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Working Memory and its Relevance for Cognitive Development

John Towse

and

Nelson Cowan

"I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail" (Abraham Maslow, 1966, pp.15-16.)

In the present chapter, we attempt to cover three principal issues. First, we will introduce and discuss some of the key findings relevant to understanding models of working memory in children, including ideas of executive functioning. Second, we will attempt to provide evidence for our contention that relying on a single index of working memory – as often happens – may restrict the appreciation of important cognitive and developmental processes. This may be especially pertinent when considering how working memory relates to other developmental processes. Accordingly, we suggest new measures of working memory to complement those already in usage. Third, we will argue that it is important to be careful in thinking about the questions to be asked of working memory processes and we offer questions that may enrich our understanding of the area.

These three issues will serve as an illustration of the potential relevance of Maslow's remark above. There exists the threat that researchers have a single index (or a small number of indices) for working memory, and as a consequence are left to interpret psychological processes according to the particular perspective offered by that performance index. However, we also recognise that this situation is not immutable, and new perspectives on working memory are emerging. There are also other reasons for concluding that we could benefit from the opportunity to reflect upon where we have reached. For on the one hand, there is widespread recognition of the importance and relevance of working memory within cognitive and developmental psychology (see Miyake & Shah, 1999). And of course the adoption of the terminology and attention on the discipline is undoubtedly flattering. And yet, on the other hand, communications with an ever-wider audience brings with it the risk that conceptual ideas become simplified to the point where they no longer represent our level of understanding in a valid way. In reaching a wider audience (in essence, as research findings become 'corporatised'), messages can lose their important nuances, subtleties, and controversies. Nonetheless, here too there are reasons to be upbeat and positive about the outlook, and to hope that there can be successful application of theoretical ideas while retaining a measure of vibrancy in the debate about the interpretation of knowledge.

Section 1: Models of working memory

Background to Baddeley's model of working memory

The model of working memory has evolved considerably over time, gradually becoming more specific and elaborated. Initially at least, data served the role of characterising working memory, not testing the model against some sharply defined alternative. In other words, several ideas about working memory developed in the absence of a formally specified model. Nonetheless, Baddeley & Hitch (1974) laid important foundations for subsequent research. Their work successfully welded together a number of important concepts connected with immediate memory. Among these were, first, the realisation that immediate memory is fragile, and limited to a small number of independent items (Miller, 1956). The definition of items is necessarily elusive, insofar as they can vary according to the availability of conceptual or semantic representations that lead to coherence (maybe individual letters, maybe words with many more letters). Second was the notion that rehearsal of items can serve an important function in warding off the effects of forgetting, which can be pernicious and rapid (Brown, 1958; Peterson & Peterson, 1959). Such forgetting was originally thought of as reflecting time-based decay (but see, for example, Crowder, 1993). Third, it is apparent that verbal memory is influenced by the physical properties of verbal information, such as the confusions among the sounds of letters (Conrad, 1964). Fourth, a structural model of processes was envisaged, with a flow of information among the components of the system, most likely a conception influenced by Broadbent (1958, 1971).

Baddeley & Hitch (1974) were responsible for setting the stage for research that followed, and to a lesser extent interpreting existing findings. Moreover, their work was primarily influential in proposing a general framework, according to which memory was thought of as allied to and integrated with cognitive processing. They certainly distinguished between a central workspace and a dedicated verbal memory system, but beyond this, many details were left open. It was only with subsequent research that the specification of a multi-component system really emerged, later to be masterfully integrated into a coherent framework by Baddeley (1986). Thus, data from Baddeley, Thomson & Buchanan (1975) revealed that immediate serial recall of verbal information is closely tied to the real-time articulation of the memory stimuli. In particular, memory for words is inversely proportional to their length, so that sequences of short words are better remembered than equivalent sequences of long words. The phonological properties of verbal items have also been shown to be relevant, allowing the appreciation of the early finding that overlapping phonological codes (e.g., for the letters “b”, “c”, “e”, “p” etc.) disrupt memory performance (Baddeley, 1966). Baddeley, Lewis & Vallar (1984) confirmed the importance of verbal labelling in the translation of visual-based memory codes into verbal ones. They showed that articulatory suppression – the repeated utterance of some simple phrase – could eliminate the word length effect and the phonemic similarity effect for visually presented material. This was assumed to occur because suppression occupied and therefore blocked the rehearsal process that would otherwise be available for the recoding of information into a verbal form.

Figure 1 provides a simplified schematic account of Baddeley’s model of working memory. It proposes a multi-component architecture, in which there are two major slave systems, the phonological loop and the visuo-spatial sketch pad, together with a recently proposed third system, the integrative episodic buffer. All these systems are held to be under the control of the so-called central executive. The central executive is the hub of the system although the other components are important, and largely independent of each other. The phonological loop is a verbal-based system, which, it is proposed, comprises a relatively passive phonological store together with an articulatory control process. This phonological loop system is used to encode printed items as well as to refresh phonological representations in working memory to prevent them from becoming inactive. The visuo-spatial sketch pad holds, as one would expect, visual and spatial representations. At least according to some accounts these are thought to be separable (see Logie, 1995; Pearson, 2001) although, because stimuli will often contain elements of both visual and spatial information, a division between them is sometimes just a convenient research device concerning emphasis, rather than a phenomenological reality.

<Figure 1. Adaptation of Baddeley’s model of working memory from Baddeley (2000)>

Baddeley’s model: implications for development and executive skills

Although working memory was proposed as a theoretical account of adult memory performance, it has been fruitfully applied to a range of developmental issues. In several cases, research has shown that changes in memory among primary school children can be attributed to the strategies that children use. Verbal recoding of visually presented material (whether images or words) is not ubiquitous (see Halliday & Hitch, 1988). At around the age of eight years of age, children exhibit, with consistency, phenomena such as word length effects and phonological similarity effects even when material is presented in a non-verbal form. Convergent with these results, children below about seven years of age are susceptible to visual similarity effects in attempting to remember pictorial stimuli (Hitch, Woodin & Baker, 1989). They show confusions between items with visually overlapping features. This has been taken to suggest that their memory may be based on relatively untransformed visual representations of the initial stimuli. Exploring this last idea in more detail, Walker, Hitch, Dewhurst, Whiteley, & Brandimonte (1997) have compared memory for recently exposed images with longer-term memories for the same stimuli, investigating how attributes of the original material may be either duplicated in internal representations or may be transformed and abstracted.

Working memory has not just been used to expose some of the processes involved in qualitative shifts in memory. Quantitative changes have also been analysed. For example, just as the word length effect has demonstrated that verbal memory performance relates to pronunciation duration, developmental changes in articulation speed may form one component of improved memory (Hitch, Halliday & Littler, 1989). As will be discussed in more details later, research has also documented a relationship between memory ability and concurrent cognitive tasks (Case, Kurland & Goldberg, 1982), so that as these concurrent tasks become executed more efficiently though development, so memory improves to a corresponding degree.

Furthermore, it is apparent that memory performance is an intricate amalgam of both immediate and longer-term memory processes. Hulme, Maughan & Brown (1991) noted that recall performance for words is superior to that of (otherwise-matched) nonwords, with both types of memoranda sensitive to the syllabic length of the stimuli. They argued that words benefit from the availability of a redintegration process. This potentially allows the recovery of the target from a partially degraded representation (a target item may be uniquely identified even with only some of the original information) and involves the application of semantic knowledge to the memory representation. Since pronunciation time affected all items equally, the data imply that rehearsal speed is a factor independent from redintegration. The study also provides an illustration how some processes (redintegration) can make a detectable, qualitative difference to recall while others (word length) affect memory in a proportional way.

