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Things to Remember

Limits, Codes, and the Development of Object Working Memory in the First Year

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The cognitive revolution of the 1960s had its roots in breakthroughs in the mathematics of machine theory, cybernetics, information, and formal systems associated with Turing, Weiner, von Neumann, Shannon, and Chomsky. For the first time, it was possible through the science of computation to glimpse—at least in principle—a physical basis for mind and mental phenomena. When Miller (1956) published his famous article on memory, it was to proclaim two things that have now become familiar. The first was that we can actually measure mental phenomena without white coats and large machines but, best of all, without embarrassment. The second was that some human memory systems have an astonishingly severe limit. There was also a third finding. Though we can (fairly) easily attach a number to this limit, and measure it in that sense, it is much harder to characterize what exactly are the units that are the subject of this limit. Miller believed the number was around seven; but he quickly showed that it was not seven of Shannon's bits but seven of something else, which he called chunks. The human memory system was not simply a channel carrying input passively but a complex system that actively recoded its throughput, as digits, letters, words, phrases, and so on, according to the goals of the task. The limit of seven reflected the structure of these codes. The twin properties of limit and code still define short-term memory research: how much can be stored and how much of what can be stored.

Miller was not the only pioneer of the cognitive revolution interested in limits. On the other side of the Atlantic, Broadbent (1958) argued that attention too was capacity limited and could be conceptualized as a channel with a limited bandwidth, just as short-term memory could. What are the relations between the limits on attention and on what can be attended to, on the one hand, and the limits of short-term memory, on the other? Are these wholly distinct mechanisms or are they related? As the chapters in this volume testify, these same questions are now being asked by infancy researchers. When do short-term memory and attentional mechanisms emerge in infancy? Do these mechanisms already show the main characteristics of the mature state and, if not, how do they differ, how do they develop toward the mature state, and what is the role of the maturation of the underlying neural systems?

The authors of the previous four chapters focused on the following list of questions:

1. What kind of memory are we studying?
2. What are the methodological challenges and limitations?
3. How does this type of memory change with development?
4. What is the relationship to neuroscientific findings? What do we currently know about the underlying brain mechanisms?

We begin by discussing each of these four questions. We then take a closer look at two central theoretical issues that were raised in chapters 3 and 4: the twin problems of limit and code. Finally, we reflect on the fifth question raised by the editors:

5. What are the main questions for future research?

What Kind of Memory Are We Studying?

The authors of the four previous chapters were asked to characterize the kind of mechanism that they are studying. Each of the four chapters emphasizes a different aspect of the short-term/working memory system. But before we look at these aspects, let's agree on a consistent terminology. Chapter 1 does a great job of clarifying the different terms used in the literature. *Short-term memory* is used to describe the temporary storage of information, with a focus on the actual temporal extent (few seconds). On the other hand, following Baddeley and Hitch (1974), working memory (WM) is the "maintenance of task-relevant information during the performance of a task" that involves more than just storage. In the neuroscience literature, the terms *manipulation* and *maintenance* are used to distinguish the active and passive aspects of this buffer (Courtney, Petit, Haxby, & Ungerleider, 1998). Reznick (chapter 1) argues that we cannot distinguish the storage component from the broader WM concept in infants. In fact, we should not even really be interested in the storage component by itself (which "exists only as a by-product of artificially induced laboratory conditions"). We agree with this view and suggest using the term *working memory* from here on.

The real question of course is not the term, but what we think it covers. An immediate issue: The concept of WM is evolving in the adult literature.

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The authors of the four chapters each cite a different new model of WM. For example, Reznick (chapter 1) brings up Nairne's notion of cue salience, Feigenson (chapter 3) mentions Cowan's theory of WM as items in the focus of attention, Oakes, Ross-Sheehy, and Luck (chapter 4) build on Luck and Vogel's findings on visual STM, and Bell and Morasch (chapter 2) refer to Engle, who emphasized the maintenance of items in memory against interference. All of these new approaches question a different aspect of the classic Baddeley model. With this many alternatives at hand, the question arises: Should infancy researchers follow these new models, stick to the classic model, or develop their own? We are definitely in favor of using models that have been proven useful in understanding WM in adults, so the last option does not seem to be so promising. Like the authors of all four chapters, we too implicitly assume a great deal of continuity in the basic structures of WM from infancy to adulthood and expect developmental changes only in quantitative aspects, such as memory capacity, or in what kinds of information get stored. As far as the issue of classic versus more recent models is concerned, we think the classic model in its updated version (Baddeley, 1998, 2003) is still very much alive and doing well.

Notes on Studying Infant WM

Reznick, Oakes et al., and Feigenson all stress the need to clearly distinguish WM from long-term memory. Reznick points out that this distinction is allowed only by those paradigms that use a limited set of experimental stimuli and that in each test probe the infant with a subset of these with replacement. This way, the infant truly has to rely on WM and not a mere recognition of novelty. We think that carefully designed familiarization and test procedures can solve this problem.

For example, in our study on infants' WM (Káldy & Leslie, 2003, 2005), we asked whether infants are able to bind object identity information to an object that changes location (tell *what* was *where*). After being familiarized to a disk and a triangle, infants saw these two objects disappear behind two spatially separated screens. After a 2-second delay, the screens were removed to reveal the two objects in swapped locations. Both 6.5- and 9-month-old infants looked longer at the unexpected (swapped) outcome (see Figure 5.1, panel 1).

