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What Can Infants Tell Us About Working Memory Development?

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Despite my focus for the past 25 years on theoretical aspects of working memory and its development in adults and elementary-school children, my graduate training at the University of Wisconsin, 1974-1980, was in the infant speech perception laboratory of Philip A. Morse, often in collaboration with Lewis A. Leavitt. My graduate research began with questions about whether 4- and 5-month-old infants would show a right-ear advantage for the perception of spoken syllables, as adults do (e.g., Shankweiler & Studdert-Kennedy, 1967), and whether auditory backward recognition masking (Massaro, 1975) could be obtained in infants. However, slight differences in the stimulus arrangement turned out to make enormous differences in the measure of auditory discrimination being pioneered in the laboratory (heart rate deceleration to a change following 15 to 20 repetitions of a pre-change sound). Failure of several experiments using that type of measure was followed by the success of conceptually similar investigations with slightly different discrimination measures (Cowan, Suomi, & Morse, 1982; Glanville, Best, & Levenson, 1977). Several hundred infants wiser I drifted away from infant research, and return to it here with great admiration for exciting advances that have been made through persistent, intrepid work.

I will describe a theoretical framework based on adults, with which to view the chapters on infants; make tailored observations about each of the chapters individually; and, finally, integrate the points made to form a comparison of answers to the questions that the authors addressed.

<1> Working memory in adults as a backdrop for infant research

<2> A brief history of working memory research

Miller (1956) had famously suggested that an individual can remember sets of about 7 meaningful units or chunks, no matter whether the units were letters, digits, words, or character combinations (e.g., with the digit string 101-011 counting as only two chunks if 101 is mentally recoded as 5 and 011 as 3, according to a binary system). However, Baddeley, Thomson, and Buchanan (1975) showed that the exact number of verbal list items that could be recalled depended not only on the number of chunks in the list, but also on the spoken duration of the items. Lists of words that could be pronounced more quickly were recalled more successfully than lists of the same number of words that took longer to pronounce. Also, when individuals were asked to pronounce small sets of the words as quickly as possible, those who could pronounce the words faster also could remember more of them. In fact, the number of words a particular person could pronounce in about two seconds was a good predictor of the length of list, composed of those same words, that the individual could recall. This was explained with the notion that a phonological form of memory persisted for about two seconds unless the memory is refreshed through covert verbal rehearsal, which presumably occurs at about the same rate as speeded overt pronunciation (see Landauer, 1962). The faster the list could be rehearsed, the larger the number of list items that could be kept active until the time of recall, analogous to a juggling act in which balls are kept in the air and not allowed to hit the ground. After that, emphasis in the field of short-term memory shifted from a chunk limit to a time limit, although the concept of a chunk limit was still occasionally investigated in nonverbal domains (e.g., Chase & Simon, 1973; Gobet et al., 2001).

The notion of not only retaining items in short-term memory and then recalling them, but actually combining them for use in diverse types of complex cognition, was the likely basis of the term *working memory* that was used (perhaps coined) by Miller, Galanter, and Pribram (1960), and was later expanded upon and made popular by Baddeley and Hitch (1974) in their summary of research on conflicts between tasks.

Working memory limits must be viewed as a strength as well as a limitation. The ability to hold ideas in mind, combine them into new ideas, and manipulate them is an obvious and basic human strength. That it begins in infancy can be illustrated by the finding that infants build expectations about the re-emergence of a moving object that disappears behind an opaque obstruction (for a review see Baillargeon, 2004). That working memory has a small capacity seems to be a human limitation, although it is possible that we would be overwhelmed with too much information to process at once if working memory capacity were unlimited. In the following sections, I discuss the definition and description of working memory and then discuss questions regarding some of its basic properties relevant to infant research.

<2> A definition and a simple model

Miyake and Shah (1999) asked their chapter contributors to define working memory before presenting their own theoretical models of it. The definitions were strikingly different from one another. Some authors provided a general definition whereas others offered a more specific description, such as a multicomponent system for the storage and manipulation of information (Baddeley & Logie, 1999) or the use of controlled attention to hold and manage information (Engle, Tuholski, Laughlin, & Conway, 1999). My own definition (Cowan, 1999) was more general. I defined working memory as the collection of mental mechanisms that hold information in a temporarily accessible form that can be of use in cognitive tasks. That definition seemed appropriate because there are multiple mechanisms involved, and because we are not yet certain of all of the mechanisms.

Cowan (1988, 1995, 1999, 2005) described working memory in a manner illustrated in Figure 1. The memory system includes a subset of elements currently in a heightened state of neural activation or accessibility, making the corresponding ideas temporarily very easy to recall. A subset of those active elements is in the focus of attention, which also must include new associations between elements that occupy the focus concurrently. Incoming stimuli activate features in memory automatically, but primarily the physical features (color, shape, tone pitch, and so on). It is true that there is evidence apparently indicating that unattended items can be perceived on a semantic level without the benefit of attention; these include one's own name (Moray, 1959) or word pairs (Eich, 1984) spoken in an unattended auditory channel. However, later evidence suggests that these findings are better explained by the hypothesis that attention sometimes wanders and picks up information that was supposed to be unattended (Conway, Cowan, & Bunting, 2001; Wood, Stadler, & Cowan, 1997).

Within this processing system as conceived by Cowan (1988), activated memory is limited by temporal decay, whereas the focus of attention is limited by the number of chunks that can be held at once: about 4 chunks on average in adults (see Cowan, 2001). Also, both aspects of working memory are limited by vulnerability to types of interference (the replacement of the relevant active representations by other ones). These proposed limits require further discussion, as does the basis of individual differences.

<2> Do representations decay over time?