In work that shows some parallels with Hulme et al. (1991), Gathercole, Willis, Baddeley & Emslie (1994) have shown that children’s memory for non-words is sensitive to the ‘wordlikeness’ of the material, the overlap between the stimuli and familiar phonotactic representations in words (see also Thorn & Gathercole, 1999). Gathercole et al. have also shown that memory for nonwords varies across children and that this relates to vocabulary acquisition. The ability to retain unfamiliar phonological items (nonwords that are distinct from items in the lexicon) may be important for the acquisition of novel vocabulary, and may be one important function of the phonological loop of working memory.

Having provided some general background to some of the important research cornerstones in working memory, it is possible to turn some issues of executive control. Baddeley's model of working memory is interesting in the context of cognitive development, since it explicitly acknowledges the role of executive skills. Moreover, executive skills encompass a range of mechanisms for regulating thought and behaviour and these are potentially relevant to other themes in the book. For example, the central executive has been argued to take on functions of mental control, including inhibitory action. Thus, among adults, the executive has been argued to play an important role in shaping responses on a random generation task, where individuals try to inhibit prepotent or overlearned stereotypical responses (Baddeley, 1986; Baddeley et al., 1998). Also, the central executive is thought to have controlling powers that influence the flow of information (so that the slave systems are directed appropriately). Aspects of this control function resonate with some features within Zelazo's CCC model and in particular the developmental growth of reflexivity and informational access at different levels of consciousness (see Zelazo, this volume: Zelazo & Jacques, 1996). Furthermore, the central executive may be involved in the retention of information during a complex task as well as possessing a control function (Baddeley & Hitch, 1974, though see also Baddeley & Logie, 1999, for a shift in position; see also Daneman & Carpenter, 1980; Just and Carpenter, 1992).

Characterising the interrelationship between memory and ongoing mentation is important in and of itself. It is also relevant in the context of the present volume because there have been arguments, for example, that theory of mind tasks may impose non-trivial demands on children's ability to manipulate and remember critical aspects of an experimental situation (Gordon & Olson, 1998). Consider a false belief task, whereby a child is witness to a state of the world (a marble placed in a box) but is also exposed to another, different, interpretation (witnessing that a puppet had seen only an early state if the world, in which the marble was in a basket, and thus a different location). False belief questions probe the child's understanding of the puppet's knowledge. Therefore, the task requires that children acknowledge not only the real state of the world but also alternative beliefs based on different perspectives, where these alternate beliefs are tenable because of particular circumstances (such as whether another individual is able to witness a critical event).

As one considers the complexity of the situation, and number of different pieces of information that are potentially relevant to the false-belief task, it begins to look plausible that working memory constraints might affect false-belief computations. Children's ability to respond correctly to false belief questions may be dependent on their ability to hold in mind multiple, contradictory representations, as well as their ability to access these representations appropriately (inhibiting their knowledge of reality to uncover other's beliefs). As Gordon & Olson (1998) note, working memory may be an important support structure for theory of mind abilities, and not just for the expression of these abilities. While STM performance has not been a useful unique predictor of false belief (Jenkins & Astington, 1996), paradigms such as backward span (Davis & Pratt, 1995) and counting span (Keenan, Olson & Marini, 1998) are more strongly associated with false belief tasks. Gordon & Olson (1998) added to this view in reporting that false belief performance was related to a dual-task paradigm in which children needed to integrate two tasks and keep track of the point they had reached on each one. While it is not our intention to analyse these data in particular, we see these studies as offering a motivation for understanding what working memory involves, as a potential means for appreciating the constraints on other cognitive domains.

However, although the central executive is potentially relevant in different ways to cognitive development as we have just described, unfortunately the research field lacks unequivocal evidence that the central executive does all (or indeed *any*) of these functions in the way that has been proposed. That is, these functions have the status of candidate executive operations. In addition, the promiscuous way in which central executive has acquired functions is potentially a substantial problem. It may generate the illusion that different aspects of research refer to some common mental mechanism, whereas they may just share a verbal label (however, see Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000, for a body of evidence pointing to how executive functions may have both common and disparate elements). In the domain of working memory span (to be discussed in more detail later) one function ascribed to the executive is that it can act as a general-purpose system that shares resources between different requirements of the task. Counting span requires the participant to find the number of target objects in an array and remember this number during additional counts. The difficulty of the counting *component* of the task has been argued to determine the ability to *remember* the answers (Case et al. 1982). In this paradigm, the executive has a free-floating role in which two functions trade-off against each other, that is, they compete for and share the limited capacity system resources. A task such as random generation provides a substantial contrast (Baddeley, 1966; for performance among primary school children, see Towse & Mclachlan, 1999). Here, the executive is invoked as a mechanism by which unwanted responses (such as those that form stereotyped sequences, as in the string 1… 2… 3… 4 when generating random numbers) are inhibited or suppressed, and a mechanism by which new strategies for less predictable responses can be generated.

The number of executive roles is problematic, and this is compounded by their heterogeneity. It should be apparent that these mental processes, of resource-sharing in one situation and response inhibition in another, are very different. Other executive functions have been proposed and these are different again. To ask the executive to carry out both all the suggested functions is a substantial burden on this abstract system (for further discussion, see Towse & Houston-Price, 2001; Zoelch, Seitz, & Schumann-Hengsteler, this volume).

In summary, we have outlined some key aspects of Baddeley's model of working memory. What has been proposed is a multi-component architecture based on storage systems that are tied to particular domains and controlled by an executive system. Working memory components interact, yet they also have considerable independence. Verbal memory is heavily linked to articulation and rehearsal activities, although it is also clear that this is not the complete story. The development of working memory involves qualitative changes in the way that information is remembered as well as quantitative changes arising from the efficiency of rehearsal and speed-related processes. The executive system is a complex controlling device, which has been given responsibility for a variety of cognitive tasks. Given the degree to which memory representations are used in mental activities, working memory is an important contributor to many cognitive phenomena.

Background to Cowan's model: implications for development and executive skills

Cowan's model (e.g. Cowan, 1999) is inherently hierarchical in its structure. While it is the case that Baddeley (1986) outlined a two-layer system (with slave systems at one level and the central executive at another), Cowan's model has three levels, and the distinctions between them are even more marked. Long-term representations form one level of memory. Within this level lie a subset, which are referred to as activated LTM representations, thus forming a second level. These representations are in a more accessible state than the full set of memory representations. The focus of attention, a subset of activated representations, forms a further, third level of mental process. The model has developed from ideas presented by Cowan (1988), and is shown in Figure 2.

<Figure 2. Illustration of Cowan embedded process model of attention>

Baddeley (2000) has proposed an episodic buffer as a fourth component of his WM model. This brings the two models somewhat closer together, in that this episodic buffer sits between the two slave systems, being the place where modality-based representations are extracted and become integrated, and the central executive (which controls its operations). However, it is worth noting that the nature of the hierarchies is different; Cowan outlines a group of *mechanisms* that have a different grain size so that they are subsets or supersets of each other. They therefore form embedded processes. Hierarchies in Baddeley's model reflect instead a chain of command for quite separate processing *systems*, where the emphasis is on the cognitive architecture and its structural characteristics. So even though both models might be thought to have three levels, the way in which these levels are envisaged to relate to each other is quite different.

Cowan's (1999) vision of working memory is that it is a collective term referring to the set of mental processes that result in representations being available in an unusually accessible state. The level of accessibility is important in order that the representations can influence how any task with a mental component is carried out. Memories *per se* are not effective in shaping mental contents. It is only when these memories are accessible (through increased activation) that they can achieve this.

Furthermore, Cowan, Elliott & Saults (2002) noted that working memory is not just the activated portion of long-term memory (the second embedded level referred to above). This is because the set of activated representations are not just free-floating, independent, and unconnected. Features need to be bound together, and there needs to be some way to recover the temporal sequence in which events take place, and to mark other episodic information; for example, which elements were activated after others and so on. This additional (in one sense, contextual) information will also form part of working memory. Such bindings are thought to occur only when representations are in the focus of attention, and once established, the links rapidly become incorporated within long-term memory. Hence the emphasis here on the collective nature of the term working memory as a set of processes that, *in concert*, produce representations that are memorable and which can be used in other circumstances.