Crucially, during both familiarization and test trials, the side of the presentation of the disk and the triangle alternated from trial to trial. This way, infants could not rely on their long-term memories about where a particular object usually was or merely associate a shape feature with a location because both shapes were associated with both locations equally across the experiment. They could only succeed in the task if they could constantly update the content of their WM, exactly as Reznick has suggested. The principle behind this method should be applied in all looking time studies of infant WM: Infants should be familiarized to all the objects and locations

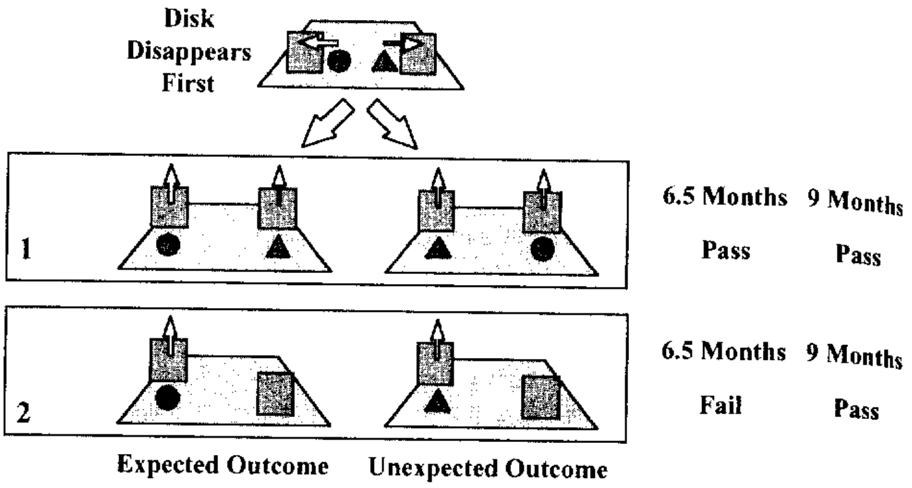

FIGURE 5.1. Summary of main findings of Káldy and Leslie (2003, 2005). Following the logic of violation-of-expectation paradigms, Pass signals that infants looked significantly longer at the unexpected outcome than at the expected outcome, and Fail signals that there was no significant difference between reactions to the two different outcomes. Before the test, infants were systematically familiarized with both of the objects appearing on alternating sides of the stage. Objects were hidden sequentially; in the sequence presented here the first object hidden was the disk on the left. Reprinted from Káldy, Z., & Sigala, N. (2004). The neural mechanisms of object working memory: What is where in the infant brain? *Neuroscience and Biobehavioral Reviews, 28,* 113–121, copyright 2004, with permission from Elsevier. See color plates.

before the final phase of the test, and in that final phase nothing that is novel in itself should appear (see also Tremoulet, Leslie, & Hall, 2000, for further discussion of this point).

One other interesting aspect of our findings was that the younger (6.5-month-old) infants solved the two-screen task in a different way from older ones (9-month-olds). Since in this task objects were hidden sequentially, we could test each group on whether they remembered both objects in the sequence (Figure 5.1, panel 1) or only the last one they had seen (panel 2). Our results showed that 6.5-month-olds did not remember the shape of the first-hidden object, while 9-month-olds did. With this method, we were able to address the question of sampling: namely, whether infants in a multiple-object task are actually tracking all the objects or just a subset of them. Indeed, for 9-month-olds, the effect size in this new experiment was larger than with the removal of both screens, showing that these infants have actually remembered both the first- and the last-hidden object.

Our conclusion was that 9-month-olds are able to bind shape information to two object indexes that followed the objects as they were moved on stage to new locations. They could remember what went where for two distinct individuals: "disk in location 1," "triangle in location 2." The 6.5-month-olds infants could do this too—bind shape information to a representation that indexed a moving object—but they could do so only for a single object. Object identity information was lost or overwritten as soon as attention went to a second object that was moved and hidden. Since we did not find any age effects within our two samples, we estimated that this new ability comes online sometime between 7 and 8.5 months of age (Káldy & Leslie, 2005). Oakes et al. (chapter 4), using a quite different paradigm, report results that match this estimate perfectly. They demonstrated that 7.5-month-old infants could bind color and location information for multiple nonoccluded objects in a rapidly changing stream of images.

We would also like to address here a critical point that Oakes et al. (chapter 4) have expressed about our paradigm. They write, "However, because during the test infants had several seconds to learn the relative locations of the objects, these data do not unambiguously rule out the influence of longer term memory systems in infants' binding of object identity and location." We believe that what they call learning (within an individual trial) is exactly what we call encoding in WM. In their introduction, they list a few examples of everyday scenarios when infants use their visual short-term memory: "Moreover, tracking objects as they are occluded and disoccluded is a common part of infants' everyday experience—VSTM is necessary for infants to recognize, for example, that a ball that rolls under the couch is the same ball that emerges from the other side a short time later." In our opinion, we tested exactly this ability in our infant subjects on each individual trial. If infants were relying on their long-term memory, then presumably they would also remember the trials they had watched previous to the test trial they were currently viewing. Because we alternated the locations of the objects across trials, long-term memory would subject stored object-identity-by-location information to severe proactive interference. Furthermore, we would not expect to see any capacity limit if long-term memory were the storage mechanism tapped by this task.

We think it is much more likely that these two different paradigms provide converging evidence on WM limits. We propose the following hypotheses: (a) infant object WM up to 7 months has a severely restricted capacity of a single item; and (b) this system develops rapidly thereafter, reaching two items by 8 to 9 months and three items by 11 to 12 months. We come back to this proposal later in the chapter.