It seems natural to compare forgetting to some inevitable process such as, say, radioactive decay. We can assume that many neurons are involved in the representation of each idea in the brain. It seems reasonable that the representation could lose the involvement of some neurons or lose some precision of neural representation and become fuzzy or inexact. If a constant proportion of neurons representing an idea ceased its activity in each unit of time, the number of neurons remaining active in the representation would decay exponentially over time. Simple studies of short-term memory seem to reflect something like exponential decay over time; for example, this is the case in studies in which two tones are presented with a variable delay between them and the participant is to indicate whether the tones differ or not. The notion of short-term memory decay was popular in early theories of information processing (Broadbent, 1958; Brown, 1958, 1959; Peterson & Peterson, 1959) and that tradition was continued by Baddeley et al. (1975), and in Baddeley's following work.

Clearly, the concepts of delay effects and of temporal decay of memory are important topics brought up in Chapters 1 - 4 of the present volume. One simple hypothesis would be that neural activity representing an idea in working memory stays active longer in adults than in infants. However, it is not clear that anything like this simple, temporally-based form of memory decay that has been so popular has ever actually been observed, at any age. (This point reinforces a similar one made by Reznick in Chapter 4 of this volume.) The problem is that there are a number of other things that can happen over a retention interval to reduce memory: (1) As time goes on, the most recent item in a series of items represented in memory can become more blended in to previous items, and therefore more difficult to retrieve. An analogy is that the last telephone pole in a series seems very distinct from the other poles when you are standing close to the pole, but much less distinct as you continue down the road (cf. Crowder, 1993; Glenberg & Swanson, 1986; Neath & Surprenant, 2003; Nairne, 2002). (2) When the memory task is the comparison of two stimuli then, as the time between them increases, there can be the increasing problem of inappropriate grouping. It may become difficult to compare the two stimuli because the first one in the trial seems to be grouped together with stimuli from previous trials, and not with the second one from the current trial. (3) There can be interference from any stimuli that are used to prevent rehearsal during the retention interval. (4) Even if there are no interfering stimuli, there can be interference from ideas that the participant may think of during the retention interval, if attention wanders from the task at hand.

A variety of studies now suggest that what has looked like exponential decay is actually nothing of the sort. For example, Cowan, Saults, and Nugent (1997) re-examined the phenomenon of forgetting in a two-tone comparison situation. In order to deal with the grouping issue, we varied not only the time between tones to be compared, but also the time between trials. That way, we could examine trials in which the time between tones varied but with a constant ratio between that time and the time between the present trial and the previous one. We observed that memory performance stayed relatively constant from 0 through 6 seconds and then rather suddenly plunged downward by a 12-second inter-tone interval.

Lewandowsky, Duncan, and Brown (2004) presented letters for serial recall and varied the inter-response time allowed in recall, ranging between 400 and 1600 milliseconds. This was done with a silent keyboard response along with repetition of a word by the participant to prevent rehearsal, or it was done with spoken recall separated by repetitions of a word to prevent rehearsal. Contrary to what would be expected on the basis of memory decay, there was little or no effect of recall time on recall accuracy. Similarly, Cowan, Elliott et al. (2005) trained children to speed up their recall in a digit span task and, even though they successfully sped up quite a bit, there was no benefit for recall. Decay does not appear to be an important factor causing forgetting in working memory, according to the recent evidence. (For convergent evidence from event-related potential recordings see Winkler, Schröger, & Cowan, 2001.)

<2> Is attention used to store information?

According to the model of information processing shown in Figure 1, the focus of attention acts as a temporary information-storage device. In order to test this hypothesis, it is necessary to make a distinction between specific and general interference with memory. For example, consider memory for an array of visual items, as in the infant research described by Oakes et al. (Chapter 2 of this volume). If there were interference with this memory from another visual object, the origin of this specific interference would be unclear. It could be interference with visual memory in particular, or with a more general storage mechanism such as the focus of attention. However, if there were interference with this visual array memory from some type of stimulus that had little in common with it, with very different memory codes used in the two tasks, then this more general type of interference would lead to a clearer conclusion. It would indicate that attention is used to maintain the visual array, and also to carry out the interfering task.

Morey and Cowan (2004) carried out an experiment in this vein. Two arrays of colored squares were to be compared to determine if a probed (encircled) item in the second array had changed color from the first array or not. This task was modeled after Luck and Vogel (1997). However, between the arrays, participants carried out one of several tasks. In the critical condition, the participant was to recite a memory load of 7 random digits. This caused a substantial decrease in performance on the visual-array comparison task. In a control condition, the participant was to recite his or her own telephone number. This task requires verbal processing but not working memory, and it had little effect on array comparisons compared to no load. Therefore, it can be surmised that the memory faculty that both tasks need is neither visual nor phonological in nature, but something more general. We believe that it is attention that is shared between the array-comparison and digit-load tasks. Of course, we do not claim that there cannot also be attention-free components in the memory of visual or verbal information.

Despite findings such as those of Morey and Cowan (2004), it is still not clear just what attention does in working memory. It could actually store the information, as Figure 1 suggests. An alternative possibility, though, is that storage per se could be non-attentional in nature, but with attention needed to defend the stored information from interference. An example of that latter possibility exists, though it is not yet clear whether the example pertains to working memory. Cowan, Beschin, and Della Sala (2004) tested memory in six densely amnesic individuals (with brain injuries or strokes) and six normal control participants. On each trial, the participant heard a story and then repeated it back to the best of his or her ability. This was followed by a 1-hour delay that was either spent carrying out various psychometric tests or was spent in a quiet, dark room. After the delay, the participant was asked to repeat the story again. Amnesic patients (unlike control participants) recalled almost nothing from the story after an hour of psychometric testing. However, after an hour spent in a quiet, dark room, four of these six patients remembered about 80% of the information from the story. This was the case even on trials in which the participant fell asleep for part of the hour (as evidenced by loud snoring). The patients who benefited from the minimal-interference delay had non-temporal sites of brain lesions, whereas those who did not benefit had temporal sites. One account of the findings is that temporal lobe sites automatically hold information for an indefinite length of time, but only until there is corruption of the memory by interfering stimuli; whereas non-temporal sites that were damaged in the other patients ordinarily reflect the use of attention to defend the memory in the temporal lobe.

