Published in final edited form as:
Adv Child Dev Behav. 2017 ; 52: 81–104. doi:10.1016/bs.acdb.2016.12.001.

Mental Objects in Working Memory: Development of Basic Capacity or of Cognitive Completion?

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Abstract

Working memory is the small amount of information that we hold in mind and use to carry out cognitive processes such as language comprehension and production, problem-solving, and decision-making. In order to understand cognitive development, it would be helpful to know whether working memory increases in capacity with development and, if so, how and why. I will focus on two major stumbling blocks toward understanding working memory development, namely that (1) many potentially relevant aspects of the mind change in parallel during development, obscuring the role of any one change; and (2) one cannot use the same test procedure from infancy to adulthood, complicating comparisons across age groups. With regard to the first stumbling block, the parallel development of different aspects of the mind, we discuss research in which attempts were made to hold constant some factors (knowledge, strategies, direction of attention) to investigate whether developmental differences remain. With regard to the second stumbling block, procedural differences in tests at different age groups, I suggest ways in which the results might be reconciled across procedures. I highlight the value of pursuing research that could distinguish between two different key hypotheses that emerge: that there is a developmental increase in the number of working memory slots (or in a basic resource that holds items in working memory), and that there is a developmental increase in the amount of detail that each of these slots can hold.

Keywords

working memory; short-term memory; capacity; focus of attention; infancy; childhood

1. Introduction

A young child who is upset that an older sibling has two cookies to her one can be appeased if the one cookie is broken in half to make two. How does this happen in the young child's mind? How is it that a child just beginning school would be intellectually lost in a classroom slightly more advanced, or an elementary school child lost in a high school environment? An ancient, naïve assumption might have been that it just takes time for a child to learn, but it might have become evident that some children learn more quickly than others in a comparable environment, so that there would appear to be a biological component. A more

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sophisticated concept, therefore, is of the readiness to learn. For a child to learn some concepts the brain must mature, with a capability to understand more complex concepts as the neural system grows. Here I consider some possibilities and then focus attention on two hypotheses about cognitive growth that seem worthy of further investigation.

I have worked on the growth of the mind with respect to one of its most fundamental properties, the number of items retained in working memory (e.g., Cowan, 2016). The term working memory in psychology refers to the small amount of information that is held in mind in order to carry out cognitive tasks (Baddeley & Hitch, 1974; Miller, Galanter, & Pribram, 1960). In learning language, a child has to hold onto a spoken word while considering what object or event it refers to. Without working memory there could be no possibility of issuing instructions for a child to follow. There would be no possibility of retaining a partial result in mind while carrying out an arithmetic problem. Understanding a new concept involves combining its elements in working memory (Halford, Cowan, & Andrews, 2007). For example, in folk terms a tiger is essentially a large cat with stripes. If one forgets that it is a cat, the concept is not differentiated from a zebra; if one forgets that it is large, one has a striped house cat; or if one forgets that it is striped, it could be a lion instead.

Clearly, what is needed for maturation of the brain is an increase in the ability to retain usable elements in working memory and to combine them or use them in the right way. Cowan (2016) recently reviewed various ways that this ability could increase with age. Some of these ways involve learning. For example, elements that have already been combined in memory are called chunks (Miller, 1956). If a child already knows about big cats, then the concept of a tiger reduces from three separate ideas or chunks (big, cat, striped) down to two (big-cat, striped). Although it is pedagogically important to know what information is typically learned by children of different ages, I do not examine that topic here because I define our task as trying to figure out what development is possible and what is not possible in development, leaving the task of figuring out what children actually know to educators and parents.

In what follows, I first provide some evidence that certain very important developmental changes taking place *outside* of the working memory system are not enough to explain developmental increases in mental capability. The general possibilities that I consider, but ultimately rule out, include possibilities that developmental growth occurs entirely through knowledge coming from experience, through the efficiency of attention, through increased encoding efficiency, or through mnemonic strategies. I then discuss an apparent developmental increase in working memory capacity and what processes might explain that increase consistently across the life span, from infancy onward, despite apparent inconsistencies between the infant and child literatures. Before I discuss the childhood development of working memory, though, it is necessary to first examine how capacity can be measured in some of the procedures that I highlight.

2. The Measurement of Working Memory Capacity

Pashler (1988) and Cowan (2001) provided some simple tools that will be used throughout this chapter to describe performance on tasks in which an array of objects is presented for study and is then followed by a probe array or a single-item probe to be judged as the same as, or different from, the studied array. These tools have been validated extensively (Rouder et al., 2008; Rouder, Morey, Morey, & Cowan, 2011) although they possibly may only be approximations if memory in fact occurs as a fluid resource rather than a fixed number of items on each trial (Fougnie, Cormiea, Kanabar, & Alvarez, 2016; Ma, Husain, & Bays, 2014). Here I provide just brief explanations to allow the rest of the chapter to be clear. Suppose an array of S items is followed by another, probe array that is the same or differs in the nature of one object in the array. The task is to indicate if the arrays are the same. Assume that the participant has k items in working memory and that the goal of the model is to estimate k. If one item in fact changes, the likelihood that the participant has that item in working memory and therefore notices the change is k/S. If the participant does not notice a change, he or she is assumed to guess that there was a change with probability g. Thus,

$$\mathrm{p(respond\ “change”\ |\ change) = p(hits) = k/S + (1 - k/S)g.}$$

When no change has occurred, the participant is assumed to be in the same guessing state, hence

$$\mathrm{p(respond\ “change”\ |\ no\ change) = p(false\ alarms) = g.}$$

One can combine these equations to show that

$$\mathrm{k = S[p(hits) - p(false\ alarms)]/[1 - p(false\ alarms)]\ .}$$

In another circumstance (Cowan, 2001), the probe shows which item may have changed, so only a single decision has to be reached. In that case, if the item in question is in working memory, the participant will know whether a change has occurred or not. The difference from the previous situation is in the false alarms:

$$\mathrm{p(respond\ “change”\ |\ no\ change) = p(false\ alarms) = (1 - k/S)g.}$$

One can show that now, in this situation, by combing equations for hits and false alarms,

$$\mathrm{k = S[p(hits) - p(false\ alarms)]\ .}$$

The value of k typically increases as the set size increases, reaching a level or asymptote at between 3 and 4 items in adults (but with individual differences ranging usually between 2 and 6 items). Sometimes, when the array sizes are very large, such as 10 items, k begins to decrease as the array size increases (e.g., Cusack, Lehmann, Veldsman, & Mitchell, 2009). I use k to describe the number of items in working memory in the developmental studies in childhood. The number of items in working memory may be smaller than capacity (when there are few array items) but it is limited by the participant's capacity.