The Nature of Representations in Infant WM

Reznick (chapter 1) suggests that "a key feature of short-term memory is the notion that an explicit representation is being sustained for some brief duration of time." He argues that looking time studies that rely on the familiar—unfamiliar distinction might reflect the existence of a representation that is not well articulated. In our view, this is not a problem with looking time studies, but one of the essential questions this method can help us solve. When we show a Minnie Mouse doll to an infant, will she remember it as a mouse doll with big round ears and a pink dress, as a black, white, and pink blob, or just as a "thing" (a Spelke object)? These are the kinds of questions that can be asked and answered by figuring out the right kinds of control conditions in further looking time tests. Each of the alternative descriptions of Minnie Mouse is potentially an alternative hypothesis that can be examined. And that is exactly what the evolving literature has been doing—empirically testing the information content of infant representations.

Indeed, both the dialectics of the theoretical controversies in the infant literature and the ingenuity of the designs used are largely directed at questions of determining what properties infants are representing. Clashes of view are invariably centered on exactly such questions. One old example is the series of experiments by Leslie (1982, 1984a, 1984b; Leslie & Keeble, 1987; reviewed in Leslie, 1994) that ruled out a succession of possible spatiotemporal properties of launching events to conclude that infants represent a causal-mechanical property as such when they view launching events (and see also the dissenting views of, e.g., Haith, 1998). One current such controversy is whether infants represent numerosity, individuals, or continuous extent when they track small sets of objects (see chapter 2)? There is nothing unusual about such questions and they are not limited to infant looking time studies. Of course, when we come to study infants, we lack the royal path of language and the ability to instruct our subjects using language. But that is true as well with the study of other species or indeed when we study systems in the adult human that are not dependent upon nor informed by language, such as the visual system. As cases in point, consider the following questions: What properties are represented in V1? Is visual attention structured by space, time, objects, or all of these? What is a visual object? So we do not agree that the question of representation is a special difficulty for infancy studies; rather, it is one of the field's most important topics.

How Should We Study WM in Infants?

Widely Different Methods

A useful way to group the methods that the previous four chapters have discussed is whether they test object location, identity, or number.

- Location of objects: delayed response and peek-a-boo (chapter 1), A-not-B (chapter 2), change detection (chapter 4)
- Identity of objects: change detection (chapter 4)
- Number of objects: cracker choice (foraging) and manual search (chapter 3)

Unfortunately, looking time studies using the violation-of-expectation method are missing from this picture, which is a regrettable shortcoming (just to note a few, besides our own studies discussed above; Mareschal & Johnson, 2003; Wilcox & Baillargeon, 1998; F. Xu & Carey, 1996, etc.). One of the reasons for this omission is that most of the researchers in this field were not using the term *working memory* to describe the system that they have been studying—but this has been changing recently (e.g., Leslie & Káldy, 2001).

Alas, terminology often has a power it should not and it can divide fields that ought to be united. One potentially unifying interest is provided by object cognition itself. Studies of adult attention over the last two decades have given an increasingly important role to objects as an organizing principle (for a review, see Scholl, 2001). Many of these ideas from object-based attention are currently being integrated into the long tradition of study of the object concept in infancy (for an early attempt at this, see Scholl & Leslie, 1999; for recent developments, see chapter 3, this volume). One of the few things that all of the authors in this volume agree on is that something important in regard to object WM develops during the second half of the first year of life. In our opinion, using widely different methods to study these questions is ideal; however, different methods underscore the need for a theory that can connect the results and frame the inevitable puzzles that are the mark of progress.

Ecological Validity

The different tasks that have been used to study infants' WM range in a wide spectrum of ecological validity from the cracker choice task (more valid?) to change detection (less valid?). Violation-of-expectation studies with three-dimensional objects tend to be on the more ecologically valid side. On the other hand, some might argue that change detection with squares flashed for 500 ms might be a straitjacket for infants' abilities. However, there are very good reasons why scientists bring nature into the laboratory. By doing so, we position ourselves so that we can analyze and compare theoretical predictions. The only really important question regarding a method is whether it reveals theoretically meaningful phenomena, and for change detection the answer, as far as we can see, is clearly positive. Ecological validity is only important insofar as it lines up with theoretical validity.

How Does This Type of Memory Change With Development?

As we noted earlier, one of the common themes in chapters 1 through 4 is that WM capacity increases steadily during the first year of life. Improvements can be measured in two separate components: (1) the number of objects or locations that infants can remember, and (2) the length of delay that infants can tolerate. The onset of WM capacity (i.e., remembering at least one object or location over the shortest possible delay) is estimated to be somewhere around 4 months (chapter 4) to 5.5 months (chapter 1). There is a steady improvement in the number of remembered objects and locations up to 12 months (which is the oldest age group tested by the authors of the four chapters). There are a few notable qualifications to this claim. Bell and Morasch (chapter 2) point out (based on a longitudinal study by Bell & Fox, 1992) that they found increasing delay tolerance in the A-not-B task only in those infants whose frontal cortex baseline activity was also increasing during the same period. This points to the importance of longitudinal studies in a field of developmental psychology where we have the advantage that this type of study only requires months and not years.