An important aspect of Cowan's model is that the focus of attention is quite limited. Cowan (2001) argued that the average capacity of the focus of attention for normal adults about four unconnected chunks. While this is in one sense a revision of Miller's 'magic number 7' (Miller,

1956) or minor adjustment of Broadbent's capacity estimate of 3 chunks (Broadbent, 1975), Cowan's analysis represents an attempt to consider the appropriate methods for evaluating capacity limits in immediate memory, and the legitimate interpretations from memory performance from a range of paradigms. Fundamentally, Cowan (2001) offers a critical analysis of whether previous claims of limited capacity are warranted, and concludes by endorsing this stance. This limited capacity may be rooted in the nature of memory representations. If the items in memory are represented by a set of features (Cowan 2001 considered pulsing feature detectors) then the degree of featural overlap increases as the number of chunks increases. Features will rapidly become confusable with each other as the number of independent items increases.

In summary, Cowan offers a model of memory that, like Baddeley's, emphasises the links between memory and attentional functioning. Cowan's model is hierarchical, comprising a set of embedded systems so that the focus of attention is a subset of active memory representations, itself a subset of long-term memory. The model postulates different constraints upon different faculties, not just in size but also in type; the focus of attention being capacity-limited and activation being time-limited and susceptible to interference. The model emphasises the multiple routes to developmental change, because the various constraints can be relaxed through biological and cognitive change.

Comparing models of working memory

It is important to recognise some of the obstacles in comparing the Baddeley and Cowan models of working memory, particularly from a developmental perspective. First, the two approaches have not received the same degree of empirical scrutiny. A far greater body of research has been built around Baddeley's framework, investigating the structural characteristics of the system components. Second, both models converge or concur in several important respects; thus they do not dispute the validity of several memory phenomena or suppositions. Unsurprisingly, perhaps, they are not entirely different, and as a consequence it is not possible to identify points of divergence in every situation. Third, it could be argued that the models are moving closer to each other, for example in the postulation of an episodic buffer for working memory (Baddeley, 2000), although see previous comments. Fourth, where these theoretical differences are sharpest (in describing the distinction between immediate and long-term memory representations) the models are more abstract, which decreases the scope for a simple experimental test to discriminate between them. Fifth, in neither case do these models stand or fall by developmental data alone. Sixth, as one turns to younger and younger children, both approaches become increasingly coy about making straightforward predictions, since the memory strategies that children have at their disposal are fewer and more primitive.

All these caveats notwithstanding, the two approaches can be separate in some respects. As already referred to, Baddeley's model is more modular in outlook. Each of the working memory slave systems operates largely independently of others. Thus verbal and visuo-spatial tasks can be combined much more easily than two tasks from the same domain (e.g., Baddeley, Grant, Wight & Thomson, 1975). Each component is thought to be neurologically distinct, and thus there is considerable autonomy amidst interacting systems. Cowan's approach is more cautious in considering the division of labour according to the type of memory involved (see Cowan, 1999). In part, this reflects a concern about representations that incorporate multiple sources of information (e.g., tactile sensory memories or acoustically-derived spatial codes). It also follows from the emphasis on memory processes rather than memory domain codes. This makes Baddeley's model particularly suited to explaining data from experiments where stimuli are created so as to have domain-specific properties.

From the perspective of cognitive development, Baddeley's model emphasises that working memory systems *per se* may not undergo major developmental changes, arguing instead that it is the way the systems are used (e.g. through increases in articulation rate, or translation between modalities of representation allowing a more appropriate memory code to be formed) that leads to older children performing better on memory tasks (see Hitch & Towse, 1995). In contrast, Cowan has suggested that acoustic information may be lost more rapidly in younger children (e.g. Cowan, Nugent, Elliott & Saults, 2000), and that the capacity of the focus of attention and the rate of transfer of information into that focus of attention also change with age (Cowan et al., 2002). Thus the rate of forgetting may differ across ages, and not just the rate at which memories are encoded. The models therefore differ in that Cowan makes more specific predictions about the nature of developmental change in memory *per se*.

Another point of divergence is that Cowan's model is more explicit in identifying multiple sources of change in processing efficiency. Thus, in Baddeley's model there has been an emphasis on articulation speed, as already discussed. While it has not been claimed that this is sufficient, and potentially the model could be elaborated so as to reflect the different ways in which developmental change takes place, Cowan has been more forthright in questioning the idea that a central, global processing rate is sufficient. For example, there may be separate processing rate parameters involved in memory search activities and in phonological processing operations, explaining why these predict independent sources of variance in children's memory performance (Cowan et al., 1998). We also noted that adopting a position whereby memory is affected by a variety of processing factors, helps to account for findings that are sometimes argued to pose problems for Baddeley's model of working memory. Thus, Kemps, De Rammelaere & Desmet (2000) noted that increases in visual memory ability could not be accounted for in terms of rehearsal speed or the phonological loop. Yet, as already indicated, this is troublesome only to the extent that these variables are the *only* relevant constraints on working memory. Of course, one needs a principled way of expanding the number of degrees of freedom through which memory can vary, lest there be an unmanageable proliferation of parameters. However, since the empirical data already offer evidence of two different speed-limited processes, and phenomena associated with each, this modification could hardly be regarded as being reckless.

It has already been noted that the models differ in terms of the extent to which they are hierarchical and modular. It has also been pointed out that Cowan's model is more process oriented, emphasising how activation of features of stimuli is important, indeed fundamental, for the memorability of stimuli. Placing activation at the forefront of the model provides a contrast to Baddeley's model wherein the core issues revolve around the appropriate laying down, refreshing, and decay of domain-specific memory traces.

To conclude, even though there are strong points of similarity, it is possible to distinguish the 'Baddeley' and 'Cowan' models of working memory in a number of ways. In general, we view the presence of alternative approaches to working memory as being very healthy (and there are others too; see Miyake & Shah, 1999) because it is through the contrasts that research can be focused in a productive way. It facilitates the appreciation of the benefits and drawbacks of looking at memory phenomena from particular vantage points and draws out different aspects of memory phenomena. These include a consideration of the number and the nature of developmental changes in working memory, the characteristics of memory systems themselves and the strategies adopted by children to preserve information for future recall.

A focus on working memory span tasks

The notion that working memory is limited in the number of things that can be remembered simultaneously, during ongoing processing, leads to the emphasis on tests of working memory that assess how many items can be remembered. The situation is akin to that of the juggler, whose reputation is built solely on the number of balls, or sticks, or knives and so on, that can be juggled simultaneously. In our fascination with the juggling, we seem to ignore whether there are other issues to be considered. Does our juggler have the ability to interact with an audience, to make them feel involved in what he or she is accomplishing, as they laugh, or gasp, or cheer at the performance? Does our juggler have the ability to develop a story as part of their juggling act, to change the tempo and potentially break up the monotony of just juggling? Indeed, does our juggler have any other tricks (up his sleeve or anywhere else)? As we begin to generate, or reflect upon, these and other questions, it becomes apparent that judging the quality of a juggler is more complex than it initially seems. And so it would seem with working memory. There are some fundamental attributes to working memory, and complex span tests clearly generate a reasonably stable, efficient and predictive score. Notwithstanding, there is more to working memory than just remembering in sequence a large set of unrelated words.