<2> Is there a capacity limit?

According to the model in Figure 1, the focus of attention is limited in adults, usually to somewhere between 3 to 5 independent chunks of information at one time. Actually, though, this is a difficult point to test with any certainty. One must show that there is a capacity limit, estimate that limit, and show that it depends on attention. Estimating the capacity limit is the most difficult part because one must make assumptions about what the meaningful units or chunks are, so that the chunks in working memory can be counted. Cowan (2001) considered a wide range of test situations in which it is presumably not possible to combine items into larger chunks, and found that performance is limited to about four items in such situations (each of which presumably constitutes a single-item chunk). For example, when lists of words to be recalled are presented along with an articulatory suppression task to block rehearsal and hence grouping, people recall about four items.

Grouping of items into multi-item chunks is difficult also in the visual array comparison task of Luck and Vogel (1997) that forms the basis of research described by Oakes et al. (this volume, Chapter 2), because the presentation is brief. In adults, the observed capacity is 3 to 4 items whether a cue is present or not. Given the dual-task results of Morey and Cowan (2004), it is very reasonable to hypothesize that this capacity limit is an attentional limit, though it could be that non-attentional processes contribute..

We have explored other ways to investigate capacity limits in adults and have found estimates similar to the limit that Cowan (2001) observed. Cowan, Chen, and Rouder (2004) taught participants pairs of words (e.g., desk - pin) and presented other words as singletons. Then we presented lists of 8 words formed from singletons or from learned pairs. With various levels of pairing knowledge, capacity was found to be fixed at about 3.5 chunks (singletons or pairs).

Chen and Cowan (2005) then elaborated on this work in an attempt to reconcile findings indicating the limit in recall is capacity-based (Miller, 1956) and findings indicating that the limit is time-based (Baddeley et al., 1975). Word pairs were taught to a criterion of 100% correct cued recall, and to 100% correct indication of the singleton status of other words. These words and word pairs were then used to form lists of varying length. We found that either a capacity limit or a time limit can occur, depending on the manner of testing and scoring. For long lists with free recall or free scoring of serial recall, a chunk limit seemed to apply. Participants recalled lists of 6 learned pairs at the same proportion correct as lists of 6 singletons, and much higher than lists of 12 singletons. However, for shorter lists with strict serial scoring, a time-related limit seemed to apply instead. Participants recalled lists of 4 learned pairs in serial recall only with a proportion correct equivalent to lists of 8 singletons, and much below lists of 4 singletons. We suggested that a capacity-limited mechanism holds the items, in keeping with Miller (1956) and Cowan (2001), but that a phonological rehearsal process greatly helps in the retention of the serial order, in keeping with most other recent work on list recall (see Baddeley, 1986).

There is a wide range of views on capacity limits, which Cowan (2005) summarized. What is interesting about this is that, in the first draft of the paper that eventually became Cowan (2001), some reviewers objected that the concept of capacity was not controversial enough to motivate the commentaries that accompany articles in the *Behavioral and Brain Sciences*. It is now clear that this is, indeed, a controversial topic, in terms of both the characterization of the capacity limit and the cause for it. Some researchers disagree on the number of items or chunks encompassed by the capacity limit, others believe instead in only a time limit, and others believe in a modality-specific limit or in no special working memory limit at all; just a single set of rules for all of memory. Length constraints prevent me from going into all of those different theoretical views.

In sum, the simple notion of decay probably should be replaced by a more nuanced notion of interference that can accrue as a function of time, with the amount of interference per unit of time greatly depending on the stimulus situation. The concept of a capacity limit measured in meaningful chunks seems sound despite difficulties in identifying chunks (for a review see Cowan, 2005). Attention is involved in that capacity limit, but it is still unclear whether attention holds information, or only defends storage against the loss of information through interference. Individual differences in working memory also could be discussed here but will be deferred to the next section, as they are part of the discussion of developmental changes during infancy and beyond.

<1> Development of working memory in infancy and beyond

As a backdrop to assess the chapters of the present volume, it is important to consider what infant research can and cannot tell us. It can tell us what abilities occur relatively early in life and therefore do not depend on an extended period of maturation or training. It can sometimes tell us which abilities co-occur and which ones are independent, and which inabilities put an infant at risk for later learning disabilities. Also, it can indicate which abilities change rapidly over the first year of life. It cannot easily tell us which aspects of ability are innate, given the far-reaching consequences of early experience, with the exception of research on newborns (and, even then, experience in the womb must be taken into account; see, for example, Morse & Cowan, 1982; Kolata, 1984). Most importantly, infant research cannot easily tell us about developmental trends from infancy to childhood, except insofar as a common procedure can be devised or a good case can be made for a fair comparison across the very different procedures typically used in infants versus children and adults. The question of what infants know always must be answered with the manner of testing kept in mind.

Each of the chapters on working memory in infancy focuses on an important section of the working memory landscape. The main themes of these chapters now are discussed within the theoretical framework that I have offered.

<2> Bell and Morasch's chapter

The chapter by Bell and Morasch was notable for its application to infants of leading views of working memory and its individual differences, and for building a methodological bridge between infants and children. I touch these topics in turn.

<3> Working memory structure and its individual variation

This chapter seems to adopt two of the major theoretical views of working memory of our time. One is the structural view of working memory proposed by Baddeley and colleagues (e.g., Baddeley & Logie, 1999; Baddeley, 2000, 2001). In this structural view, there are separate modules for the storage of spatial and verbal information (the phonological and visuospatial stores) as well as a recently-added module that stores links between elements of different types, the episodic buffer. All of them are regulated by central executive processes. The Bell and Morasch chapter also adopts the view about individual differences in working memory proposed by Engle and colleagues (e.g., Engle et al., 1999; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2002). According to this view, individual and developmental differences in working memory come from differences in the functioning of the frontal lobes, resulting in differences in the ability to control cognition. My own views are not far from these, but there are differences on both accounts.