3. Sources of Childhood Development of Working Memory: Is there a Fundamental Increase in Capacity?

There are a number of processes that could account for developmental increases in working memory performance from the early elementary school years through adulthood. I next consider these one at a time to make the case that it is reasonable to suspect that there is a fundamental increase in capacity, in addition to other important factors.

3.1. Childhood working Memory Development is Probably Not Entirely Based on Learning

One thing that is important from our point of view is to establish that there is an implication of brain growth for cognitive development that cannot just be attributed to increasing knowledge across ages coming from experience. One might build a case that, indeed, knowledge growth is enough to explain the maturation of the mind. In one approach showing the dramatic role of knowledge, Chi (1978) examined the ability of six children in third through eighth grade, and adults, to remember both lists of digits and the positions of pieces on a chess board. These, however, were not just any children and adults. The adults were somewhat familiar with chess, but the children were chess experts. The finding was that although the adults substantially outperformed the children on digits as in many previous studies, the children dramatically outperformed adults on remembering chess configurations. Clearly, knowledge plays a key role in working memory so it is worth asking: if adults and children can be equated on knowledge, will an age difference still be found?

Case, Kurland, and Goldberg (1982) further showed that knowledge affects processing efficiency. In one experiment, participants were to remember and then immediately repeat each list of spoken words and, in a separate task, listen to isolated words and repeat each one as quickly as possible. Young children repeated items slower than adults and remembered commensurately fewer of these items. When adults were given a different set of items, nonsense words, their repetition rate slowed to match the children's rate with real words, and the adults' working memory performance was accordingly reduced to match the children. Thus, there is no question that knowledge is an important factor in working memory development.

Cowan, Ricker, Clark, Hinrichs, and Glass (2015) examined working memory with knowledge varied, in children in the U.S. ranging from first through seventh grades and adults, using briefly-presented arrays of English letters and arrays of unfamiliar characters for which the contribution of knowledge should be greatly diminished (illustrated in Part A of Figure 1). The goal was to determine whether equating knowledge across age groups would eliminate age differences in working memory performance.

Each array was followed by a single character that was to be judged present in the array or absent from it. This kind of task becomes more difficult as the number of items in the array increases (Luck & Vogel, 1997). Cowan et al. (2015) found that performance was especially low in children in the first grade, the youngest age group tested, because some children did not know the letters very well. These children were excluded from the study, which also included older children and adults. Performance on the letters was much better than it was on the characters, showing a robust role of knowledge, but the rate of developmental change was nevertheless very similar for letters and unfamiliar characters. (Using z scores to examine the relative performance levels of different participants in each task, the developmental growth curves for letters and familiar characters fell on top of one another.) This result suggests that there is a fundamental development of the capacity of working memory that cannot be attributed to the increase in knowledge. In this task, knowledge was equated across age groups by making the materials very similar and excluding children who didn't know their English letters well. If knowledge had accounted for the developmental growth, there should have been a faster rate of improvement across age groups for letters than for unfamiliar characters as knowledge accrued. If knowledge is all there is and it was equated across age groups, there should have been no remaining developmental growth in this experiment, yet in fact there was a dramatic developmental improvement in z scores that was almost identical for letters and unfamiliar characters.

Another approach to the same issue was taken by Gilchrist, Cowan, and Naveh-Benjamin (2009). Series of short, unrelated sentences were orally presented for oral, verbatim recall (e.g., *our neighbor sells vegetables; we welcomed the family; my temper causes trouble; the birds circled above*). This procedure allows for a measure of items in working memory (the number of sentences for which at least one substantive word was recalled) and a measure of knowledge (the number of words per sentence recalled given that at least one word was recalled). In 7-year-old children through adults, the measure of knowledge was about 80% of the words in the sentences that were at least partly recalled; but the measure of items in working memory increased steadily with age despite this apparent success in equating for linguistic knowledge needed to perceive these simple sentences.

It still remains possible that, as the brain grows, it is able to apply knowledge even in cases in which unknown material is presented. A particular unfamiliar character might be recoded in a way that is mnemonically helpful (e.g., as a wavy squiggle resembling a sign for the ocean, with a periscope sticking out of it). It should, however, be easier to use knowledge in a situation in which the elements are well-known. Some of the letters in an array might be put together to resemble a known English word, for example. Still, a case can be made that more research is needed to show the full contribution of knowledge.

3.2. Childhood Working Memory Development is Probably Not Entirely Based on Increases in the Efficiency of Attention Allocation

Another hypothesis about cognitive growth that can be suggested, this time based on research on individual differences in adults, is that differences in capacity might occur because less-capable individuals are not as efficient in focusing on the important items in the environment. Research by Vogel, McCollough, and Machizawa (2005) examined this possibility. They asked that participants examine an array in which some items were to be attended and other items were to be ignored. Their participants were to attend to a field with 2 targets (e.g., the spatial orientations of 2 red bars), or 4 targets (e.g., 4 red bars). Sometimes, 2 targets were interspersed with 2 distractors that were to be ignored (e.g., 2 blue bars). An event-related potential brain signal was used to indicate the memory load that the individual held in mind. Those with high spans were able to limit their performance to the relevant bars, and therefore their brain signals indicated a considerably larger memory load with 4 targets than with 2 targets. Other individuals were limited to fewer items in working memory and thus showed smaller brain difference between 2- and 4-target trials. Notably, when these lower-capacity individuals were presented with 2 targets and 2 distractors, their brain responses suggested that they were trying to retain both targets and distractors in working memory, making the process of using the contents of working memory more difficult. The hypothesis that lower-span individuals do not inhibit memory for distractors also has been put forward as an explanation for the decline in working memory that occurs with cognitive aging (Stoltzfus, Hasher, & Zacks, 1996).

Not all findings have been favorable to the hypothesis that lower-capacity individuals fail to filter out less-relevant items as well as higher-capacity individuals. Gold et al. (2006) examined this hypothesis in a comparison of adults with and without schizophrenia using a procedure in which there were more- and less-often-tested items. In one experiment, for example, the colors of items of one particular shape were tested on 75% of the trials and the colors of items of another shape were tested on only 25% of the trials. The tendency to remember more of the items that are tested more often was found not only in participants without schizophrenia, but to a similar extent in those with schizophrenia. What distinguished best between the groups was simply how many of the objects were remembered, summed across the more- and less-often-tested shapes. Similarity, Mall, Morey, Wolf, M.J., and Lehnert (2014) recorded eye movements to show that low-span participants tended to look at task-relevant items more than task-irrelevant items, to the same extent as higher-span individuals.