Here is where we should discuss a particular aspect of Oakes et al.'s (chapter 4) project as well. They studied the different developmental trajectories of remembering object identities, locations, and the binding of identity and location information for multiple objects using a change detection paradigm. The results showed gradual improvements in all three domains between 4 and 12 months of age. However, regarding the third question, binding object identities to locations, we think it is important to raise the issue of sampling. In Oakes et al.'s paradigm, all three objects changed location or identity from one trial to the next, and infants could notice the change by focusing their attention on only one of the objects. We propose a control experiment to test whether infants were sampling the set. In this version, only two of the objects (randomly chosen from the set of three) are swapping their identities (color). Let's say that in Trial 1 infants see red in Location 1, blue in Location 2, and yellow in Location 3. Then in Trial 2, they will again see red in Location 1, but yellow in Location 2 and blue in Location 3. Infants need to track at least two out of three objects to notice the change. If the estimates of power are in the same range as in the original study, then it is possible to conclude that infants in that paradigm can track what is where for multiple objects.

What Is the Relationship to Neuroscientific Findings? What Do We Currently Know About the Underlying Brain Mechanisms?

Reznick (chapter 1) rightly points out that most of the pediatric anatomical and neuroimaging studies are not specific enough for developmental psychologists to connect to. He suspects that behavioral researchers will show the way to neuroscientists. We agree with this view, but at the same time, we would like to point out that it is not impossible to make connections between the neurophysiological literature and behavioral studies. The authors of chapters 1 through 4 attempted to make these connections (only Bell and Morasch, chapter 2, were able to rely on results from their own laboratory). We will first summarize these attempts, then outline our take on the neural underpinnings of WM in infants.

Diamond's now classic studies from the 1980s (Diamond, 1985; Diamond & Goldman-Rakic, 1989) showed the importance of the dorsolateral prefrontal (PF) cortex in solving the A-not-B task, the immortal Piagetian test of object-location memory. Indeed, Bell and Morasch (chapter 2) start their discussion of WM as an example of PF functions, implying implicitly that PF involvement is a defining characteristic. (Later on, based on their own studies, they add occipital activity as another factor.) Reznick (chapter 1) cites Diamond as well, along with WM studies with older children that showed posterior parietal and anterior cingulate activity besides PF. The different theories regarding the function of the two visual streams are also prominent. The Goodale-Milner theory asserts that the dorsal stream processes visually guided action, while the ventral stream's main function is object recognition. Reznick uses this hypothesis to explain the performance differences found in infancy studies that measure reaching versus looking behavior. We are inclined to disagree with this hypothesized connection, since both reaching and looking are visually guided behaviors and therefore depend on the dorsal stream. We believe that Oakes et al. (chapter 4) approach the dorsal-ventral question in a fruitful way. They suggest that trying to determine whether the dorsal or the ventral stream develops first based on behavioral data is currently problematic: There is evidence for both possible scenarios. They also suggest that the integration of information from both of the streams is key to the binding of object identity to locations, and we are highly sympathetic to this idea. In fact, we characterized our own results with 9-month-olds (see above) as evidence for dorsal-ventral integration (Káldy & Leslie, 2003). Based on recent adult functional magnetic resonance imaging (fMRI) and event-related potential (ERP) studies, Oakes et al. also argue for a role for the posterior parietal cortex in binding multiple object identities to locations. While this region is definitely involved in remembering object identities (it shows sustained activity during the memory delay), there is also ample evidence that the medial temporal cortex is involved in object-location binding (Milner, Johnsrude, & Crane, 1997; Sommer, Rose, Glascher, Wolbers, & Buchel, 2005).

Our hypothesis for the neural substrates of infant WM differs from the classic model, as we suggest that the PF cortex might not play a central role in object and location memory in infants. Instead, we argue for the involvement of medial temporal structures (Káldy & Leslie, 2003; Káldy & Sigala, 2004). In Káldy and Sigala (2004), we presented a detailed argument based on a comprehensive review of the neuroscience literature. Here we will only briefly summarize the three main lines of research that support our hypothesis: two independent single-cell studies with macaques and an infant ERP study.

First, a subset of neurons in the temporal and PF cortices exhibit object-and/or place-specific delay activity (Suzuki, 1999; Suzuki, Miller, & Desimone, 1997). This delay activity can act as a bridge between the first presentation of the object and the test. Importantly, this activity persists in both the temporal and PF cortices regardless of intervening objects (Suzuki et al., 1997). Prior to this report by Suzuki and her colleagues, only PF neurons were believed to respond in such a way. Survival of a memory trace in the face of subsequent input is a necessary feature of short-term memory (as opposed to iconic memory, for example). So while PF neurons have the same characteristic (as Oakes et al., chapter 4, have pointed out as well), we think it is more parsimonious to suggest that in human infants, in the first year especially, it is the faster maturing temporal area that has the central role.

Second, Baker and his colleagues (Baker, Keysers, Jellema, Wicker, & Perrett, 2001) demonstrated that neurons in the temporal cortex (in the anterior part of the superior temporal sulcus) respond to objects that gradually become occluded. This response is maintained for up to 11 seconds following complete occlusion. Baker et al.'s is the first study to use natural, progressive occlusion of three-dimensional objects; in previous studies of WM in macaques, objects disappeared suddenly on a computer screen. This methodological aspect makes it very relevant for infant studies of object cognition, as infants respond differently to progressive occlusion than to implosive disappearance: Infants only expect object persistence in the case of progressive occlusion. This claim, established almost 40 years ago by Bower (1967), has garnered some new support recently. A high-density ERP study by Kaufman, Csibra, and Johnson (2005) with 6-month-old infants found that activity in the temporal cortex was related to maintaining an object in memory in a naturalistic occlusion situation. There was comparably less activity in this area when, instead of becoming occluded, the object gradually disintegrated. An earlier study by the same research group (Kaufman, Csibra, & Johnson, 2003) measured ERP responses in infants while they were watching a possible and an impossible outcome scenario in a simple object permanence task. Results showed that brain activity was different in the temporal cortex in these two conditions.