One difference pertains to the evidence concerning separate visual and spatial modules (Baddeley, 1986). The evidence is not as stark as Bell and Morasch make out. They say that "verbal and spatial aspects of working memory are uncorrelated, with this functional independence true for children as well as adults," citing Gathercole, Pickering, Ambridge, and Wearing (2004). However, functional independence does not mean an absence of correlation. In structural equation models of performance in children aged 6-7, 8-9, 10-12, and 13-15 years observed by Gathercole et al., the path coefficients between the verbal and spatial memory factors were .41, .32, .33, and .35, respectively; moderate relations well above zero. Functional independence presumably means only that the model worked better with separate verbal and spatial memory factors than with the measures combined into one factor. It is true that a factor reflecting central executive processes was correlated with verbal and spatial memory factors at a much stronger level.

In my recent book (Cowan, 2005) and in older sources (going back to Cowan, 1988), I have explained why I do not favor a modular view but prefer the representation shown in Figure 1. My alternative account would state that any type of memory sustains the most interference from additional stimuli with similar features (e.g., verbal interference with verbal memoranda and spatial interference with spatial memoranda). I prefer this formulation because it allows for types of memory that Baddeley's (1986) formulation does not cover. For example, it is unclear in his model how tactile features would be processed, or how speech sounds coming from different spatial locations would be processed. For me, those are just stimuli that activate different physical and sometimes semantic features in memory.

The episodic buffer (Baddeley, 2000) lessens the distinction between our models inasmuch as new links between elements in memory (e.g., new associations between words) can be held in the episodic buffer in his model and in the focus of attention in my model. Another possibility for my model is that these new links can be formed in the focus of attention and then held for a while without effort, as activated memory.

I also doubt that the elegant view of Engle et al. (1999) completely captures the basis of individual differences in working memory. Instead of attributing these totally to differences in the control of attention, I have suggested that a broader function of attention is relevant (Cowan et al, 2005). When the task requires that a goal must be maintained despite prepotent stimuli that work against the goal, as in the A-not-B error that Bell discusses, then the focus of attention must *zoom in* to hold on to the goal with great intensity. In this case, the goal is to recall where the toy was hidden last and not to be swayed by the habit of reaching into one of the containers. This matches Engle's beliefs. However, when the task simply requires multiple elements to be held at once, the focus of attention must *zoom out*, up to the capacity limit, to allow the elements to be apprehended and held concurrently. An example is memory for visual arrays of objects, as discussed by Oakes (Chapter 3, this volume).

Presumably, the focus of attention cannot fully zoom in and zoom out at the same time. Preliminary evidence that multi-item memory and a goal-conflict situation interfere with one another was provided by Bunting and Cowan (2005). We showed that recall of words from a list matching a particular semantic category (e.g., different animal names) was diminished if the words in that category were printed in one color and the probe category word (e.g., the word "animals") was only occasionally printed in a different color, so as to cause a goal conflict.

Cowan et al. (2005) found that not every successful measure of working memory has to involve the control of attention. It is true that the typical working memory task used for children and adults requires alternate processing and storage of information. Thus, for example, in counting span tasks, a child must indicate how many objects are on each screen and then remember the sum, repeating all of the sums after several screens. That sort of storage-plus-processing task correlates very well with intelligence in adults; much better than does a simple digit span. However, Cowan et al. found just as good basic correlations using tasks that do not require combined storage and processing. This class of tasks was called "scope of attention" tasks because they were thought to index the number of separate items that could be quickly absorbed from a sensory memory into the focus of attention. One example is the visual array comparison task we have already discussed (e.g., Morey & Cowan, 2004), and another example is running memory span (Pollack, Johnson, & Knaff, 1959).

In our version of running span, a string of digits is presented at a rapid, 4-per-second rate. The list length ranges from 12 to 20 digits and the list ends unpredictably, after which the participant is to recall as many items as possible from the end of the list, in order (typically recalling the last 3 or 4). In that sort of task, it is impossible to use rehearsal or grouping (Hockey, 1973). Instead, the participant must listen passively and then, presumably, transfer items from the end of the list into a categorical form for recall.

Scope-of-attention tasks based on apprehending information from a stimulus field (e.g., visual array comparisons; running memory span) correlated with verbal and nonverbal intelligence subtests, high school grades, achievement tests, and other working memory tests about as well as did the storage-and-processing tests. So individual differences in working memory may not stem entirely from the control of attention in a goal maintenance state (zoomed in), but also in an apprehension state (zoomed out).

It is not clear that individual differences occur entirely in the frontal lobes. For the array comparison tasks, using an fMRI measure, Todd and Marois (2004) found individual differences in more posterior regions of the brain that are related to attention, but probably not to its control. Nevertheless, it is quite possible that individual differences in the scope of attention arise at least in part from frontal mechanisms controlling the scope of attention (making it zoom in and out as needed). Vogel, McCollough, and Machizawa (2005), using an event-related potential measure, found that individuals who could recall the most items in an array also were the ones who could do the best job of filtering out irrelevant items; these people could focus efficiently on the relevant items. Cowan, Fristoe, Elliott, Brunner, and Saults (in press) examined measures of both the scope of attention and the control of attention in children and adults, and found them to be partly related and partly independent. They are parts of a multifaceted attention system that varies a great deal among individuals and across ages.