Cowan, Morey, AuBuchon, Zwilling, and Gilchrist (2010) examined this issue of filtering in elementary school children and adults using a procedure modeled after Gold et al. (2006). In their procedure, illustrated in Part B of Figure 1, each array involved a grid with colored circles and triangles. In the most important condition, there were two colored circles and two colored triangles in an array, with a unique color for each object in the array. In the cover story that was used to make the task more interesting for the children, these objects were “students” in a “classroom.” The array of 4 objects was followed by a single probe object that was presented at the correct location (in the cover story, sitting at the right desk), that was sitting at a location that had been occupied by a different object (in the cover story, sitting at the wrong desk), or that was not found in the array at all (in the cover story, a student that did not belong in the classroom). The response was to use the mouse to click on the location where the student belonged; if the student belonged nowhere in the classroom (i.e., items absent from the array), the correct response was to click on a door icon to send the student to the principal.

Although Cowan et al. (2010) used different instruction conditions in different trial blocks, the most critical trial block was one in which memory for items of one shape (e.g., circles) were tested on 80% of the trials, whereas items of the other shape (triangles) were tested on the remaining 20% of trials. The youngest participant group, with children as young as 7 years, remembered far fewer items than the other groups (summed across the more- and less-often-tested items) but they did better on the more-often-tested items, to the same extent as the older groups. The adults remembered about 1.5 of the 2 items of the 80%-tested shape vs. only about 1.0 out of 2 of the 20%-tested shape (a 0.5-item drop; in all, ~2.5 items in memory), and the 7-year-olds similarly remembered about 0.8/2 vs. 0.4/2 in these conditions (a comparable 0.4-item drop; but in all, only ~1.2 items in memory).

There was an age difference in the ability to favor the more-often-tested items, however, for larger arrays of 3 more- and 3 less-often-tested items. With that higher memory load, the youngest age group no longer favored more- over less-often-tested items. Cowan et al. (2010) concluded, therefore, that 7-year-olds allocate attention in this task as efficiently as adults unless their working memory is sufficiently overloaded. Attention apparently must be shared between storage and processing (Daneman & Carpenter, 1980; Kane, Bleckley, Conway, & Engle, 2001) and with too much to store, the process of allocating attention becomes inefficient in these young children. Still, this age difference in efficiency for larger arrays cannot explain the age differences in capacity, which occurred even with smaller arrays for which all age groups allocated attention similarly.

3.3. Working Memory Development is Probably Not Entirely Based on an Improved Efficiency of Encoding

Many studies have suggested that younger children have a slower speed of processing than older children or young adults (e.g., Kail & Salthouse, 1994). This slower speed of processing could come into play in several ways in working memory tasks. First, some have argued that what we take to be concurrently-held items in working memory could result from a rapid circulation of attention between these items, one at a time (e.g., Gaillard, Barrouillet, Jarrold, & Camos, 2011; Cowan et al., 1998). Insofar as that happens, it simply suggests that what can be taken as a multiple-item capacity limit on a macroscopic time scale might be considered a speed limit on a microscopic time scale. There is, however, another way in which processing speed or efficiency could provide a more fundamental alternative to a capacity limit and that is with respect to encoding.

Cowan et al. (2010) presented the array of objects at a rapid pace, as is typical in this kind of change-detection experiment (e.g., Luck & Vogel, 1997). It seems possible that children would not be able to encode items into working memory at the same rapid pace that has been demonstrated in adults (Vogel, Woodman, & Luck, 2006). To pursue that possibility, Cowan, AuBuchon, Gilchrist, Ricker, & Saults (2011) conducted an experiment similar to the key conditions of Cowan et al. (2010), involving an array with 2 circles and 2 triangles of different colors on each trial, but with one critical difference. Instead of presenting all items briefly and concurrently, each item was presented individually at a slow rate of 1 s per item. The developmental result was the same as before: children as young as 7 years allocated attention to the shape tested on most trials as well as adults did, but they remembered considerably fewer items overall. Encoding speed cannot be the basis of the difference observed by Cowan et al. (2010) after all.

3.4. Working Memory Development is Probably Not Entirely Based on an Improved Use of Covert Rehearsal as a Mnemonic Strategy

One of the most often investigated bases of developmental changes in working memory has to do with the observation that it is possible to apply different strategies to carry out a particular task. Flavell, Beach, and Chinsky (1966) examined children's memory for lists of easily nameable objects and found developmental increases in the tendency to verbalize items as they were presented. Other work has shown developmental increases in the speed with which items can be named or identified (Case et al., 1982; Hitch, Halliday, & Littler, 1989) or recited (Hulme & Tordoff, 1989), and it is possible that covert verbal rehearsal could underlie improved performance, given that memory maintenance through covert verbal rehearsal has been proposed within standard theories of working memory (e.g., Baddeley & Hitch, 1974; Baddeley, Thomson, & Buchanan, 1975).

Articulation can be suppressed through the repetition of a word during the presentation of items to be remembered or during a retention interval (e.g., Baddeley et al., 1975). Morey and Cowan (2004) found that suppressing articulation had no effect on the memory for nonverbal arrays in adults. Nevertheless, to investigate the role of rehearsal developmentally, Cowan et al. (2011) included three conditions that differed in what participants had to do following the presentation of each successive array item. In one condition, they said nothing; in another, they said “wait” to suppress articulation of the presented item; and in a third condition they named the color of the object just presented, to encourage covert rehearsal. These conditions differed in the overall level of performance, but the developmental pattern was the same in each condition, and still supported the finding that there was an age difference in the number of items retained from 4-item arrays of circles and triangles, but no age difference in the allocation of attention to the more- versus less-often-tested shape. These results suggest that rehearsal cannot account for the capacity findings.

3.5. The Estimated Rate of Childhood Working Memory Development Appears to Depend on the Test Procedure

The procedures discussed in the previous section that show increases in working memory capacity, with some confounding factors controlled, indicate steady increases throughout the elementary school years. Other findings, however, indicate earlier maturity.

Finding a long developmental course with a simple procedure, Cowan et al. (2005, experiment 2) used a simple array-comparison procedure with arrays of colored squares, in which only one color can change between the array and probe displays. That experiment showed developmental growth in children from second to fourth to sixth grades. Riggs (2006) found a similar trend, but with younger ages, with improvement between 5, 7, and 10 years of age. The developmental trend was similar in a very different procedure in which lists of spoken digits were unattended at the time of their presentation, with occasional lists attended and recalled following a post-list cue (Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999). In that procedure, the assumption is that capacity limited the amount that could be retrieved from a fading sensory trace into the focus of attention when the post-list cue arrived. Using a wider variety of typical working-memory procedures, Gathercole, Pickering, Ambridge, and Wearing (2004) found steady increases in working memory performance from 4 to 15 years.