Our own work, in collaboration with others, illustrates this issue. We recently studied a group of children who were given several widely used tests of working memory. Among these tests was reading span, and we dwell on this task for a while in order to illuminate several empirical findings and theoretical conclusions. In the implementation of reading span that we used, children read aloud a series of incomplete sentences from a computer screen. They generated an appropriate word to complete the sentence before it was removed from view and the next sentence appeared. Thus, they might see "The rocket went into outer __" and they would be expected to say "space". After all the sentences in a series had been completed, children were cued to recall the completion words that they had produced, recapitulating the order of production. The provision by children of the expected completion word shows that they have, at least in broad terms, engaged in appropriate comprehension processes. Children began with sets of two sentences to read and therefore two words to remember. In those cases where children could remember all the target words on at least one of three attempts, the number of sentences in the series was increased (from two to three, from three to four, etc.) and the procedure continued. When children were unable to recall the words at a given length, testing stopped. Figure 3 provides a prototypical test scenario, in which a child remembers the target words from two of the three two-sentence lists, but fails to remember the target words from the three sentence trials.

The child makes a variety of recall errors, including failing to remember an item altogether, making serial order errors, and making item errors.

< Figure 3. An example testing protocol showing success and failure at reading span >

With such a procedure, one can estimate the reading span for a particular child, the highest sequence length for which the child can correctly remember the target words. Indeed, one can take different measures of memory performance. One can identify the point at which recall errors first appeared in the children's memory responses. Alternatively, one can note the point where the majority of the three recall attempts were unsuccessful. Alternatively still, it is possible to determine the point where none of the three recall efforts were successful. In each case, one can derive an estimate of memory ability, but according to different criteria. For the purposes of obtaining stable measurements, and simplifying the process of analysis, these three separate points along the forgetting function can be combined into an overall measure of memory recall.

It is worth noting at this point that a variety of research studies have confirmed that measures of reading span are good predictors of children's cognitive abilities, for example correlating with assessments of scholastic attainment (e.g., Hitch, Towse & Hutton, 2001) and measures of early reading development (e.g., Leather & Henry, 1994). Tests of working memory are superior to tests of short-term memory as predictors of a range of cognitive tasks (see Daneman & Carpenter, 1980). Since the working memory span task requires both language processing ability (in reading aloud, understanding the sentence, and generating a suitable completion) and memory (retaining the final word for later recall), it is not surprising that there is a popular argument that the task reflects the capacity to combine these two different mental functions of processing and retention. According to some influential views (Daneman & Carpenter, 1980; Daneman & Hannon, 2001), these mental functions are separate and play off or trade-off against each other and span reflects the residual ability to remember once processing has been accomplished. That is, working memory span represents a dual-task paradigm.

On the basis of several important studies over a number of years, Randy Engle and colleagues have concluded that working memory span is a critical window on the capacity to engage in controlled attention, and as an index of a domain-general skill that involves the maintenance of information in the face of interference (e.g. Engle, Tuholski Laughlin, & Conway, 1999; Kane & Engle, 2003). According to this position, WM = STM + controlled attention. Therefore, working memory and short-term memory partially overlap. At the same time, short-term memory tasks involve just the retention of information, while working memory tasks are constructed in such a way as to "present a secondary task to interfere with the primary retention task." (Kane & Engle, 2003).

Several aspects of their model are germane to the present discussion. They very much emphasise the domain-general nature of working memory capacity. So, while they acknowledge the impurity of particular tasks, and therefore recognise that performance must be made up of domain-specific processes also, they hold that the core, underlying construct of working memory involves a general ability. They also suggest that WM capacity may be substantially linked to general fluid intelligence. The working memory construct is quite closely allied to the idea of central executive in Baddeley's model. "Thus, when we use the term 'WM capacity'… we are really referring to the capability of the executive-attention component of the working memory system" (Kane & Engle, 2003, p. 638). It should be recognised that they argue that controlled attention is not wholly a function of the number of items being remembered, so that WM capacity may be strained by the maintenance of just a single item (for example, when interference is especially pernicious). However, their empirical work often involves a comparison of individuals who have been pre-screened into the upper and lower quartiles on an operation span test. Therefore, the groups differ in terms of their ability to remember items at the same time as they complete a sequence of arithmetic problem verifications. The notion of capacity as the ability to remember more or less items on working memory problems is woven into the fabric of their theoretical garments. Finally, it is clear that their approach to understanding working memory lies in an individual-difference approach. It is through the relationship between WM span on the one hand and complex cognitive skills on the other that the functioning of working memory is to be understood. This is something that we shall return to later.

Section 2: the multi-faceted nature of working memory in children

In this section, we analyse further the idea of the working memory span paradigm as a dual-task situation, in which performance is determined by the ability to share mental resources between the memory and processing requirements. According to this view, attentional processes serve to preserve memory traces in an accessible state. However, at least in the case of primary school children, it is clear to us that there is more to the story. In particular, we wish to point to some of the additional phenomena that can influence how children perform working memory tasks. Paradoxically, it may be that because the memory and the processing activities take place at separate points in time, memory is at the mercy of the processing events. Therefore, in a reading span task, engaging in reading comprehension for a presented sentence leaves memory activity 'on hold'. When reading processing is slow, either because of some developmentally immature apparatus, weak strategies, or experimentally-imposed delays, then memory representations are left to wither for longer. This results in lower estimates of working memory, whether for younger children, for poorer readers, or for participants completing more time-consuming experimental conditions.

One source of experimental data that is consistent with this perspective on working memory tasks is that there are strong correlations between estimates of children's working memory span and the duration required to complete the processing phase of the task (Towse et al., 1998). We have also reported that this relationship is not true in the same way for adults, in that processing rate for this population is not a reliable determinant of span (Towse, Hitch, & Hutton, 2000; see also Engle, Cantor & Carullo, 1992). Therefore, restricting the scope to children between 8 and 11 years of age, where data have been collected, we can note that statistically controlling for individual differences in children's processing (in reading times) attenuates the relationship between working memory span and external ability measures. It is certainly worth adding the further caveat that partialling out processing time does not account for all of the variance between working memory and cognitive abilities such as reading and number skills (Hitch et al., 2001). However, controlling for processing time may attenuate this relationship to the point where working memory span is no more predictive of ability than short-term memory span (Hutton & Towse, 2001). That is, it may go *some way* to explaining the special status of working memory span tasks in children, so that *WM=STM + controlled attention* can be simplified to *WM=STM + variation in skill at processing*. While other studies appear to show that working memory tasks are better predictors than short-term memory tasks of children's scholastic abilities (e.g., Leather & Henry, 1994), there are few studies we are aware of that have fully taken account of the modulating effect that the processing task has on working memory. Therefore, this remains an important issue for further investigation, particularly in the light of differences we have referred to between children and adults.

We argue that it is feasible to conclude, therefore, that working memory capacity is driven by more than just the ability to combine mental resources for some cognitive task alongside memory operations. In other words, working memory capacity in children is not singly determined by resource-sharing ability. (Similarly, it is not necessarily the case that *WM=STM + controlled attention*, unless the latter parameter is defined so broadly as to risk being over-inclusive.) Indeed, the notion that working memory is the umbrella term for a series of embedded processes (Cowan, 1999) serves to illustrate how one might ask whether there should be such a sharp divide between the two aspects of the working memory span task, the processing and the memory. For memories, as a set of highly activated representations, are memories because of the processing operations that have taken place. Thus the processing may become part of the memory trace itself, and not just play the role of a secondary task.

To return to the study at hand, we investigated whether there might be yet further attributes relevant to working memory performance. To do so, we examined not only the quality of memory recall responses, but also the timing of the successful response sequences. For every correctly recalled response sequence, we measured the preparatory interval (the initial pause before the child began to respond), word durations (the time taken to articulate the words in recall) and the inter-word intervals (the temporal gaps between each response). Thus, rather than respond to the multifaceted nature of working memory by collecting data from multiple tasks, we sought to collect multiple measures of processing from a particular task of interest, giving prominence to different measures of response timing.