<3> Working memory: A bridge between infants and children

One of the most difficult aspects of studying early development is that the same methods generally do not apply across age groups. In the thinking of Piaget (for a recent review, see Feldman, 2004), there was the notion of vertical décalage, in which the course of development repeats itself at different levels. For example, a baby displays the egocentrism of not remembering that its mother continues to exist when not present, and this egocentrism dissolves with infant maturation; but a young child may display the egocentrism of thinking that the sun exists only to provide light for people. Tied to this is the notion of horizontal décalage. An infant can demonstrate knowledge of the existence of hidden objects through eye movements, and later can do so through hand movements to retrieve the object.

If this description of development is apt, a difficulty for developmental researchers is that tests with different methods can look as if they yield contradictory results. For example, according to Figure 1 of the Bell and Morasch chapter (Chapter 1 of this volume), 5-month-old infants tested with looking outperform 7-month-old infants tested with reaching. How, then, is one to make fair comparisons between groups that had to be tested using different methods, such as infants and children?

Given this common problem, it is quite important when continuity can be found between testing methods in infants and young children. Bell and Morasch explained how the A-not-B method could be used in infants and children. They also explained a relation between baseline EEG power and working memory in infants, and it seems likely that this type of response also will be a valid, comparable indicator in children and adults.

There are still some important methodological details to ponder. Infants are distracted in order to avert their gaze from the testing apparatus during a retention interval in the A-not-B paradigm. However, distraction also introduces interference. It might be useful for infant experiments to be carried out systematically varying the nature of the stimuli used for distraction. For example, distractors could be visual, auditory, or tactile. Visual distraction introduces interference most similar to the visual displays to be remembered. Another possibility is to turn the lights off during the retention interval and back on at the time of test. There is no easy answer to this question of how to impose a distraction period in a valid way, but it seems important to remain aware of the issue.

<2> Chapters by Feigenson and by Oakes, Ross-Sheehy, and Luck

The issues involved in both of these chapters is the capacity of visual working memory, and the Oakes et al. chapter also considers the process of the binding of features to one another within the held objects. It seems helpful to consider these chapters jointly.

<3> Capacity and infant working memory

These two chapters (this volume, Chapters 2 and 3) show a very nice convergence of evidence suggesting that infants, by 10 months of age, can hold in working memory 3 or 4 objects. There is a slight discrepancy in that Feigenson shows a capacity of 4 objects only if the objects form larger groups (Chapter 2 of this volume, Figure 1), whereas Oakes et al. show a capacity of 4 haphazard, presumably ungrouped objects by infants of a comparable age (Chapter 3 of this volume, Figure 4). Another discrepancy comes into play if one considers that children in the lower elementary school years typically display a smaller capacity of only a little above 2 of these items, gradually rising with age to the 3+ items that adults recall on average (Cowan, Elliott et al., 2005), when tested on arrays of 4 items using an array-comparison procedure comparable to Luck and Vogel (1997).

These discrepancies make it clear that the various tests of capacity cannot be considered pure indications of capacity alone, which surely must increase monotonically during infancy and childhood. There are sometimes simple strategies or behaviors that can be used to work around the capacity limit, and there are sometimes impediments to performance other than capacity. For example, consider the infant procedure of Ross-Sheehy, Oakes, and Luck (2003) shown by Oakes et al. (Chapter 3 of this volume, Figure 2). Capacity is gauged by the detection of changes in the color of one object at a time within a 3-object display. However, imagine what would happen if an infant attended solely to one of those objects. There would be intermittent changes in that object, so it would not be necessary to focus on all of the objects in order to differentiate between a changing and a non-changing display. In practice, the infants' attention probably vacillates between the changing and non-changing arrays so a 1-item attention fixation seems unlikely. The actual capacity could be somewhere between 1 and 3 items, though.

In the array-comparison procedures applied to older children and adults (Cowan, Elliott et al., 2005; Cowan, Fristoe et al., in press; Luck & Vogel, 1997), it is possible that there is another limit in performance aside from capacity. It is possible that apprehension of all items in an array into working memory is attention-demanding and that this process sometimes fails in children because their attention wanders while an array is presented.

As was briefly mentioned above, evidence linking capacity to the control of attention in adults was provided recently by Vogel et al. (2005). They have obtained a lateralized component of event-related electrical potentials that increases as the size of the array to be remembered increases from 2 to 4 objects. This set-size-related increase correlates well with working memory capacity in the same task (Vogel & Machizawa, 2004). Critically, Vogel et al. (2005) presented a situation in which the relevant feature of bars to be remembered was their orientations, and in which only the bars presented in one color were to be remembered. They found that the brains of high-performing individuals responded to arrays that included 2 relevant (e.g., blue) and 2 irrelevant (e.g., red) bars in the same way as their brains responded to arrays containing 2 relevant and no irrelevant bars. In contrast, the brains of low-performing individuals responded to arrays of 2 relevant and 2 irrelevant bars in the same way as their brains responded to arrays containing *4* relevant and no irrelevant bars. So low-span individuals were unable to save working-memory space by excluding the irrelevant items.

Perhaps individuals of this sort have low spans for sets containing only relevant items at least partially because they are unable to adjust the focus of attention to the right breadth at the right time, or are in some other way unable to focus on the arrays efficiently. So the capacity estimates that Cowan, Elliott et al. (2005) obtained in children could underestimate their true maximal abilities. Indeed, Cowan et al. found that estimates of the *maximal* performance levels of children were closer to the 3 to 4 items usually observed as an adult mean.

There is recent neuroimaging evidence in adults from Xu and Chun (in press) on the distinction between the number of items apprehended in working memory (which may be relevant to Feigenson's procedures, described by her in Chapter 2 of this volume) and identification of those items (which may be relevant to the procedure of Ross-Sheehy et al., 2003, described by Oakes et al., Chapter 3 of this volume). One area of the posterior cortex (the inferior intraparietal sulcus) displayed increased neural activation as the number of items to be remembered increased, to a limit of 4 items. However, other areas of the posterior cortex (the superior intraparietal sulcus and the lateral occipital complex) displayed increased neural activation only up to the behavioral limit. This limit can be about 4 for simple objects, but substantially less than that for more complex objects. One account of the infant data as well as the data on older individuals is that the limit of about 4 objects changes little across ages from about 10 months of age onward, whereas the complexity-dependent processing limit changes much more with age.