Riggs (2011) examined memory for the orientation alone or both orientation and color of objects in an array. Developmental increases from 7 years to 10 years to adulthood were the same for both kinds of test. This result suggests that the ability to remember both features, orientation and color, does not develop later than the ability to remember just one feature per object. It would have been helpful to see memory for color alone, as it is typically easier than either orientation-alone or orientation-plus-color (e.g., Hardman & Cowan, 2015).

Other researchers have suggested that under different test circumstances, capacity can reach maturity considerably earlier than the above results would indicate. Simmering (2012) used a modified array-comparison procedure with colored squares, designed to eliminate interference between trials (Shipstead & Engle, 2013) by presenting alternative trials on the left versus right sides of the field. That procedure produced performance that was not different from a standard array-comparison procedure. In both cases, performance increased between 3 and 7 years and by 7 years reached a mean of about 3.5 items, similar to what is typically found in adults. Unlike the other developmental studies just discussed, though, each color was allowed to occur only once per array (i.e., selection of colors for the array without replacement). This kind of procedure should allow the use of some kind of novelty-detection signal when a new color appears in the comparison array, unlike the usual procedure in which novelty maybe absent if a color changes to the same color that already exists elsewhere in the array. Yet, when colors are selected without replacement in adults, the result is about the same, with capacity limited to about three-and-a-half objects (Rouder et al., 2008).

Perhaps, then, there is a developmental increase in how many different objects can be kept active at once, reaching an asymptote of between 3 and 4 objects on average by about 7 years of age, but with further developments after that age in the ability to keep in mind separate but identical tokens (e.g., discriminating a difference between a set of four objects that are *red, red, blue, and green*, respectively, versus *red, blue, blue, and green*). I will return to this possibility of the late development of object individuation after discussing the infant literature.

In a very different procedure, Pailian, Libertus, Feigenson, and Halberda (2016) also suggested developmental change that reached an asymptote by about 7 years. Their measure of capacity was indirect; a flickering array of objects always included one changing object, and it was assumed that the search through the array to find the changing object occurred k objects at a time for an individual with a capacity of k objects. Therefore, the reaction times revealed the capacity. The estimated capacity by 8 years equaled the capacity in adults. This result provides further support for the notion of some basic capacity that is mature early in the elementary school years, but with abilities of object individuation needed only in some tasks and maturing later in childhood.

3.6. Summary of Child Research

The observations on children's development of working memory have fit a consistent pattern. Development is difficult to decipher given that many aspects of development co-occur. I have described a series of experiments in which various possible developmental factors have been highlighted, one at a time: knowledge, attention allocation, encoding efficiency, and the use of covert rehearsal. For each one, I have shown that when the factor is equated across age groups, developmental improvements in working memory remain. These findings are summarized in Table 1 (see also Cowan, 2016, Figure 1). In the various procedures I have discussed, the number of items held in working memory increases with age between 7 years and adulthood. In each case this developmental increase in capacity was observed with a reasonable measure of the efficiency of processing (relevant knowledge**,** attention allocation efficiency, or effects of rehearsal) equated across groups.

Yet, the skills involved in these tasks may involve not only holding a certain number of objects in mind, but also distinguishing between those objects and allowing the possibility of multiple identical objects. Under certain circumstances, mature behavior may occur by 7 or 8 years, so further investigation is needed. Hold that thought until we can examine what happens in infancy and how it seems to conflict with the results from children, calling for careful thought about how the results with different procedures from different age groups might be reconciled and integrated.

4. Development of Working Memory Capacity in Infancy

Research in infancy has profoundly changed the common perception of development in many areas, including the area of working memory. A common view is that many skills that appeared to develop only at some point in childhood, as seen for example in Jean Piaget's theory of cognitive development, prove to have beginning forms earlier, at some point in infancy. The research on working memory in infancy seems to fit this rule. A number of studies, taken together, appear to have been interpreted as indicating that infants already acquire the ability to keep about 3 items in working memory (for a review see Cowan, 2016). This finding is remarkable because it seems to suggest that the infants know more than children early in the elementary school years! I assume that this cannot be the case, and therefore that the theoretical question of interest is which particular differences in the infant versus child working memory task procedures account for the apparent drop in capacity between infancy and childhood.

A few of the infant studies taken together illustrate where the field has gone and how I believe it might be interpreted. Ross-Sheehy, Oakes, and Luck (2003) presented in each trial successive arrays of colored spots on the left and right sides of a screen. During each trial, with each array presentation an item on one side of the screen changed color compared to the last array, whereas there was no change on the other side. The experimental logic exploited babies' general preference for novelty. The expectation was that babies would prefer to look more at the changing side of the array if the changes were noticed, as that side would then provide more novelty than the unchanging side. Ten-month-old infants looked longer at the changing side for 4-item arrays, but not for 5-item arrays. This would appear to indicate a capacity of 4 items in infants, as in adults, but the capacity estimate should not be taken at face value; an infant would not have to encode all array items in order to notice some of the changes, so this repeated-presentation procedure cannot provide a capacity estimate. Oakes, Baumgartner, Barrett, Messenger, and Luck (2013) eliminated the repeated-presentation aspect of the procedure and replaced it with a one-shot procedure, but the larger set sizes necessary to estimate a capacity limit were not included in the experiment.

Another procedure that has been used to examine working memory capacity in slightly older infants is one in which items are placed into a box and infants have the opportunity to retrieve items from a box. The best performance has been obtained when the items are all different (Zosh & Feigenson, 2015). Infants 13-months old will search for the first two items and often will search for a third item. If, however, 4 items are placed in a box, the infants' predominant response is to search for 3 objects and then stop looking.

On the surface, this response pattern suggests that 13-month-olds often have 3 items in working memory. Notice, though, that by chance, on most trials the first 3 objects that the infant retrieves will not be the same as the 3 objects that are held in working memory. Cowan (2016) noted that this pattern of responding can occur in two ways. His calculations show that if the infants held specific items in mind and withdrew objects from the box until finding matches for the specific items in working memory, then capacity would appear to be about 2 because holding about 2 items in mind would result in about 3 items being drawn on average before those 2 specific items are found. Alternatively, it is possible that an infant holds about 3 items in mind, but without comparing specific feature information so that any 3 items withdrawn from the box would presumably displace the ones in working memory and the infant would be happy with those new 3 items, inasmuch as working memory is full.