The majority of the neuroscientific literature on memory is focused on macaque electrophysiological and adult human imaging studies. Drawing conclusions about mechanisms in the infant brain from these results is notoriously difficult because of the difference in the nature of the tasks. We believe that the temporal cortex hypothesis outlined above is especially attractive, precisely because it has received independent support from high-density ERP studies conducted on young infants. Indeed, the studies by Kaufman et al. (2003, 2005) point the way to linking infant behavioral findings to macaque electrophysiological findings.

Some Theoretical Issues

Motivation and Top-Down Effects

One major problem that none of the authors have discussed is whether the abilities that we test in babies are truly equivalent to adult WM. What constitutes a "task" and "task-relevant information" for an infant? What do adults do in similar paradigms without explicit instructions? We know very little

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about these issues. Our guess is that some of the gaps in performance between infants and adults would be significantly smaller if adults were tested without verbal instructions (see, e.g., Xu, Carey, & Quint, 2004).

Limits and Codes

The question of how many locations or objects infants can remember has been widely discussed in the present volume and elsewhere. Oakes et al. (chapter 4) present data showing an increase in the number of objects for which infants can track the color in a change detection task. Feigenson (chapter 3) shows that infants have a capacity limit in a two-set counting paradigm of around three to four items. Feigenson then argues that the fact that this number corresponds to the number that has been found in various visual memory tasks in adults (for a summary, see Cowan, 2001) is evidence that infants use the same memory system that adults use. In our work, we also took part in the number game. In Káldy and Leslie (2005) we concluded that somewhere between 7 and 8.5 months of age, infants become capable of remembering the location of two distinct objects.

However, as Feigenson points out, object complexity might complicate the picture and the appealing theory of a fixed number of slots in WM needs to be modified. Alvarez and Cavanagh (2004) questioned the claim that however many short-term memory slots there might be, each slot could hold an essentially unlimited amount of information (Luck & Vogel, 1997). Since Miller's notion of the chunk and the failure of classic information theory to capture memory load in terms of bits, there has never been a good way to measure this load. Alvarez and Cavanagh made an ingenious end run around this problem by taking independent measures of search rate in an attention experiment as proxy for information load in a memory task. When they did this, they found that the greater the information load (slower search rate) for each stimulus item, the fewer items one can hold in memory. Intriguingly, their regression data projected that if the information load of items were zero, short-term memory would still have a maximum capacity of four items. Remarkably, adult short-term memory is limited both by the information load of each item in each slot and by a maximum of four slots. These new ideas need to be researched with infants.

Objects and WM

Although adult WM seems to be fractionated into systems for different kinds of information, such as the phonological loop, the visuospatial sketchpad, and object WM, infant studies have principally focused on object WM. Although none of the chapters addressed the properties of the infant phonological loop, speech processing and word boundary segmentation develop rapidly during the first year. So there is little reason to doubt that infants possess this type of short-term memory system too.

In part, the focus on objects derives from a research tradition stemming from Piaget's work on the object concept. Piaget was concerned not with the question of memory as such but with the question of when infants could be in a position to believe that objects continued to exist behind an occluder. For Piaget this was a matter of fundamentals. He postulated that infants were a sensorimotor system that lacked powers of recall or representation. So although Piaget stressed that infants were active organisms, they could be active only in the limited sense that they could act and react within current stimulation, including the stimulation created by their own actions. This meant that infants would lose an object to the "void," even if they continuously attended to it, if it passed out of sight behind an occluder and the infants had not already activated an action schema while it was still visible. The loss of cognitive contact with the object under these circumstances is, according to his account (Piaget, 1955), the reason infants fail the A-not-B task and subsequently continue to fail invisible displacement tasks. He argued that a belief in the persistence of objects depends upon a mental system that can, as it were, step in for the object that no longer excites by putting a mental representation or image in its place. Piaget argued that this representational intelligence, despite all appearances to the contrary, was not constructed until the last half of the second year.

The contemporary view is now shaped by a more computational understanding of the nature of representation as something basic to any information processing system—one of the legacies of the cognitive revolution—and by a series of landmark experimental studies showing that even very young infants can represent occluded objects (Baillargeon, 1986; Baillargeon, Spelke, & Wasserman, 1985; Diamond, 1988; Spelke, Breinlinger, Macomber, & Jacobson, 1992). Much current research is therefore focused upon identifying and understanding the nature and development of the neurocognitive mechanisms that make this possible.

Object Files and WM

Feigenson in chapter 3 summarizes a rich and fascinating series of experimental findings on the limits of infants' ability to track multiple objects under occlusion. Her studies using measures of looking times, manual search, and foraging behavior produce converging evidence that infants are limited to tracking three individual objects concurrently. This limit, she argues, is strikingly similar to the limit of four items that current studies of visual WM has determined for adults (Alvarez & Cavanagh, 2004; Cowan, 2001). Feigenson then argues that the limit on infants' multiple object tracking reflects their WM limit.