<3> Binding and infant working memory

Another key issue that Oakes raised (Chapter 3 of this volume) was how infants learn to bind features together. For example, in an array-comparison procedure with colored objects, correct performance depends upon more than knowing which colors were present in an array; it depends on knowing whether a particular color appeared at a particular location (provided that the stimuli are designed to allow more than one instance of the same color in an array). A priori, many researchers have expected that holding binding information in working memory requires attention, because the perception of binding requires attention (Treisman & Gelade, 1980). However, the findings of studies with array-comparison procedures have indicated that dividing attention surprisingly does not impair performance any more when binding information is required than when it is not required (Allen, Baddeley, & Hitch, submitted; Cowan, Naveh-Benjamin, Kilb, & Saults, in press; Yeh, Yang, & Chiu, 2005).

Further explanation would help. Binding is needed to detect a change in the associations between items' features in an array (e.g., the correspondence between color and location) but binding is not needed to detect a change to some feature that was not present anywhere in the trial previously (e.g., a new color). Perhaps divided attention affects all types of trials because the binding information is automatically stored, provided that the items themselves are attended and stored. Comparable performance levels are found when binding versus simple item information is tested, provided that these types of trials are put in separate trial blocks designed to equate guessing factors (Cowan, Naveh-Benjamin et al., in press). These findings tend to support the suggestion of Oakes et al. (this volume, Chapter 3) that "if the binding of features depends specifically on the intraparietal sulcus, then we should also observe that infants who can bind features are the same infants who can represent multiple objects in VSTM."

Finally, if bound features are automatically held, this raises the question of the role of attention in working memory, which Feigenson (Chapter 2 of this volume) also raised. It is not necessarily the case that binding information is held attention-free. It could be instead that attention is needed to maintain objects and that this maintenance already includes the feature bindings, or at least some feature bindings such as those between objects and their locations. Such an approach would be consistent with two concepts from cognitive neuroscience: (1) the concept of an object file in working memory (Kahneman, Treisman, & Gibbs, 1992) with its features bound and intact, and (2) the concept that the frontal and parietal lobes of the brain function, respectively, as an anterior attention system largely responsible for controlling attention and a posterior atttention system largely responsible for representing attended information such as object files (Cowan, 1995; Posner & Peterson, 1990).

<2> Reznick's chapter

It is difficult to comment comprehensively on Reznick's chapter because it already is a broad, integrative review with commentary built in. I endorse his question for better definitions and methods to examine working memory in infancy and beyond. I will focus on a consideration of two fundamental questions that he raises: what terms to use for temporary memory in infants, and what the future may hold for infant research.

<3> Terms for temporary memory in infants

Reznick's thoughtfully commented on what it is that one can study in infants. He suggested that the study of cognitive capacity in infancy was a study of working memory and not short-term memory. How would one decide?

The relation between short-term memory and working memory has been thought of in various ways within the recent cognitive psychology and neuroscience literature. According to one perspective short-term memory is a passive holding device (or set of devices) and working memory is the combination of that holding device along with attention processes that control it (Engle et al., 1999):

short-term memory tasks + use of attention = working memory tasks

According to a slightly different perspective, though, all information has to be held with the help of attention unless some sort of trick is applied, such as covert verbal rehearsal, which can be used to circumvent the attention limit (Barrouillet, Bernardin, & Camos, 2004; Oberauer, Lange, & Engle, 2004). Then one can characterize short-term memory tasks as those in which such a trick is used to circumvent the attention limits:

working-term memory tasks + use of mnemonic strategies = short-term memory tasks

Our recent work provides some support for the latter formulation. Although simple digit span tasks do not correlate well with intelligence in sixth-grade children or adults, who can use rehearsal well, it correlates very well in younger children (Cowan, Elliott et al., 2005; Hutton & Towse, 2001), who are known to be inefficient in covert verbal rehearsal (Ornstein & Naus, 1978). It is the core capacity that may correlate with intelligence, not the special strategies. It therefore makes perfect sense to assume that the concept being studied in infants is working memory, without the benefit of rehearsal.

<3> What the future may hold for infant research on working memory

Reznick pleaded for methods to study infants' working memory that are flexible, efficient, and valid on an individual-subject basis. I endorse this. Additionally, though, the future of working memory in infancy may involve an expansion of topics. It may cover not only studies of the development of capacity and memory resilience as noted in all of the chapters of this volume, but also studies of the development of grouping and recoding processes so important for the most efficient use of this capacity (Miller, 1956). The pervasiveness of recoding must not be forgotten. Its role can be illustrated by considering Reznick's comment (in Chapter 4 of this volume) that "Baddeley and Hitch's model of working memory...to its credit...draws a clear distinction between working memory for auditory and visual information." Actually, it does not do this exactly. To understand why not, consider that when pronounceable visual stimuli are presented to adults, the amount of confusability depends on similarities in their pronunciation, and not primarily in how they look. As a prime example, it is quite difficult to recall, in order, the similar-sounding letters *b, v, t, c, d, p, g* (Conrad, 1964). The reason for this is high confusability, inasmuch as the printed stimuli tend to be mentally converted to a phonological form for covert verbal rehearsal, and these letters sound alike. The Baddeley and Hitch model is excellent at describing stimuli in terms of their more abstract, phonological versus spatial coding. That theory is less well-suited for explaining why, beyond the phonological code, there is an advantage for spoken as opposed to printed verbal stimuli toward the end of a list (on this modality effect see, for example, Cowan, Saults, & Brown, 2004; Penney, 1989).