A body of research has established some important phenomena associated with response timing in short-term memory tasks, when individuals have been asked to remember sequences of digits and words. It is clear that recall response times are coherent measures, in that they can vary systematically in particular circumstances, and in general performance is interpretable within a theoretical framework, with several notable characteristics. First, response durations change significantly over development; children become quicker to say the response words, the preparatory interval declines, and they pause for shorter amounts of time between each word (Cowan et al., 1998). Second, however, what differentiates children who have higher spans from their peers with lower spans are the pauses and the word durations, not the preparatory intervals. Third, when children are given more stimuli to remember, the inter-word pauses increase but the preparatory intervals do not (Cowan et al., 1998). Fourth, when the articulation duration of the stimuli are increased (e.g. using multisyllabic rather than monosyllabic words) the inter-word pauses do not increase (Cowan et al. 1998), which contrasts with the robust and widely-cited phenomenon that memory performance itself declines as a function of word length (Baddeley, Thomson & Buchanan, 1975; see also Cowan, Nugent, Elliott & Geer, 2000). Fifth, individual differences in pauses during recall offer a significant predictor of memory performance that is distinguishable from overall speed of processing functions. Cowan et al. (1998) found that both inter-word pauses and estimates of speeded articulation correlated with span, but did not correlate with each other. Sixth, while it is the case that children with superior memory span recall items more quickly for equivalent sequences, overall recall length at the maximal span level is longer for children who have higher spans (Tehan & Lalor, 2000).

Therefore it is apparent that for studies of short-term memory, analysis of recall timing delivers a variety of potentially important phenomena, permitting quite detailed inferences about memory processes. Cowan et al. (1998) have argued that inter-word pauses provide an index of memory search and recovery operations during recall. These operations incorporate representations from all list items. Yet, given that pauses do not increase as word length increases, the search process does not rely on verbal rehearsal in any straightforward way. Furthermore, a variety of analyses indicate that pauses reflect processes that are separate from the preparatory interval, since these two variables often show different patterns of sensitivity. Although it has been argued that forgetting of memory items can occur during recall (Cowan et al., 1992), in the context of response timing there does not seem to be a fixed temporal window of opportunity, within which responses must occur, and beyond which errors are inevitable. This conclusion is based on the finding that participants differ in the length of overall response durations at their maximal level. Evidently, the strategy for accessing internal representations is relevant. Further, insofar as pause measures are correlated with span and independent of other speed measures, we can deduce that pause measures do not just reflect some global speed of processing variable (Kail & Salthouse, 1994). Finally, the developmental changes in (different) response timing processes underline the multi-faceted nature of cognitive development.

There are two important gaps in our knowledge of response timing that we sought to address through empirical study. First, we examined the relevance of response timing for working memory paradigms, as opposed to short-term memory paradigms. It is apparent from the arguments articulated earlier that working memory and short-term memory are distinguishable (in methodology and in predictive prowess), and it is possible that, as a consequence, response timing exhibits quite a different profile in working span tasks. Second, we evaluated the extent to which phases of the response were related to external cognitive abilities, in particular scholastic skills. An important driving force behind the interest in working memory measures, as we have already seen, is the powerful and reliable correlations between working memory and cognitive ability. Is it the case that the patterns of recall contribute to the predictive power of working memory tests?

To this end, across two experiments, children and adults were given a reading span test, a counting span test (in which an array was counted with this cardinal value being remembered) and a listening span test (participants listened to a sentence and decided whether it was true or not, and remembered the last word in the sentence). Various measures of ability were collected. These included reading and numerical skills attainment and high school grade percentiles (for counting span and listening span). It is also relevant to note that counting span and listening span were assessed alongside digit span. This provided a control task so that working memory performance could be compared directly with short-term memory performance, and performance verified against findings in the existing literature.

One of the most striking aspects of the results was the length of the response pauses in the case of reading span and listening span. While the response durations of *words* was comparable to measures obtained from previous studies involving STM tasks – important in showing that children were not globally slower – the preparatory intervals and even more so, the inter-word pauses, were much slower. While previous research might suggest (for children around the age of 8 years of age) preparatory intervals lasting about 0.6 s and pause durations of approximately 0.2 s (values corroborated by digit span data in Cowan et al., 2003), the preparatory intervals in reading span were over 3 seconds, and the pause durations over 2 seconds. This can also be observed from the overall response durations shown in Figure 4. Children were clearly doing something very different with reading span and listening span compared with digit span tasks, or counting span tasks (where pauses were more alike digit span, though still longer).

<Figure 4. Mean duration (in seconds) of recall within correct responses at each group to two item lists in Experiment 2 of Cowan et al., 2003.>

Despite difference in the absolute lengths of the response duration segments, in general the pattern of performance matched previous findings. This can be illustrated by the differences in response duration according to recall abilities. Children with better memories recalled items more quickly, though they took longer to recall their answers at the terminal level. Children did not all operate within a constant window of recall opportunity. Sensitivity to list length was also examined, and the first and second inter-word pauses were equivalent, showing no sharp gain in moving towards the end of the list.

In several different ways, the data reinforce our view that there is great value in multiple measures of working memory. Response timing measures help to reach a number of conclusions. We would argue, on the basis of the results just described, that there can be important differences between working memory tasks, with the data helping to throw new light on how working memory tasks function. The differences challenge some claims that working memory measures are fundamentally alike (e.g. Turner & Engle, 1989) because they all involve a combination of concurrent mental operations and memory. In the present data, the overall response times in reading span and listening span were substantially different from those of counting span (and digit span). Basically, participants were taking far longer to recall the memory items when the processing element involved the comprehension of linguistic material rather than numerical calculations. Our interpretation of these data is that in tasks like reading span and listening span, participants have representations that are not just about the target word itself, but also about the processing event that generated it. This rich memory means that participants have other words (from the sentence) to think about and reject, and also have the potential to use these words as cues to the target item itself. This makes the memory search process more protracted. In the counting span test, the processing operations have considerable overlap, involving in each case the enumeration of target objects always beginning with the same sequence (counting up from "1"). There is little in the way of distinctive information in the processing that can contribute towards the identification of the memory items, making memory recall much quicker. Likewise, in digit span, there is no accompanying contextual information to the presentation of the numerical memory items.

We also note that other empirical data are consistent with the view that working memory tests may be distinguishable. For example, Hitch et al. (2001) noted that, for the children they studied, while both reading span and operation span correlated with the rate of completing the processing requirements, the form of that relationship was different. Operation span changed with numerical processing speed more than reading span changed with reading speed. One explanation for this finding is that representations of the sentences provided support for the memory items, making the rate of forgetting slower than found for operation span, where arithmetic formed the processing event. This of course fits very well with the interpretation just outlined.

Further evidence to distinguish working memory span tests in the way outlined has been reported by Copeland and Radvansky (2001). They reported that, among adults, a reading span task was accompanied by a reverse phonemic similarity effect (so that lists of rhyming items were remembered *better* than lists of non-rhyming items), while an operation span test followed by equivalent memory words, because a word followed each sum, produced the conventional similarity effect in which rhyming or overlapping phonological content hampered recall performance. Copeland and Radvansky suggested that their reading span task was influenced by semantic representations of the sentences. The processing events for reading span provided a scaffold around which recall can be attempted, and in such cases a phonological rhyme provides a helpful cue.

Moving on from a consideration of experimental analysis of response segments to individual differences in recall, of course it was a stated aim of the study to assess the commonality between response timing measures and cognitive abilities. For reading span, response timing measures correlated with standardised tests of reading and number skills and this was separable from the relationship between memory performance *per se* and cognitive ability. Furthermore, among older children, response timing measures across span tasks (listening span, counting span, and digit span) correlated with cognitive ability after controlling for span scores themselves. This offer further evidence that response time measures afford a different and distinctive insight into memory processes.