Central to her argument is that infants track objects using internal representations called object files. Kahneman and Treisman (1984) coined this term in developing a new model of adult visual attention (see below). Simon (1997), Leslie, Xu, Tremoulet, and Scholl (1998), and Scholl and Leslie (1999)

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applied these and related ideas to outline a new theory of infant object concept development that departed radically from previous approaches. We discuss this in more detail below. For now, an object file represents a single object; to represent a set of objects requires a one-to-one corresponding set of object files. These multiple representations are stored in WM and take up multiple memory slots. When available slots run out, the infant loses track of the set. Feigenson skillfully presents convergent findings from a wide range of studies that indicate that the infant numerosity limit on small sets and the infant WM limit are one and the same. She then goes on to provide and consider evidence that infants eventually are able to circumvent these limits by chunking object files in memory. We shall return to the idea of infant chunking below; but lest we move too fast to the first conclusion regarding convergence, we should raise some warning flags.

One Limit or Many?

Could the findings of a limit of three in number and individuation studies and in studies of WM be a simple coincidence? Coincidence should be the last thing a working scientist believes in, so let us be clear what we have in mind here. The question is: Does the infant limit of three (or four) in studies of short-term object identity memory and in studies of object numerosity judgment arise from the very same neurocognitive mechanism? If the answer is yes, then it is no coincidence but a deeply principled finding. On the other hand, if the two limits stem from different neurocognitive mechanisms, then we may only have coincidence. In this regard, it seems that the numbers three or four do crop up as limits across contexts where it is hard to imagine any single common mechanism. For example, FINSTs, a kind of visual index (Pylyshyn, 1989; see below) that allows tracking of multiple objects moving with Brownian motion, are limited in adults to around four. Pylyshyn (2003) argues that FINSTs ("fingers of instantiation") are part of a preattentive mechanism and so their limit would have to be independent of WM. Likewise the subitizing limit in adults is around four and can be observed in tasks that do not demand WM (e.g., the orientation detection task of Sagi & Julesz, 1984). The number of core noun phrases (without prepositions) that verbs can take as arguments is limited to three or four (the verb *bet*, perhaps uniquely, can have four). It is unlikely that this particular limit has anything to do with object WM. Many more arguments can easily be added by way of preposition phrases to make quite intelligible sentences. There may be yet general reasons why three or four are the "magic" numbers in so many different cases without that reason being object WM limits.

Convergence or Divergence?

Some evidence points away from convergence. Oakes et al. (chapter 4) describe evidence from a rapid presentation change-detection paradigm that infant short-term memory limits increase from around one item at 6.5 months to around three (possibly four) items at 12 months. Káldy and Leslie (2003, 2005) used a looking time method that required infants on a trial-by-trial basis to track the changing locations of two differently shaped objects. Infants up to 7 months could remember the identity of only one object following occlusion of the other object. By 8.5 months, infants could robustly remember the identity of two objects. These two sets of studies show a changing WM limit over the second half of the first year, increasing from a severely restricted single item around 6 months to a more adultlike three (or four) items by 12 months. However, there is no evidence from numerosity studies of a similarly changing limit over the same period. The results from both Feigenson's and others' labs (e.g., Simon, Hespos, & Rochat, 1995; Wynn, 1992, 1996; Wynn, Bloom, & Chiang, 2002) seems instead consistent with an unchanging numerosity limit of about three from age 5 or 6 months onward. The available developmental data actually appear to dissociate the small numerosity limit of three and the WM limit of three (or four). We return to this puzzle later.

Object Files: Indexes and Feature Bundles

Because Feigenson and colleagues have made extensive use of the idea of object files in accounting for their findings, let's take a closer look at this idea. Kahneman and Treisman (1984; Kahneman, Treisman, & Gibbs, 1992) introduced the idea of an object file because they perceived a missing link in traditional accounts of object perception. In traditional accounts, bottom-up sensory information is thought to directly activate long-term semantic memory traces; once the appropriate semantic categories have been activated—and only then—can the objects in the scene be identified and tracked. The task of keeping track of objects that change location was conceived of as a search task. Initial contact with an object results in a description in memory that is a combination of the sensory information and the semantic information it activated. When the object moves, the scene must be searched to discover which item in the scene matches this object representation. When an item is found matching the description in memory, then it must be the same object. This traditional view has a long history (and one version of it can be discerned in Piaget's writing). Object representations in the traditional view are essentially feature bundles of one sort or another, including perhaps a semantic category label or a word, activated bottom-up but imposed top-down on sensory input. For Kahneman and Treisman, this view missed important phenomena. For example, objects can be tracked through space without being identified (described); the same object can be tracked through changes in its identification ("It's a bird! It's a plane!"); and two "identical looking" objects can be perceived as distinct if there is a minute spatiotemporal gap between the two, while two radically different looking objects can readily be seen as a single transforming object (frog changes into a prince).

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To accommodate such phenomena, Kahneman and Treisman introduced an intermediate level of object representation, which they called the object file. Object files are temporary object representations that interface between sensory information and long-term semantic information. They have two basic functional parts. The first and in many ways most important part of the object file is a continuously updated spatiotemporal code that locates the object corresponding to the object file. This is the indexing function of the object file; the file points at the object it refers to. We can think of this function as the file's "folder"—a container with only (continuously updated) spatiotemporal coordinates written on the folder's tab.

The second basic function of an object file is that the folder can have further information added, taken away, or changed. We can think of this as the sheets of paper that a folder might contain, each sheet having some property written upon it, either from sensory input or from long-term semantic storage. Together, the folder plus any information it may contain is an object file. In thinking about object files, we need to keep clear these two distinct functions. The folder may be empty, but it can still index and track an object without describing that object. In this regard, object file theory distinguishes itself radically from traditional theory. In traditional theory, an object representation is just a bundle of features; it consists of nothing but a sheaf of papers, as it were. Without features, there is no feature bundle; without a bundle, there is no object representation. But an object file can represent and track an object even if its folder is empty.