The evidence with this procedure favors the latter hypothesis. Zosh and Feigenson (2012) arranged a switch so that 3 items hidden in the box (e.g., a cat, a shoe, and a bus) were not the same ones that were there to be retrieved from the box (e.g., a car, a duck, and a brush), yet these changes did not increase the time 18-month-olds spent looking in the box. The switches did make a difference when only 1 or 2 items were hidden in the box, so it appears that the feature information was lost (or at least, not usable in the same way) when too many items were added to working memory.

Kibbe & Leslie (2013), on the other hand, suggest that infants are able to keep track of the specific shapes presented at 2 locations by the age of 9 months, and are able to keep track of the shapes presented at 3 locations by 12 months. This conclusion is based on a task in which two or three simple shapes (triangle, square, or circular disc) are placed behind barriers and then one of these is revealed, with looking time as the dependent measure. Looking time should increase if a switch is noticed and at 12 months of age it was noticed for 3 simple shapes. Keeping track of the binding between shape and location is difficult even for adults (e.g., Cowan, Blume, & Saults, 2013), so much so that this finding suggests near-adult-like performance by 12 months unless the difference can be attributed to differences between the procedures used in the infant and adult studies. One potential limitation of the Kibbe and Leslie (2013) finding is that infants were always tested on the second of three locations. It is possible that infants allocated most of their attention to that location after the first trial, and therefore did not have to store in mind all three locations in order to notice many of the changes in the second location.

The notion that infants have objects in working memory but do not completely include all of the features of those objects is consistent with several kinds of adult studies. Work by Kahneman, Treisman, and Gibbs (1992) supports the notion of an object file, which is a marker that an item exists whether or not the object is complete with all of the important features. The notion of an object file with only some features bound to it, or with the need for attention to maintain binding, can result in errors of feature binding (e.g., Wheeler & Treisman, 2002), such as forgetting which shape went with which color. At one time, it was believed that adults' working memory representations of objects include all of the objects' physical features, inasmuch as participants could attend to 4 features of the objects with the same performance level as a preselected 1 feature of those same objects (Luck & Vogel, 1997). However, several studies have failed to replicate that finding, instead showing that memory of features is somewhat independent (Wang, Cao, Theeuwes, Olivers, & Wang, 2016) or that memory of any one kind of feature from multi-featured objects in an array (e.g., color) comes at the expense of memory for another kind of feature (e.g., shape) (Cowan et al., 2013; Hardman & Cowan, 2015; Oberauer & Eichenberger, 2013).

It would be theoretically possible that infants do not encode all of the features of objects, or that the features are encoded but then not tightly bound to the objects in working memory, so that it would be possible for an infant to be content to retrieve the correct number of objects without caring about the details of the objects. The results of Zosh and Feigenson (2015) favor the latter account. Previous work combined with that of their 2015 paper showed that when the objects are all identical, fewer of them are retrieved than when the objects differ, suggesting that infants process the differences between objects. When the objects retrieved do not match the ones hidden it is possible that the infants even realize that something has changed, but are not committed to the specific features of the objects hidden when working memory is overwhelmed because their attention has shifted to using the limited available working memory to keep track of the *number* of items retrieved, with not enough capacity left to keep track of *which* objects have been retrieved. Some such account would help to explain why Zosh and Feigenson (2012) found that 18-month-old infants appeared to care about the switch given 1 or 2 hidden items but were unconcerned about the switch given 3 hidden items.

4.1. Summary of Infant Research

The infant studies leave many issues yet to be resolved but on the whole seem consistent with the view that older infants in some basic sense have in mind about 3 objects, rather like adults, but with the amount of detail in each object increasing with age both within and beyond infancy.

5. Reconciliation of the Infant and Child Literatures

Let us emphasize at this point some fundamental limitations in developmental research. First, it is clear that many processes change together in development, so it is difficult to identify which changing process is critical to the improvement of any one function at a macroscopic level, such as working memory and how it is used. Second, we lack techniques that can be applied without modification throughout the developmental life span, so it is not easy to track the fate of any particular process. Respecting these limitations, we nevertheless can propose a hypothesis regarding developmental change from infancy through childhood.

The extant data seem consistent with a view in which the number of items in working memory is not the whole story. To be sure, there are studies suggesting an increase with age in the number of items stored in infancy, and an increase with age in the number of items stored in childhood. Regarding the latter, much of the review was dedicated to research indicating that developmental changes in capacity cannot be explained away through the development of concomitant processes such as knowledge or strategies, even though development of those processes undoubtedly also occurs.

There is evidence, though, of developmental increase in the features bound to each object file, or the strength with which that binding takes place. In infancy, 18-month-olds acted as if they cared about the particulars of objects in working memory when 1 or 2 items were hidden and had to be stored in working memory, but were not concerned about particulars any more when 3 objects were hidden and had to be stored in working memory (Zosh & Feigenson, 2012).

Is there further evidence of a similar trend in childhood? In an ongoing study we (C. Blume and N. Cowan, in preparation) have observed a striking difference between the apparent number of object files in working memory, which changes little across the elementary school years, versus the number of preserved objects with at least one informative feature, which changes markedly across the elementary school years. We tested working memory in a situation in which no binding between features was needed because each item had only a single relevant feature. Specifically, we examined children’s memory for 5-item arrays in which each item was a square of a single color. The array was followed by a single-square probe to be recognized as a color that was present in the array, or absent from the array. Location information was not needed because the probe was centrally presented. Memory performance increased steadily as a function of age from about 7 years through adulthood. Probably because of a procedure that had some challenges for the participants (a 500-ms blank period after the array and then a mask presented for 4000 ms), performance increased steadily from only about 1 item in working memory in 7-year-olds to just under 3 items in adults. On some trials, moreover, a metamemory response was obtained during the 4000-ms masking period that preceded the memory probe. (Memory performance was only mildly affected by this added metamemory response.) In particular, when the fixation point of the masking array had a “?” symbol, the participant was to indicate how many array colors he or she still had in mind. Amazingly, children of all ages indicated on average about 3 colors held in mind, despite the fact that this was a dramatic overestimate in the younger children.

Combining across the infant studies and this metamemory result in children, there may be a constant or relatively constant number of object files that are kept active in working memory, about three; but the ability to bind the informative features to each object file may increase with age in infancy and childhood, making the object files useful for increasingly challenging test situations.