We would argue that working memory span tests are complex multi-faceted paradigms, and the predictive power of working memory span tests in children arises from the interplay between a series of cognitive processes. There is no single answer to the question, “What makes working memory special?” We have advocated above the conclusion that there are differences between working memory span tests. Our second conclusion is that there are different processes contributing to any one working memory task. Different and distinctive measures of working memory performance are available. The data do not challenge the view that the family of working memory tests share some important attributes, nor the view from some findings, that they may be comparable. Clearly, it remains the case that working memory tests generally predict complex cognitive skills. Instead, what the data challenge is the conclusion that because there are some points of comparability, they can be regarded as the same tests, or that they can always be measured by a global parameter. Some measures may be highly effective in capturing particular phenomena. Yet other measures may provide additional and complementary sources of evidence about the composition of working memory. We regard it as important to acknowledge both sides of this coin.

A further potential implication following on from these conclusions is that different theoretical models of working memory span performance may be applicable to particular instantiations of the task. Thus, accounts that focus on the importance of inhibiting irrelevant information when accessing target memoranda may be most suited to tasks like reading span. This is because here we have evidence that memory for processing events are used at the point of recall, and therefore may interfere. Models that propose controlled attention contributes to the task may have most to say about tasks in which the processing and memory events are more distinct. In operation span tasks in which an arithmetic operation is followed by a memory word, there is a greater element of dual-tasking (at one point encoding and transforming a sum, at another point encoding a word) and processes that facilitate the execution of independent operations may be germane. It is possible that task-switching models, emphasising the loss of memories during processing, captures a phenomena that cuts across span tasks (e.g., see Towse et al., 1998). Nonetheless, it is quite conceivable that it has a greater impact in some situations than others, such that slow processing is more damaging for operation span than reading span (Hitch et al., 2001). The exciting – and at the same time challenging – perspective is that different models of span may be explaining different aspects of a family of tasks.

We believe that the data warrant a third, more specific conclusion too. We feel that the data re-affirm how different aspects of response timing can usefully be differentiated. Preparatory intervals, the gap between the response cue and the start of the participants' recall sequence, are not the same as the intervals that occur between each word, and neither of these are just reflections of the word recall responses. Unsurprisingly, it remains an important challenge to fully articulate the set of processes involved at each phase of the response. Nonetheless, these data, along with others, fully warrant the attempt to specify what the various phases represent.

The empirical data, then, make a case for the utility of gathering different measures of working memory. This better allows the capture of a range of working memory skills and mechanisms. There is a methodological advantage to the use of different tests also. Different tests provide a useful source of converging evidence for conclusions that are appropriate with a particular data set. Because a working memory test, by design, is quite complex in structure, it can sometimes be difficult to identify precisely which aspect of any task is crucial is shaping the results. Different tests can help to isolate the relevant variables. In addition, if the processing event in working memory tests is manipulated, there are various ways in which this might be accomplished (e.g. Towse et al., 1998). Establishing the same pattern of results across different working memory tests allows stronger conclusions to be drawn, in that idiosyncratic effects of particular manipulations or particular characteristics of certain measures can be ruled out. For example, we can be fairly confident that the long preparatory intervals in reading span do not occur because children generated this memory item for themselves, because slow responses were also found in listening span, where children instead verified the semantic legitimacy of the presented material. As a second example, where Towse et al. (1998) manipulated the processing duration of the working memory trials, they inevitably resorted to different ways of lengthening the processing phase of counting arrays, arithmetic sums and incomplete sentences. It becomes harder to argue that findings represent artefacts of how the processing material was altered. In sum, with a complex task, there are advantages in collecting convergent evidence from different paradigms to make the conclusions more robust.

In this section, we have relied on empirical data from working memory span tests, to advance our view that there are several important attributes that contribute to recall performance. Working memory span is not just a function of some global memory ability. Rather, there are multiple processes, skills, traits, and possibly strategies that give rise to the characteristics of working memory span. Indeed, we have argued that it is oversimplified to regard all working memory span tasks as comparable; there are reasons to distinguish span tasks and to consider how differences between them might impact upon the way that children handle the task requirements. As part of our belief that multiple measures of working memory help to understand the task, we have also argued that the analysis of the duration of the various phases of recall offers an important set of evidence about working memory processes.

Section 3: asking the right questions about working memory

Drawing upon working memory theory for cognitive development

Research into memory development has been captivated by the attempt to explain a few salient research questions. In particular, the dominant agenda item has been "How much?" so that empirical research is directed at the attempt to identify memory capacity in children and chart its changes. Associated with this question is the issue of whether changes in memory performance – an increase in digit span or reading span for example – occurs because there is a growth in memory capacity, or because of the way a relatively fixed and invariant capacity is utilised (see, Case, 1985; Dempster, 1981; Kail, 1991; Pascual-Leone, 1970). This is a difficult question to address, and Cowan (2001) has argued that a variety of converging evidence is probably required for its resolution. There are different ways in which stimuli can be delivered so that participants have little opportunity to recode items, or chunk them into higher order units, which would of course give rise to the impression of capacity changes.

We fully recognise that measurement of memory capacity has played an important part in the collective understanding of memory, and that capacity constraints may be a fundamental memory characteristic. Much of the chapter thus far has framed questions about working memory in terms of how many items an individual can successfully retain in mind and produce at a relevant time. However, it need not follow from this stance that capacity constraints are the only characteristic of memory, that there is a single, catch-all variable that can explain memory phenomena. Indeed, we have already noted that estimates of response timing processes shows the multiple and partially independent components of memory performance. The model of working memory outlined by Cowan explicitly recognises the point that some aspects of the system may be capacity limited (in particular, the focus of attention) yet other aspects may be limited by different parameters (e.g. the level of activation).

Thus, we would argue that researchers who wish to incorporate aspects of working memory into their particular studies of cognitive development should be aware that the question, "How much?" is not the only one that can or should be asked of memory. There is a need to be sensitive to parallel questions. Other questions that may be pertinent include:

"How long?" It is important to consider the extent to which memories need to be kept in an active state for different durations. One would expect children to forget more information when they have to remember it for longer intervals (in the case of working memory span tasks, see Towse & Hitch, 1995; Towse et al., 1998). Potentially, one could look to various causal explanations for this phenomenon (in particular, degradation in the quality of representations in the absence of any sustaining process - so called time-based decay - or the influence of interference from competing memory traces). Yet, the phenomenon exists and is worthy of consideration regardless of how the details of it should be best explained. Data from Cowan et al. (2000) on the rate of forgetting of acoustic information could also be interpreted in this context.

“What tricks?” Cowan (2001) has shown that estimates of capacity (the how much question) vary according to the degree to which ancillary mnemonic processes are allowed to combine of chunk memory items into meaningful clusters. The example of ‘SF” (Ericsson, Chase & Faloon, 1980) is a good case study of an exceptional ability to recode a sequence into higher order units or chunks and therefore bypass the conventional limits on memory capacity. Yet, the phenomenon usually illustrates how one can *circumvent* memory limits, rather than substantially change them.

“What form?” This issue arises out of the premise that not all memories are created equal, and the modality of the memory representation can have an important influence on its characteristics. In fact, it is probably an oversimplification to see all memories as exclusively belonging to one modality, since in many cases there will be multiple codes, including forms of semantic coding. Nonetheless, the modality of presentation can be important as it forms the initial source of a representation. Similarity or overlap in the features that code for a memory are particularly important, such that phonological similarity is important (Baddeley, 1966), as is visual similarity (Hitch, Halliday, Schaafstal & Schraagen, 1988) and semantic similarity (Poirier & Saint-Aubin, 1995). In some cases, the direction of similarity effect can be reversed, so that similar items become well remembered (Copeland & Radvansky, 2001), which may arise because the rhyme can be used as a recall cue.