The way that Kahneman and Treisman thought of an empty object file as tracking an object was analogous to the way that a finger might track a moving object. When one picks out an object in a scene by touching it with one's index finger, the finger picks out the object without describing it. If you see only the finger, you have no idea whether it is touching something red or round or whatever. Instead, the finger helps you find the object by helping you find the object's location. Now imagine: When the object moves, the finger sticks to the object and moves with it.

The concept of the *sticky index* was highlighted and developed in Pylyshyn's FINST theory (Pylyshyn, 1989, 2000). Pylyshyn argued that even spatiotemporal information does not have to be added to a folder; a coordinate code does not have to be written on the folder's tab. We can do without even that much descriptive information. Instead, a simple winner-takes-all network can solve the correspondence problem—matching the mental index to an item in the visual world—without explicitly representing coordinates in the object file (Pylyshyn, 2003).

Howsoever it is implemented in the brain, indexing is an important and necessary function for any organism that tracks objects in real time. Leslie and colleagues chose to use the term *object index* in developing their approach to the infant object concept in order to emphasize this crucial and novel aspect of both object file and FINST theories (Leslie et al., 1998). An object file may or may not contain a feature bundle, but it must minimally contain an index.

We have briefly reviewed object indexing theory because the notion of a representation that does not describe but simply points at the world is an unusual idea with which many readers will not be familiar. It has allowed a new approach to the old problem of the developing object concept. These issues are discussed further in Leslie et al. (1998) and at greater length in Scholl and Leslie (1999; see also Tremoulet et al., 2000; also Krøjgaard, 2004, for an insightful review of more recent developments). Another reason is that indexing is relevant to both limits and chunking.

Are WM Limits Fixed or Do They Change With Development?

Chapters 3 and 4 lead us to a fascinating puzzle. If the WM capacity limit develops over the second half of the first year, why does the small numerosity limit not also develop in lock step? How can older infants exceed the small numerosity limit by chunking if that limit reflects a limit on active object files? How is numerosity information being encoded into WM? Perhaps the data that raise these puzzles will prove unreliable or not sufficiently comprehensive. In this case, as we learn more, the puzzles will simply dissolve. One possibility is that the WM limit of one at 6 months only appears along with an information load. Perhaps infants in numerosity experiments somehow operate with an information load per item that approaches zero. If so, they would be able to display more of their WM capacity, showing up as the numerosity or unloaded-WM limit of three. The upshot would be that the fixed limit on WM does not after all change with development (at least from 5 months onward), while its ability to carry an information load does.

Y. Xu and Chun (2006) have shown that the two different ways in which WM is limited, by total amount of information and by a fixed number of objects (Alvarez & Cavanagh, 2004), may correspond to dissociable neural systems. At least for static unoccluded objects, object WM tasks activate the superior intraparietal sulcus (IPS) together with the lateral occipital complex in a way that correlates to the total amount of information to be retained. The same tasks activate the inferior IPS in a way that indicates that it automatically stores a fixed number of objects (up to four) and tracks their locations. Xu and Chun may have found one of the neural systems underpinning the cognitive distinction between the descriptive information in an object file (the "sheets") and the nondescriptive object index. Indeed, they suggest that inferior IPS is a "spatial indexing mechanism that maintains spatial attention over a fixed number of objects at different spatial locations" (p. 94). It remains to be seen whether inferior IPS implements the sticky indexes required for tracking objects that change location and become occluded. Likewise, it remains to be seen whether superior IPS maintains identity information for moving occluded objects. We therefore do not know how these neural systems relate to those discussed earlier. However, the importance of posterior systems for object WM is again made clear.

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These new findings with adults (Alvarez & Cavanagh, 2004; Y. Xu & Chun, 2006) suggest a possible resolution to the puzzle of why infant WM capacity appears to increase between 6 and 12 months (Káldy & Leslie, 2003, 2005; chapter 4, this volume) while the numerosity limit does not. The increase in WM capacity is seen in tasks that require infants to store identity information (shape or color) for the objects. These tasks may tap superior IPS-lateral occipital complex or some other neural system that represents the descriptive information necessary for identification for a subset of the attended objects. The fixed numerosity limit, on the other hand, may reflect inferior IPS (or some other neural system) that indexes objects by location and has a fixed limit of three or four. On this account, it becomes critical to determine whether these dissociable neural systems show differences in their rates of growth and maturation. The identity storing component should show slower growth and maturation, picking up from around 6 months and continuing at least until 12, while the indexing system should grow and mature earlier and more rapidly and change less after 6 months.

One fly in the ointment for this account comes from Feigenson's cracker tracking tasks (Feigenson, Carey, & Hauser, 2002). We had to assume that in numerosity tasks, infants bind near zero information to their object indexes. However, in these tasks infants need to accumulate the continuous extent (size) of each of the objects they track into the containers. They therefore bind size features to the indexes. This seems to be no different from binding shape (Káldy & Leslie, 2003, 2005) or color (Káldy, Blaser, & Leslie, 2006; Ross-Sheehy, Oakes, & Luck, 2003) features. So the puzzle remains.

A resolution of this puzzle will still leave a puzzle about chunking. We still have an infant indexing limit of three together with a capacity to represent two sets of two (four objects). We turn to this in what remains of our chapter.

Can Object Files Be Chunked?