Of course, this hypothesis raises a host of additional questions. Suppose the children had active memory for the colors but these active features (e.g., in the color-feature map of Wheeler & Treisman, 2002) were not bound to the object files. Wouldn’t the activation of the features themselves be enough to determine whether the probe was in the array or not? That might be the case on the first trial of the experiment, but across trials there is a buildup of proactive interference; the participant might not be able to tell whether “red” is active from the present trial or from a previous recent trial. It might take limited working memory capacity to overcome this proactive interference and determine whether the object files of the current trial are associated with particular active features in memory. Indeed, it has been proposed that a key function of working memory is to help overcome effects of proactive interference (Cowan, Johnson, & Saults, 2005) and it has been found that array performance is susceptible to proactive interference (Shipstead & Engle, 2013). In fact, when items are drawn from a new, meaningful set on each trial rather than drawn from a repeating set, the typical limit of working memory capacity does not apply (Endress & Potter, 2014).

What I propose, then, is a general developmental course across infancy and childhood in which object files change little but the informativeness of those object files improve markedly with development. Figure 2 depicts this developmental principle. In a recent review, Kibbe (2015) has provided more detail about how the featural information associated with each object improves in infancy, and there is as yet considerably less information on the distinction in childhood. Cowan et al. (2010) did find that memory for the simple feature of color developed earlier than the memory for the binding between color and shape or between color and location, but much more detailed information is needed.

If the furnishing or featural filling-in of objects in working memory improves across child development, what will the implications be for young children’s experience and behavior? One could speculate based on the present chapter. Consider the young child at this chapter’s opening who was upset that an older sibling had two cookies to her one. If the older sibling or adult breaks the child’s cookie in two, this doubles the number of cookie-object files and the child may be satisfied because she now has two good things and does not take into consideration, or hold in working memory, the halving of mass within each cookie-object. Neither of the present half-cookies is compared to the original, glorious whole cookie. Yet, this kind of funny error will not prevent important learning by the child because the space in working memory is useful as a vehicle for new ideas. The child can have a working memory slot for the word dog and another for an actual dog, allowing the special moment when the word and animal are together in working memory concurrently and are successfully bound together; the word-referent pair is suddenly learned. Still, limitations in the child’s use of working memory for careful comparison may contribute to typical errors like thinking that a horse is also a kind of dog (overextension), or that the word dog only applies to this one dog (undergeneralization). Until working memory matures further, it may be difficult for the child to distinguish a tiger from all three of its conceptual neighbors (striped house cats, stripeless lions, and zebras). Young children may remember and even repeat sequences of several events in a favorite book, but this kind of learning may not apply well to a situation in which several instructions must be followed, with each instruction carefully compared to the current state of affairs. So it is that putting away several toys upon request involves both remembering the instruction to do so and comparing that instruction to the actual room with still-scattered toys.

Regardless of the fate of the current evidence, discrepancies, hypotheses, and speculations, I look forward to a blossoming field in which the difficult problem of the transition between infancy and childhood is directly approached, a field in which there already is some growing interest (e.g., Simmering, 2012; Pailian et al., 2016).

Acknowledgments

This is a draft of a paper for *Advances in Child Development and Behavior*. This work was completed with support from NIH Grant R01-HD21338. I thank Lisa Feigenson for helpful discussions.

References

Baddeley, AD., Hitch, G. Working memory. In: Bower, GH., editor. The psychology of learning and motivation. Vol. 8. New York: Academic Press; 1974. p. 47-89.

Baddeley AD, Thomson N, Buchanan M. Word length and the structure of short term memory. Journal of Verbal Learning and Verbal Behavior. 1975; 14:575–589.

Case R, Kurland DM, Goldberg J. Operational efficiency and the growth of short term memory span. Journal of Experimental Child Psychology. 1982; 33:386–404.

Chi, MTH. Knowledge structures and memory development. In: Siegler, R., editor. Children's thinking: What develops?. Hillsdale, NJ: Erlbaum; 1978.

Cowan N. The magical number 4 in short-term memory: A reconsideration of mental storage capacity. Behavioral and Brain Sciences. 2001; 24:87–185. [PubMed: 11515286]

Cowan N. Working memory maturation: Can we get at the essence of cognitive growth? Perspectives on Psychological Science. 2016; 11:239–264. [PubMed: 26993277]

Cowan N, AuBuchon AM, Gilchrist AL, Ricker TJ, Saults JS. Age differences in visual working memory capacity: Not based on encoding limitations. Developmental Science. 2011; 14:1066–1074. [PubMed: 21884322]

Cowan N, Blume CL, Saults JS. Attention to attributes and objects in working memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2013; 39:731–747.

Cowan N, Elliott EM, Saults JS, Morey CC, Mattox S, Hismjatullina A, Conway ARA. On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. Cognitive Psychology. 2005; 51:42–100. [PubMed: 16039935]

Cowan N, Johnson TD, Saults JS. Capacity limits in list item recognition: Evidence from proactive interference. Memory. 2005; 13:293–299. [PubMed: 15952261]

Cowan N, Morey CC, AuBuchon AM, Zwilling CE, Gilchrist AL. Seven-year-olds allocate attention like adults unless working memory is overloaded. Developmental Science. 2010; 13:120–133. [PubMed: 20121868]

Cowan N, Nugent LD, Elliott EM, Ponomarev I, Saults JS. The role of attention in the development of short-term memory: Age differences in the verbal span of apprehension. Child Development. 1999; 70:1082–1097. [PubMed: 10546336]

Cowan N, Ricker TJ, Clark KM, Hinrichs GA, Glass BA. Knowledge cannot explain the developmental growth of working memory capacity. Developmental Science. 2015; 18:132–145. [PubMed: 24942111]

Cowan N, Wood NL, Wood PK, Keller TA, Nugent LD, Keller CV. Two separate verbal processing rates contributing to short-term memory span. Journal of Experimental Psychology: General. 1998; 127:141–160. [PubMed: 9622911]

Cusack R, Lehmann M, Veldsman M, Mitchell DJ. Encoding strategy and not visual working memory capacity correlates with intelligence. Psychonomic Bulletin & Review. 2009; 16:641–647. [PubMed: 19648446]

Daneman M, Carpenter PA. Individual differences in working memory and reading. Journal of Verbal Learning & Verbal Behavior. 1980; 19:450–466.