As infants develop, sensory processing may allow them not only a more precise perceptual representation with which to work (Cowan et al, 1982), but also a much richer set of abstract codes with which to retain and mentally manipulate experiences in working memory, for the good of cognition, performance, and social interaction.

<1> A summary comparison of answers to the five questions posed to authors

There are some striking convergences between chapters, reflecting the zeitgeist, and there are some differences in approaches in answering a few of the five questions.

<2> 1. *What kind of memory are you studying? What does it permit the infant/young child to do (i.e., what is its function/functional significance)? To what kind of adult memory does it correspond?*

Reznick differentiated between short-term memory and working memory, and suggested that infant researchers are studying working memory. The connotation of this distinction is that what is being studied is not some passive storage device, but primarily the attention-demanding retention of key information needed for a task. This opinion seems to mesh well with what the other chapters describe. The A-not-B procedure studied by Bell and Monasch depends on maintaining the goal so as to avoid making a prepotent response, and the procedures described by Feigenson and by Oakes et al. involve apprehending multiple items from a field. The adult research (e.g., Morey & Cowan, 2004) does suggest that this type of memory is attention-demanding.

Of course, passive storage probably also is used along with attention in working memory, and the infant findings so far would not be able to distinguish clearly whether any passive type of storage lasts longer as infants get older. There is some indication that, at least in the case of auditory sensory memory for unattended speech sounds, passive storage might persist longer over time with development during elementary school (Cowan, Nugent, Elliott, & Saults, 2000). However, for the most part, the development of more passive types of short-term memory probably require rehearsal strategies that do not begin in infancy and do not develop fully until middle childhood.

<2> 2. *How do you measure this type of memory? What are the challenges in measuring it? What are the limitations of the methods we have for measuring it? What are the recent advances (if any) in measuring this type of memory?*

A fundamental difference between measures provided by the authors was in the kind of limit imposed. Feigenson, as well as Oakes et al., used procedures in which the number of elements was manipulated to determine the point at which the infant's limit was exceeded. The task was basically to retain the number of items (Feigenson) or to retain the features of each item (Oakes et al.). In contrast, Bell and Monasch, as well as Reznick, described data in which relatively simple stimuli were presented and a time delay with distraction was imposed. In both cases, tough problems must be tackled.

First, according to the theoretical framework depicted in Figure 1, the number of items that can be apprehended depends on attention. The recent research I described indicates that we do not yet know what attention does; it could actually hold the information, or it could defend the information against interference. One challenge is to determine the exact role of attention here, both in infant research and beyond.

There are more fundamental challenges in determining the effects of a delay. The delay has to be filled with a distraction that also can cause interference. According to one view, what distinguishes one infant from another (or one age group from another) is the ability to use attention to overcome this interference. The need to attend during a long delay may be a vigilance task. We cannot yet be sure if there is a different component of age differences in responding after a delay that is independent of attention and depends instead on some sort of decay parameter even though, as Reznick noted, there is no clear evidence for a decay process (except perhaps in sensory memory; see Cowan et al., 2000).

<2> 3. *What do we know about how this type of memory changes with development? What kinds of developmental changes have you (and others) observed?*

There seems to be a clear consensus among the researchers that working memory becomes much more robust during the second half of the first year of life. This was true across a wide range of procedures. There are differences between procedures in the detailed nature of the abilities of each age, which can be attributed to differences in task demands as I have discussed. However, there is more similarity than difference.

<2> 4. *Why does this type of memory change? What are the mechanisms underlying the development of this type of memory?*

The reviewers consistently pointed to developmental maturation of the frontal lobes as a cause of the better control of attention, which in turn allows better maintenance of information in the face of interference. Although I concur, I tried to emphasize that the attention system should be viewed more as a multi-component network with a more substantial contribution of posterior regions than some of the researchers noted. Portions of the parietal lobes are involved in the integration of information from the different senses and may reflect the actual seat of attention, as opposed to the frontal lobes, which act more as the controller of attention (Cowan, 1995; Posner & Peterson, 1990). It is not yet clear to what extent age differences in the ability to apprehend multiple items at once depends on maturation of the posterior regions, as opposed to maturation of the frontal regions exerting control over how the posterior regions are used.

The other basis of change in working memory that I have stressed is knowledge, which allows multiple items to be grouped into a single chunk. The process of forming new associations seems close to the binding issue that Oakes et al. brought up. However, we must also consider not only how easily binding can occur, but also what the benefits of already-bound knowledge may be in making working memory efficient.

Actually, it is difficult to imagine that knowledge would form the primary basis of change during the first half of the first year of life, when we know that maturational changes are so predominant (aside from the very real possibility of environmental stimulation being necessary for normal brain maturation). However, knowledge is a secondary factor that should not be ruled out. The kind of knowledge that could be relevant to the tasks that these researchers have used might be very basic, to the point that we might not recognize them as knowledge. Regarding tests with delay periods, for example, infants might have learned that objects that disappear sometimes do reappear. They might even have learned that maintaining attention on the object helps it to reappear; in normal life, if the baby seems interested, parents may be more likely to make the object reappear. Regarding tests with multiple objects to be apprehended, the infant may have learned the link between a certain number of objects and certain patterns that this number of objects can make. Pattern recognition is, in fact, one of the current theories of how the enumeration of small numbers of objects occurs (Logan & Zbrodoff, 2003). Infants also might have to learn very basic things about types and tokens, such as the fact that when a similar shape occurs more than once in different colors, this represents two completely separable objects (unlike, say, an object and its shadow, which represent a single object; or an object that appears first in one place, and then in another place as someone moves it). We still don't know how much of this is innate or learned.

<2> 5. *What are the questions and issues on the horizon for the study of the development of this type of memory?*

All of the chapters seem to point to one major question on the horizon, which is how fair comparisons can be made across age groups, given that different methods seem applicable and impose different processing demands. As I have noted, there are some important leads in this regard, such as the application of infant procedures to older children and adults when it is possible and the use of physiological measures (Bell & Monasch, Chapter 1, this volume). The question of later development took a different twist for Feigenson, who suggested that a certain basic capacity may reach its mature level by 1 year of age. Clearly, this is a provocative hypothesis that can only be tested when the right methodological bridges between infants and children have been found.

