988). *What mad pursuit: Personal view of scientific discovery.* New York: Basic Books.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behaviour, 19*, 450-466.

De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (1999). The contribution of working memory resources in the verification of simple mental arithmetic sums. *Psychological Research, 62*, 72-77.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The Psychology of Learning and Motivation.* (Vol. 44, pp. 145-199). New York: Elsevier.

Feuerabend, P. (1991) *Three dialogues on knowledge.* Oxford: Blackwell.

Gooding, P. A., Isaac, C. L., & Mayes, A. R. (2005). Prose recall and amnesia: More implications for the episodic buffer. *Neuropsychologia, 43*, 583-587.

Karlson, P., Allen, R. J., Baddeley, A. D., & Hitch, G. J. (in press). Binding across space and time in visual working memory. *Memory and Cognition.*

L'Hermite, F. (1983). "Utilisation behaviour" and its relation to lesions of the frontal lobes. *Brain, 106*, 237-255.

Logie, R. H. (1995). Visuo-spatial working memory. Hove: Lawrence Erlbaum Associates.

Logie, R. H., Della Sala, S., Wynn, V., & Baddeley, A. D. (2000). Visual similarity effects in immediate verbal serial recall. *Q J Exp Psychol A, 53*(3), 626-646.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*, 279-281.

Luria, A. R. (1959). The directive function of speech in development and dissolution, Part I. *Word, 15*, 341-352.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*, 81-97.

Miyake, A., & Shah, P. (Eds.). (1999). *Models of working memory: Mechanisms of active maintenance and executive control.* New York: Cambridge University Press.

Naveh-Benjamin, M., Craik, F. I. M., & Peratta, J. (2000). The effects of divided attention on encoding and retrieval processes: the resiliency of retrieval processes. *Quarterly Journal of Experimental Psychology, 53*, 609-626..

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behaviour. In R. J. Davidson & G. E. Schwarts & D. Shapiro (Eds.), *Consciousness and self-regulation. Advances in research and theory* (Vol. 4, pp. 1-18). New York: Plenum Press.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception and Psychophysics, 16*, 283-290.

Phillips, W. A., & Baddeley, A. D. (1971). Reaction time and short-term visual memory. *Psychonomic Science, 22*, 73-74.

Pieroni, L., Rossi-Arnaud, C., & Baddeley, A. D. (in press) What can symmetry tell us about working memory? In A. Vandierendonck & A. Szmalec (Eds). *Spatial working memory.* Hove: Psychology Press.

Popper, K. (1959). *The Logic of Scientific Discovery.* London: Hutchison.

Rossi-Arnaud, C., Pieroni, L., & Baddeley, A. D. (2006). Symmetry and binding in visuo-spatial working memory. *Journal of Neuroscience, 139*, 393-400.

Rudner, M., Fransson, P., Ingvar, M., Nyberg, L., & Rönnberg, J. (2007). Neural representation of binding lexical signs and words in the episodic buffer of working memory. *Neuropsychologia, 45*, 2258-2276.

Rönnberg, J., Rudner, M., & Foo, C. (2010). The cognitive neuroscience of signed language: Applications to a working memory system for sign and speech. In L. Bäckman & L. Nyberg (Eds.), *Memory, aging and the brain: A festschrift in honour of Lars-Göran Nilsson* (pp. 265-286). London: Psychology Press.

Stuss, D. T., & Knight, R. T. (2002). *Principles of frontal lobe function.* Oxford: Oxford University Press.

Tulving, E., & Patkau, J. E. (1962). Concurrent effects of contextual constraint and word frequency on immediate recall and learning of verbal material. *Canadian Journal of Psychology, 16*, 83-95.

Ueno, T., Mate, J., Hitch, G. & Baddeley, A. (in preparation). Disruption of binding in visual working memory.

Ueno, T., Allen, R. J., Baddeley, A. D., Hitch, G. J., & Saito, S. (submitted). Disruption of visual feature binding in working memory.

Vandierendonck, A., & De Vooght, G. (1997). Working memory constraints on linear reasoning with spatial and temporal content. *Quarterly Journal of Experimental Psychology, 50A*, 803-820.

Vandierendonck, A., De Vooght, G., & Van der Goten, K. (1998). Interfering with the central executive by means of a random interval repetition task. *Quarterly Journal of Experimental Psychology, 51A*, 197-218.

Vandierendonck, A., Kemps, E., Fastame, M. C., & Szmalec, A. (2004). Working memory components of the Corsi blocks task. *British Journal of Psychology, 95*, 57-79.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27*(1), 92-114.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*, 48-64.