Endress AD, Potter MC. Large capacity temporary visual memory. Journal of Experimental Psychology: General. 2014; 143:548–566. [PubMed: 23937181]

Flavell JH, Beach DH, Chinsky JM. Spontaneous verbal rehearsal in a memory task as a function of age. Child Development. 1966; 37:283–299. [PubMed: 5941895]

Fougnie, D., Cormiea, SM., Kanabar, A., Alvarez, GA. Strategic trade-offs between quantity and quality in working memory. Journal of Experimental Psychology: Human Perception and Performance. 2016. Mar 7. Advance online publication. http://dx.doi.org/10.1037/xhp0000211

Gaillard V, Barrouillet P, Jarrold C, Camos V. Developmental differences in working memory: Where do they come from? Journal Of Experimental Child Psychology. 2011; 110:469–479. [PubMed: 21664622]

Gathercole SE, Pickering SJ, Ambridge B, Wearing H. The structure of working memory from 4 to 15 years of age. Developmental Psychology. 2004; 40:177–190. [PubMed: 14979759]

Gilchrist AL, Cowan N, Naveh-Benjamin M. Investigating the childhood development of working memory using sentences: New evidence for the growth of chunk capacity. Journal of Experimental Child Psychology. 2009; 104:252–265. [PubMed: 19539305]

Gold JM, Fuller RL, Robinson BM, McMahon RP, Braun EL, Luck SJ. Intact attentional control of working memory encoding in schizophrenia. Journal of Abnormal Psychology. 2006; 115:658–673. [PubMed: 17100524]

Halford GS, Cowan N, Andrews G. Separating cognitive capacity from knowledge: A new hypothesis. Trends in Cognitive Sciences. 2007; 11:236–242. [PubMed: 17475538]

Hardman K, Cowan N. Remembering complex objects in visual working memory: Do capacity limits restrict objects or features? Journal of Experimental Psychology: Learning, Memory, and Cognition. 2015; 41:325–347.

Hitch GJ, Halliday MS, Littler JE. Item identification time and rehearsal rate as predictors of memory span in children. The Quarterly Journal of Experimental Psychology. 1989; 41A:321–337.

Hulme C, Tordoff V. Working memory development: The effects of speech rate, word length, and acoustic similarity on serial recall. Journal of Experimental Child Psychology. 1989; 47:72–87.

Kahneman D, Treisman A, Gibbs BJ. The reviewing of object files: Object specific integration of information. Cognitive Psychology. 1992; 24:175–219. [PubMed: 1582172]

Kail R, Salthouse TA. Processing speed as a mental capacity. Acta Psychologica. 1994; 86:199–255. [PubMed: 7976467]

Kibbe MM. Varieties of visual working memory representation in infancy and beyond. Current Directions in Psychological Science. 2015; 24:433–439.

Kane MJ, Bleckley MK, Conway ARA, Engle RW. A controlled-attention view of working-memory capacity. Journal of Experimental Psychology: General. 2001; 130:169–183. [PubMed: 11409097]

Kibbe MM, Leslie AM. What’s the object of object working memory in infancy? Unraveling ‘what’ and ‘how many’. Cognitive Psychology. 2013; 66:380–404. [PubMed: 23770623]

Luck SJ, Vogel EK. The capacity of visual working memory for features and conjunctions. Nature. 1997; 390:279–281. [PubMed: 9384378]

Ma WJ, Husain M, Bays PM. Changing concepts of working memory. Nature Neuroscience. 2014; 17:347–56. [PubMed: 24569831]

Mall JT, Morey CC, Wolf MJ, Lehnert F. Visual selective attention is equally functional for individuals with low and high working memory capacity: Evidence from accuracy and eye movements. Attention, Perception, & Psychophysics. 2014; 76:1998–2014.

Miller GA. The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychological Review. 1956; 63:81–97. [PubMed: 13310704]

Miller, GA., Galanter, E., Pribram, KH. Plans and the structure of behavior. New York: Holt, Rinehart and Winston, Inc; 1960.

Morey CC, Cowan N. When visual and verbal memories compete: Evidence of cross-domain limits in working memory. Psychonomic Bulletin & Review. 2004; 11:296–301. [PubMed: 15260196]

Oakes LM, Baumgartner HA, Barrett FS, Messenger IM, Luck SJ. Developmental changes in visual short-term memory in infancy: evidence from eye-tracking. Frontiers In Psychology. 2013; 4:1–13. [PubMed: 23382719]

Oberauer K, Eichenberger S. Visual working memory declines when more features must be remembered for each object. Memory & Cognition. 2013; 41:1212–1227. [PubMed: 23716004]

Pailian H, Libertus M, Feigenson L, Halberda J. Visual working memory capacity increases between ages 3 and 8 years, controlling for gains in attention, perception, and executive control. Attention, Perception, And Psychophysics. 2016; 78:1556–1573.

Pashler H. Familiarity and visual change detection. Perception & Psychophysics. 1988; 44:369–378. [PubMed: 3226885]

Riggs KJ, Simpson A, Potts T. The development of visual short-term memory for multifeature items during middle childhood. Journal of Experimental Child Psychology. 2011; 108:802–809. [PubMed: 21257180]

Riggs KJ, McTaggart J, Simpson A, Freeman RPJ. Changes in the capacity of visual working memory in 5 to 10 yearolds. Journal of Experimental Child Psychology. 2006; 95:18–26. [PubMed: 16678845]

Ross-Sheehy S, Oakes LM, Luck SJ. The development of visual short-term memory capacity in infants. Child Development. 2003; 74:1807–1822. [PubMed: 14669897]

Rouder JN, Morey RD, Cowan N, Zwilling CE, Morey CC, Pratte MS. An assessment of fixed-capacity models of visual working memory. Proceedings of the National Academy of Sciences (PNAS). 2008; 105:5975–5979.

Rouder JN, Morey RD, Morey CC, Cowan N. How to measure working-memory capacity in the change-detection paradigm. Psychonomic Bulletin & Review. 2011; 18:324–330. [PubMed: 21331668]

Shipstead Z, Engle RW. Interference within the focus of attention: Working memory tasks reflect more than temporary maintenance. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2013; 39:277–289.

Simmering VR. The development of visual working memory capacity during early childhood. Journal Of Experimental Child Psychology. 2012; 111(4):695–707. [PubMed: 22099167]

Stoltzfus, ER., Hasher, L., Zacks, RT. Working memory and retrieval: An inhibition resource approach. In: Richardson, JTE.Engle, RW.Hasher, L.Logie, RH.Stoltzfus, ER., Zacks, RT., editors. Working memory and human cognition. New York: Oxford University Press; 1996. p. 66-88.