“From what?” Rather than ignoring the mental processes that give rise to the memoranda, it might well be fruitful to consider the source of the information being retained. These may be derived from processes that the participant engages in, or the items may be self-generated, which is known to affect the quality or durability of the memory representations (Slamecka & Graf, 1978). A further illustration of the issue at hand comes from the research described in detail earlier. Cowan et al (2003) have shown that response timing patterns are quite different for reading span and counting span tasks. Although these both represent working memory span tasks, the processing in the former case (sentence comprehension) produces a much richer and distinctive memory than the processing in the latter case (enumeration of object arrays). We have already referred to the argument that this can explain why responses are much slower for reading span than say counting span, with children having more elaborated memories and therefore more cues for recall when sentence comprehension forms a context.

"What cause"? Killeen (2001) provides an overview of Aristotle’s four “becauses”, noting the complementary nature of different causal accounts of psychological phenomena. *Formal causes* are abstract models or logical maps that explain behaviour, and much of this chapter, in considering different models of working memory, evaluate how satisfactory these are with respect to phenomena of interest. In considering the *Material causes* of developmental change and individual differences, that is the agent(s) responsible for an event, we would argue that there does not seem to be a logical reason why they must be the same. Moreover, the causal explanation could involve both biology and learning. And since there are multiple parameters that change with development, it may well be important to understand the dynamics and interactions among them. Some changes may be little more than epi-phenomenal, some may be *efficient causes* – the triggers for change – others may represent the developmental change itself.

Thus, it is possible that differences in the speed of cognitive processing produce working-memory differences. Yet, is it also possible that working memory differences produce speed differences (just as a computer with more memory may run a program faster)? Moreover, a basic difference in working memory at a young age could allow more able children to learn processing strategies and acquire knowledge more efficiently than less able children by a later age point. One reason to think of this as at least plausible is that a person might have to attend to several aspects of a stimulus array at the same time in order to bind them together in memory to form a new concept (see also Andrews & Halford, 2002, for a wider discussion). Clearly, understanding the direction of causality adds to the complexity of the task of discriminating between potential sources of developmental change in theory of mind, executive function and working memory.

Killeen (2001) also refers to the *final cause* of behaviour, i.e. its functional significance, and this is an issue taken up by Cowan (2001) in referring to the reasons why limited capacity may be important. Restrictions in working memory may help younger children to focus on the most germane aspects of the environment and to remember the immediate precursors of an event. As children's accumulate experiences and their mental world becomes enriched, so their growing working memory allows them to interpret events in a more sophisticated and complex way.

Working memory and executive skills

The issue of executive skills is important, indeed fundamental, to the current volume. Yet, despite this importance, its nature has remained elusive and controversial. In the case of working memory, it also takes on a promiscuous role, acquiring functions from a variety of paradigms, with seemingly little regard for how well or coherently these functions sit alongside each other (for more details, see Towse & Houston-Price, 2001). Thus in the domain of working memory span, which has formed a core component of the present chapter, one influential idea is that the executive can act as a general-purpose system that shares resources between different task requirements of 'processing' and 'storage'. Counting span requires the participant to find the number of target words in an array and remember this number during additional counts. The difficulty of the *counting* requirement has been argued to shape the ability to *remember* the answers (Case et al., 1982). In this paradigm, the executive has a free-floating role in which two functions trade off against each other, that is they compete for the limited capacity of the executive system. Engle et al. (1999) have set out a somewhat different view, according to which the executive is responsible for controlled attention, which means the maintenance of representations in an accessible state in the presence of interference. The processing requirements provide interference for memory items, and in this sense, the account preserves the notion of competition for mental resources between the two sub-tasks that make up working memory span.

Random generation has also been hailed as an executive task (e.g. Baddeley, 1966; for random generation data among primary school children, see Towse & Mclachlan, 1999; Zoelch et al., this volume). In this instance, the executive is invoked as a mechanism by which unwanted responses (e.g. those that form stereotyped sequences) are inhibited or suppressed, or a mechanism by which new strategies for less predictable responses can be generated (Baddeley et al., 1998). The control function in random generation is the selection of unconnected responses, which is made difficult by the very natural process of having associations between responses. In general, little mention is made of a direct role of memory representations, and instead the emphasis is on the management of internal associations between response alternatives and the selection of appropriate strategies for generating responses.

Leaving to one side a specification of how something like the central executive could carry out the range of tasks assigned to it, there are a number of indications that links exist at some level between working memory functioning, executive control processes, and atypical development such as autism. We have already noted the logical and empirical relationship between theory of mind and working memory (Gordon & Olson, 1998). It is also becoming apparent that working memory span tasks, while not synonymous with executive function tasks, do correlate with them, both in adults and in children (e.g., Lehto, 1996; Lehto, Juujarvi, Kooistra & Pulkkinen, 2003; Miyake et al., 2000). There is some preliminary evidence that autistic individuals generate random sequences differently from controls (Williams, Moss, Bradshaw, & Rinehart, 2002), and more generally, a body of evidence that is consistent with autism being connected to aberrant executive functioning (Russell, 1997; but see also Perner & Lang, 1999).

Nonetheless, a substantial research programme is required to specify the links between these different research domains in a more sophisticated and satisfactory way. Our collective understanding of a topic such a working memory *per se* has developed enormously over the past 30 years. Yet, it is apparent that we have much more to learn. Furthermore, attempts to examine the connections between working memory and other concepts have not always reflected the range of issues that could be argued to be important in understanding what working memory represents. Just as there is a need to ask a range of questions about working memory, we need to consider a variety of questions about executive functioning.

Conclusion

Working memory is a dynamic and evolving area of psychological research. It combines fundamental research into adults' performance, with developmental perspectives as well as applied studies. It is an area of quite intense study and not surprisingly, there are several controversies and uncertainties. While working memory research has not tackled issues to do with preschool children in any particular detail, nonetheless it is clear that developmental processes incorporate both qualitative and quantitative changes. Tasks involving working memory come in different shapes and guises. Some of these clearly incorporate elements of temporary retention of information, where the focus is very much on the number of independent memories that an individual can cope with. Other tasks focus more of the executive or control aspects of performance. This family of tasks reveal the complexity of working memory, and the utility of incorporating different measures into an assessment of performance, because working memory cannot be meaningfully rendered down to a single dimension. To take up Maslow's challenge, we need to ensure that we can resort to more than just a research hammer when we consider how to deal with the range of psychological issues that we would like to confront.

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Figure Captions

Figure 1. Adaptation of Baddeley's model of working memory from Baddeley (2000).

Figure 2. Illustration of Cowan embedded process model of attention.

Figure 3. An example testing protocol showing success and failure at reading span.

Figure 4. Mean duration (in seconds) of recall within correct responses at each group to two item lists in Experiment 2 of Cowan et al., 2003.