Finally, Reznick (Chapter 4, this volume) has a vision that working memory observed in infancy will turn out to be related to social regulation and general intelligence, and will turn out to predict and to be involved in various developmental disabilities. An encouraging observation in that regard is that one attention-related process measured in infancy is known to predict later intelligence. In particular, habituation of attention to a familiar object (and in some instances dishabituation to a change) predicts later intelligence and predicts disabilities; for a recent review, see Kavšek (2004). Although habituation is an attention function, the theory of Sokolov (1963) holds that habituation depends on construction of a neural model of the stimulus in the brain, which would seem to be a working memory function. (For modern support of Sokolov see Cowan, 1995). Methods for distinguishing between different attention functions in children (Rueda, Posner, & Rothbart, 2005) also might be adapted to infants.

<1> Concluding remarks

I share with the authors of these four chapters an optimism that methods can be devised to link together the research on infants and children, to begin to construct a developmental psychology of working memory that includes infants. A profound outcome of this endeavor could be a richer understanding of the way in which working memory governs early cognitive development and the grasp of consciousness (cf. Piaget, 1976; Zelazo, 2004).

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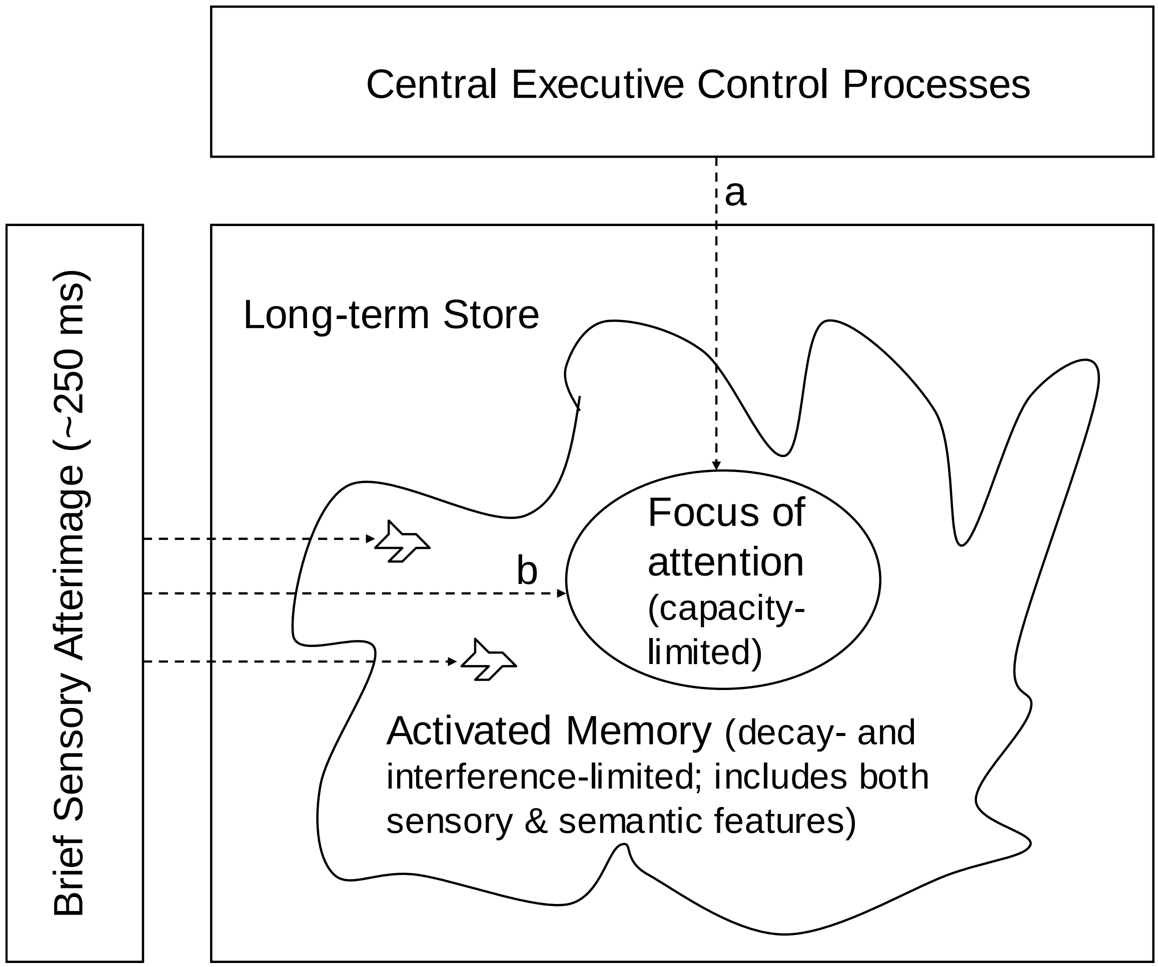
Figure Captions

Figure 1. An illustration of the theoretical framework for the information processing system as described by Cowan (1988, 1995). The focus of attention is controlled by both executive processes (a) and orienting to changed stimuli (b). Whereas the automatic activation of features is only partial, the focus of attention allows a deeper, more semantic perceptual analysis, and it includes new links between memory elements activated concurrently. The theory makes at least two controversial claims about working memory: (1) that activated memory is prone to temporal decay, and (2) that the focus of attention is limited to a small, fixed number of separate chunks.

Figure 1


Central Executive Control Processes
a
Brief Sensory Afterimage (~250 ms)
Long-term Store
Focus of attention (capacity-limited)
b
Activated Memory (decay- and interference-limited; includes both sensory & semantic features)