Vogel EK, McCollough AW, Machizawa MG. Neural measures reveal individual differences in controlling access to working memory. Nature. 2005; 438:500–503. [PubMed: 16306992]

Vogel EK, Woodman GF, Luck SJ. The time course of consolidation in visual working memory. Journal of Experimental Psychology: Human Perception and Performance. 2006; 32:1436–1451. [PubMed: 17154783]

Wang, B., Cao, X., Theeuwes, J., Olivers, CNL., Wang, Z. Separate Capacities for Storing Different Features in Visual Working Memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2016. Jul 11. Advance online publication http://dx.doi.org/10.1037/xlm0000295

Wheeler ME, Treisman AM. Binding in short term visual memory. Journal of Experimental Psychology: General. 2002; 131:48–64. [PubMed: 11900102]

Zosh JM, Feigenson L. Memory load affects object individuation in 18-month-old infants. Journal of Experimental Child Psychology. 2012; 113:322–336. [PubMed: 22932473]

Zosh JM, Feigenson L. Array heterogeneity prevents catastrophic forgetting in infants. Cognition. 2015; 136:365–380. [PubMed: 25543889]

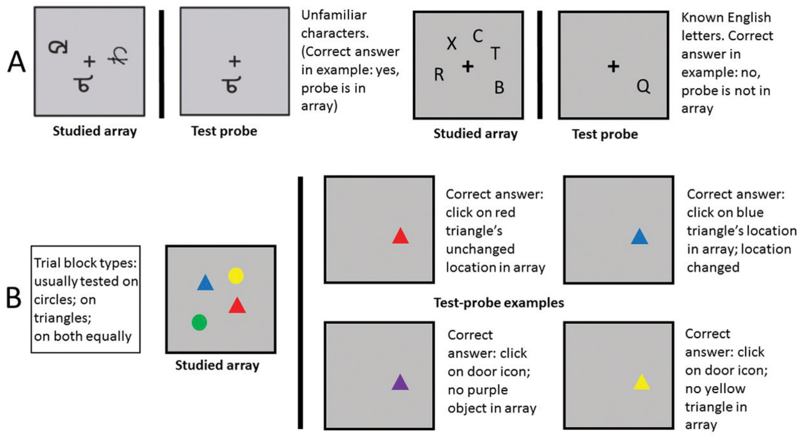

Figure 1.

Illustrations of the procedures used in visual working memory tasks with children. The dark vertical bar in each case represents a delay between the end of the materials to be remembered and the beginning of the probe item. **Part A**, Cowan et al. (2015); **Part B**, Cowan et al. (2010).

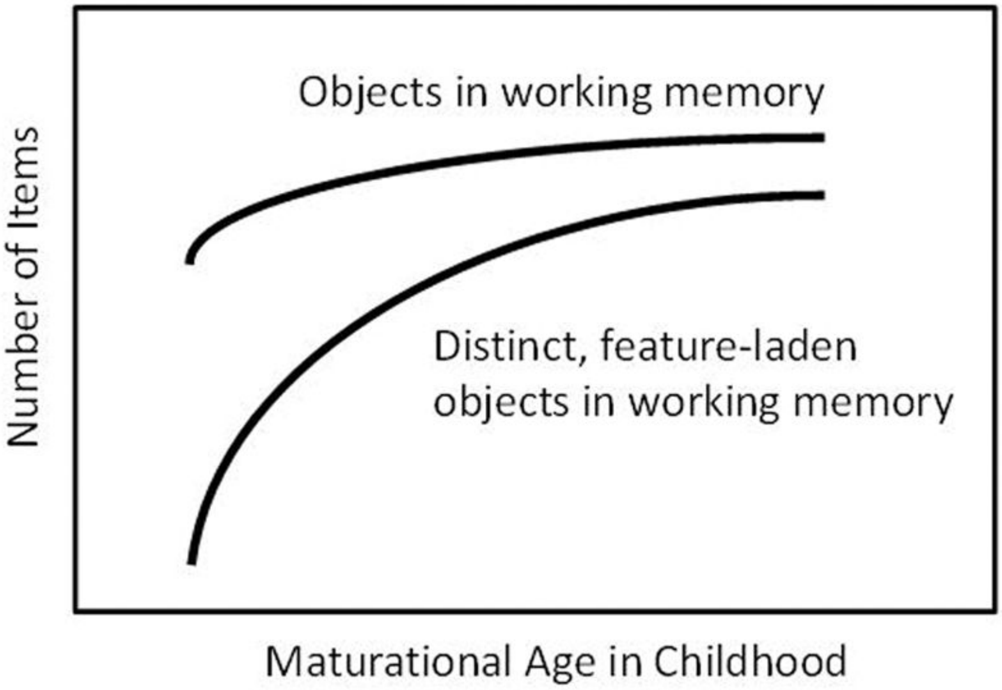

Figure 2.

A schematic diagram of how we might obtain different rates of development for different procedures. The number of objects in working memory (top line) might be larger than the number of distinct, feature-laden objects that can be discriminated from one another. In-between curves might also exist, for partly-distinguished objects.

Table 1

Chunks in working memory and processing efficiency measures in 4 experiments

	Chunks in Working Memory		**Processing Efficiency**	
Experiment/Type of materials	**7–9 Years**	**College**	**7–9 Years**	**College**
Gilchrist et al. (2009)	2.5 (0.25)	3.1 (0.25)	0.79 (0.02)	0.80 (0.02)
Lists of short sentences				
Cowan et al. (2015, 1-s)	1.89 (0.22)	4.41 (0.16)	0.68 (0.05)	0.70 (0.01)
Arrays of English letters				
Cowan et al. (2010)	1.50 (0.10)	3.00 (0.13)	0.60 (0.06)	0.58 (0.03)
Arrays of colored shapes				
Cowan et al. (2011)	1.99 (0.13)	3.15 (0.09)	0.58 (0.04)	0.52 (0.02)
Temporo-spatial sequences of colored shapes			0.57 (0.03)	0.57 (0.01)

Note. Data from 4 experiments showing age differences in the estimated number of chunks in working memory, when processing efficiency has been equalized across ages. The first row of results reflects memory for at least one content word from each simple, spoken sentence indicating access to that sentence within 4-sentence lists; the second row, letters in a briefly presented spatial array; the third row, colored objects in a brief spatial array; and the fourth row, colored objects in a slower, spatiotemporal array. The measures of processing efficiency are, in the first row, the proportion of words recalled from accessed sentences for which at least one content word was recalled; in the second row, memory for letters divided by the sum of memory for letters and unfamiliar characters; in the next two rows, memory for the colors of the more-relevant shape divided by that for both shapes together, for 4-item arrays in the silent condition; and in the fifth row of numbers, another efficiency measure for Cowan et al. (2011), memory for colors from trials with silence divided by memory for colors from the sum of the silent and speak-an-irrelevant-word conditions.