Figure 1

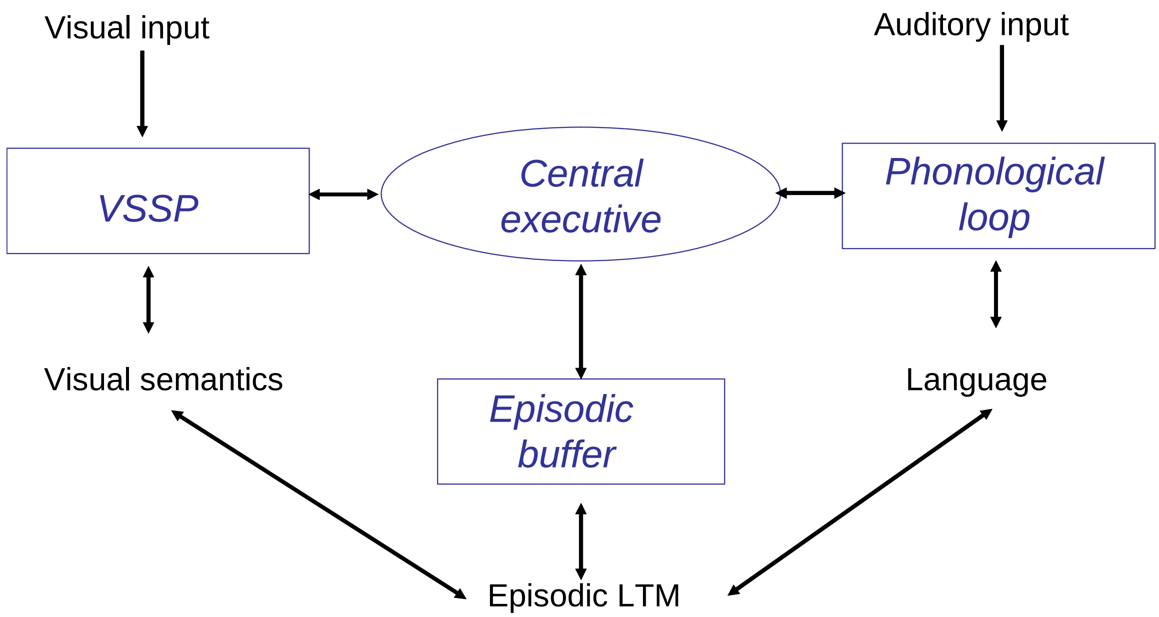

Visual input
Auditory input
VSSP
Central executive
Phonological loop
Visual semantics
Episodic buffer
Language
Episodic LTM

Figure 2

Cowan's model of working memory

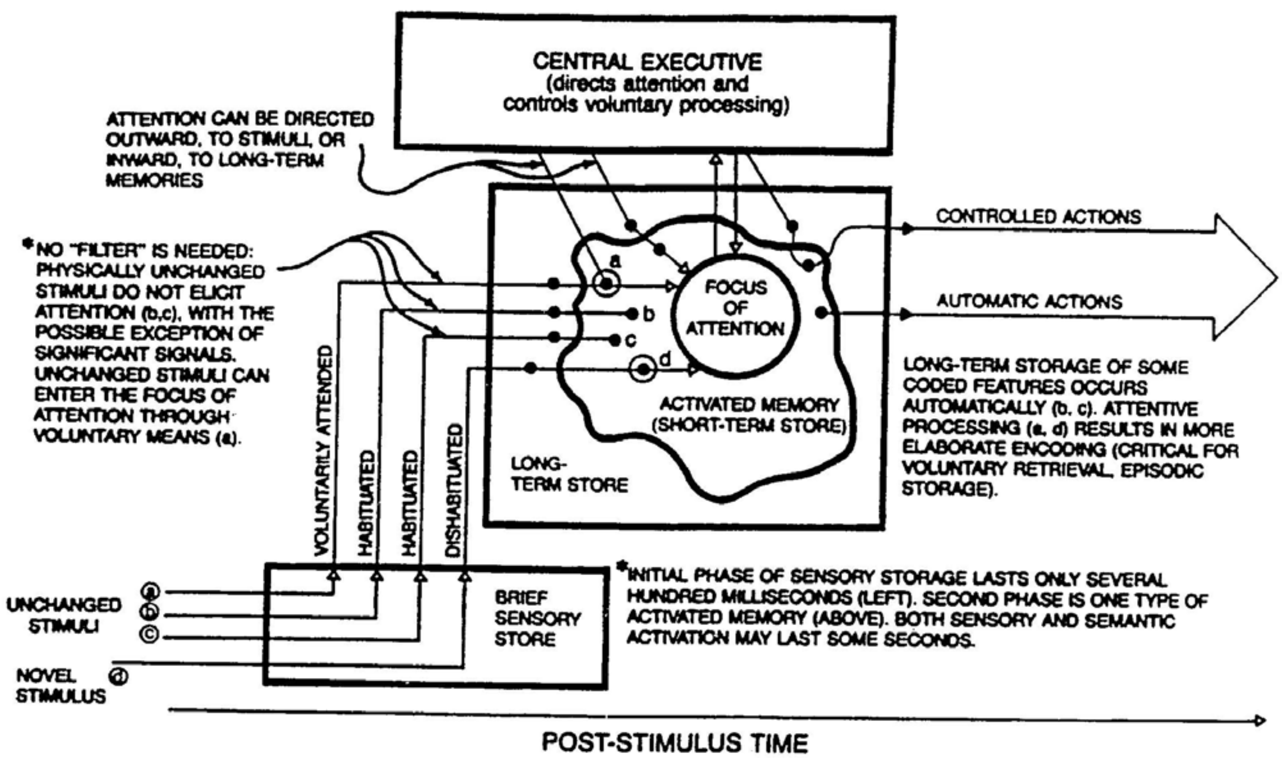
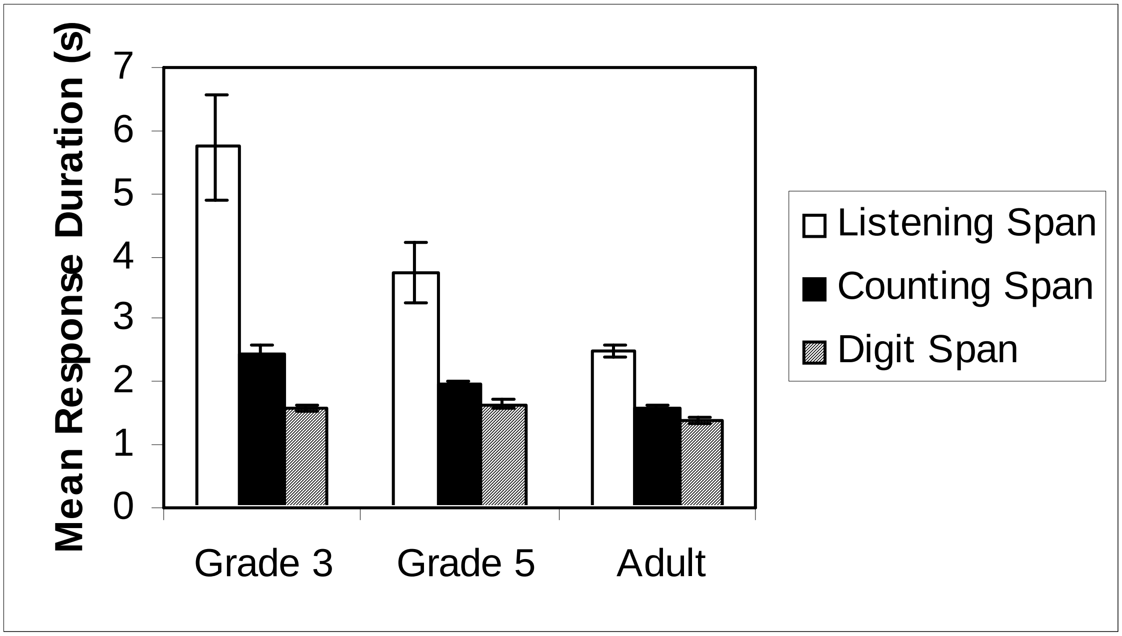


Figure 3

Sentence and response	**Recall attempt**	**Outcome**
There are twelve months in a ___ year I wear socks on my ___ feet	Year… feet	✓
Every day I wash and comb my ___ hair Ben ran fast and won the ___ race	Hair … fast	✗
The opposite of cold is ___ hot Cows eat the long green ___ grass	Hot … grass	✓
Food and water makes plants ___ grow Mary got home and unlocked the ___ door We see things with our ___ eyes	grow… ?…?	✗
The dog was happy and wagged his __ tail Mum and I read a story from a ___ book If I hear a joke it makes me ___ laugh	Book… laugh… tail	✗
At night I go to bed and fall ___ asleep The next number after four is ___ five Jane skips with a skipping ___ rope	Asleep… five… book	✗

Figure 4


Mean Response Duration (s)
7
6
5
4
3
2
1
0
Grade 3
Grade 5
Adult
Listening Span
Counting Span
Digit Span