The way in which object files represent numerosity is indirect and implicit. For each object in a set, there is a corresponding object file actively indexing it. Because object files are temporary representations that actively index the location of moving objects, it makes no sense to store object files in long-term storage. Information in the feature bundle might find its way into long-term storage, but the index must be actively maintained in the here and now.

If object files alone are used to implicitly represent the numerosity of sets of objects, there will be a limit to the set size that can be so represented.[1] Moreover, it should be difficult to circumvent this limit, given a need to actively maintain indexes for moving objects and fixed resources. What are the possibilities? If active object files could be placed in long-term storage, there should be no limit on how many can be active; but apparently there is a limit. If object files could be endlessly packed into WM slots, there would be no limit; but again there is. If object files could be packed into WM slots up to a maximum number per slot, then the limit should be the maximum number of object files per slot multiplied by the number of WM slots. On this last account, an adult limit of four and an infant limit of three both suggest that the maximum number of object files per WM slot is about one. So far there is no obvious way to chunk the active object files themselves in order to escape the indexing limit.

Might a single object file index multiple objects? Could a single index point at a collection, like a flock of birds? This seems entirely plausible. Unfortunately there is a cost. Bear in mind that numerosity is represented implicitly by the number of object file indexes. If a single object file is used to index a set of objects, the numerosity represented is not the number of individuals in the set but the number of sets (one). Two such object files would represent two sets, but the number of individuals in each set simply goes unrepresented. Wynn et al. (2002) showed that, in displays where common motion defines distinct collections, infants can distinguish the numerosity of sets of blobs. But indeed, their infants had no idea how many individuals were in each set.

So how do Feigenson's infants not only know that there are two sets of objects but also know how many individuals are in each set? Recall that Feigenson and Halberda (2004) showed that 14-month-old infants will search for two sets of two objects, apparently knowing there are exactly two objects in each of two boxes. Inasmuch as this total of four exceeds the previously established indexing limit of 3, the results are puzzling. Feigenson suggests that the infant chunks the objects into sets. But just how is that done?

Perhaps infants were searching for two total amounts of stuff (Feigenson, Carey, & Spelke, 2002), but that seems unlikely. In a looking time study, Leslie and Chen (in press) familiarized 11-month-old infants with a pair of disks (XX) moved individually from and replaced behind a screen, followed by a pair of triangles (YY) displayed in the same way. Another group were familiarized with a repeating disk-triangle (XY) pair. The infants familiarized with two pairs (XX-then-YY) looked longer when the screen was removed to reveal only a single disk-triangle pair (XY) than did infants familiarized with the single (XY-then-XY) pair. If, however, the screen revealed two pairs, the looking times reversed. Now infants familiarized with the single pair looked longer than infants familiarized with the double pairs. These findings suggest that infants can individuate successive pairs of objects based on sequential shape differences between pairs. We thus have converging evidence from looking time in younger babies that infants chunk.

Representations That Chunk Past the Limit: Integers and Pairs

If infants can track two pairs of objects, how do they track that fourth object when their three object files are already used up? They need to free up an index to track the fourth object, but then they lose track of the object that

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We should consider the possibility that infants have another option besides object files for the exact, nonnoisy representation of small numerosities. One possibility that has not been explored in the literature is that infants have the integer representations ONE, TWO, and THREE (but not FOUR) available (for further discussion, see Leslie, Gallistel, & Gelman, in press). Another possibility, also not explored hitherto, is that infants have specific set representations, SINGLETON, PAIR, TRIPLET but not QUADRUPLE (see Leslie & Chen, in press). Either representation, integer or specific-set, would encode small numerosities without a Weber fraction, would chunk object sets so that exactly one, two, or three (but not four) objects can be represented per WM slot, and would allow up to a three-object set to be represented at a point in development (e.g., 6 months) when the infant may have only a single WM slot available. At this time, the literature on discrete number representation has considered only two possibilities, accumulator magnitudes and object files. Perhaps it is time to consider some of the many other possibilities.

Questions for Future Research

The four chapters in this part demonstrate that this is an exciting time in research on infant WM. New findings, new questions, and multiple maturing experimental methods are combining to promise further advances. At the same time, infancy research is making fresh gains by establishing theoretical connections with and exploiting advances being made in the study of adult WM and visual attention. Finally, it is becoming ever clearer just how important neural systems development is in driving cognitive development in infancy.

We already touched on a number of specific questions that are coming into focus and which require new efforts. Here we highlight: What is the relation between the development and maturation of anterior (PF) and posterior (temporal and parietal) brain systems for control of WM and attention, and what are the implications for infant cognitive development (chapter 4)? How does information about objects get bound to information about their locations (chapter 4)? How can we develop paradigms that can be used equally with infants, toddlers, older children, and adults, thus making the comparisons more seamless (chapter 2)? How can we relate WM development to other cognitive abilities (chapter 1)? What is the relation between the numerosity limit and developments in infant object WM (chapter 3)? Does development of infant WM involve an increase in the number of slots or an increase in the information carrying load of each slot with number of slots constant, or is there an increase in both the number of slots and their carrying load? Last century's breakthroughs in understanding the general nature of information machines have opened new perspectives on a very special machine: the mind-brain of the human infant. In this century, the nature of its limits and its codes are sure to remain key topics of investigation.

Note

1. The evidence for a limit comes from multiple object tracking in adults, where the limit is usually around four (Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999; Trick & Pylyshyn, 1994a, 1994b; but see Trick, Jaspers-Fayer, & Seth, 2005) and from Feigenson's studies with infants (reviewed in chapter 3), where the limit appears to be three.

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