LIFESPAN COGNITION

MECHANISMS OF CHANGE

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The Early Development of Executive Functions

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Executive function, also called *cognitive control* (Miller & Cohen, 2001); *effortful, conscious,* or *executive control*; or *supervisory attention* (Shallice, 1988), is required whenever going "on automatic" would be insufficient and especially when it would lead one astray. Classes of situations in which executive functions are required include (1) novel tasks and situations that require (2) concentration, (3) planning, (4) problem solving, (5) coordination, (6) change, (7) conscious choices among alternatives, or (8) overriding a strong internal or external pull.

Component cognitive abilities that constitute what collectively is known as *executive function* include the following:

1. *Inhibition*, that is, the ability to ignore distraction and stay focused, and to resist making one response and instead make another
2. *Working memory*, that is, the ability to hold information in mind and manipulate it
3. *Cognitive flexibility*, that is, the ability to flexibly switch perspectives, focus of attention, or response mappings

These abilities are crucial to all forms of cognitive performance. The ability to inhibit attention to distractors makes possible selective and sustained attention. The ability to inhibit a strong behavioral inclination helps make flexibility and change possible, as well as social politeness. Inhibition thus allows us a measure of control over our attention and our actions, rather than simply being controlled by external stimuli, our emotions, or engrained behavioral tendencies. The ability to hold information in mind makes it possible for us to remember our plans and others' instructions, to consider alternatives, and to relate one idea or datum to another, including relating the present to the future and the past. It is critical to our ability to see connections between seemingly unconnected items and to separate elements from an integrated whole; hence, it is critical to creativity, for the essence of creativity is to be able to disassemble and recombine elements in new ways, and to consider something from a fresh perspective.

While it is difficult to resist a natural inclination, after awhile executive function is no longer required to do that *as long as* one keeps within that same behavioral set. For example, on the classic Stroop task (MacLeod, 1991, 1992; Stroop, 1935), color words appear in the ink of another color (for example, the word *blue* might be printed in green ink). It is difficult to report the color of the ink, ignoring the word, but it is far easier to do that consistently than to switch back and forth between reporting the ink color and reporting the word. It is switching (resetting one's attentional focus, reorienting one's mindset) that is most difficult and epitomizes the twin needs for active maintenance (working memory) and inhibition, the hallmark of when concerted executive control is most clearly needed. Together, working memory and inhibition make it possible for us to quickly and flexibly adapt to changed circumstances, take the time to consider what to do next, and meet novel, unanticipated challenges.

There is strong evidence that areas of both dorsolateral and ventrolateral prefrontal cortex play a pivotal role in mediating executive functions. The evidence comes from a variety of sources, including brain-damaged patients (Barcelo & Knight, 2002; Koski & Petrides, 2001; Stuss, Floden, Alexander, Levine, & Katz, 2001; Stuss et al., 2000), functional neuroimaging of healthy adults (Braver, Reynolds, & Donaldson, 2003; Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001; Duncan & Owen, 2000; MacDonald, Cohen, Stenger, & Carter, 2000), studies using transcranial magnetic stimulation (TMS; Jahanshahi & Dirnberger, 1999; Mottaghy, Gangitano, Sparing, Krause, & Pascual-Leone, 2002), and studies of macaque monkeys (Diamond & Goldman-Rakic, 1985; Funahashi, Chafee, & Goldman-Rakic, 1993; Rainer, Assad, & Miller, 1998).

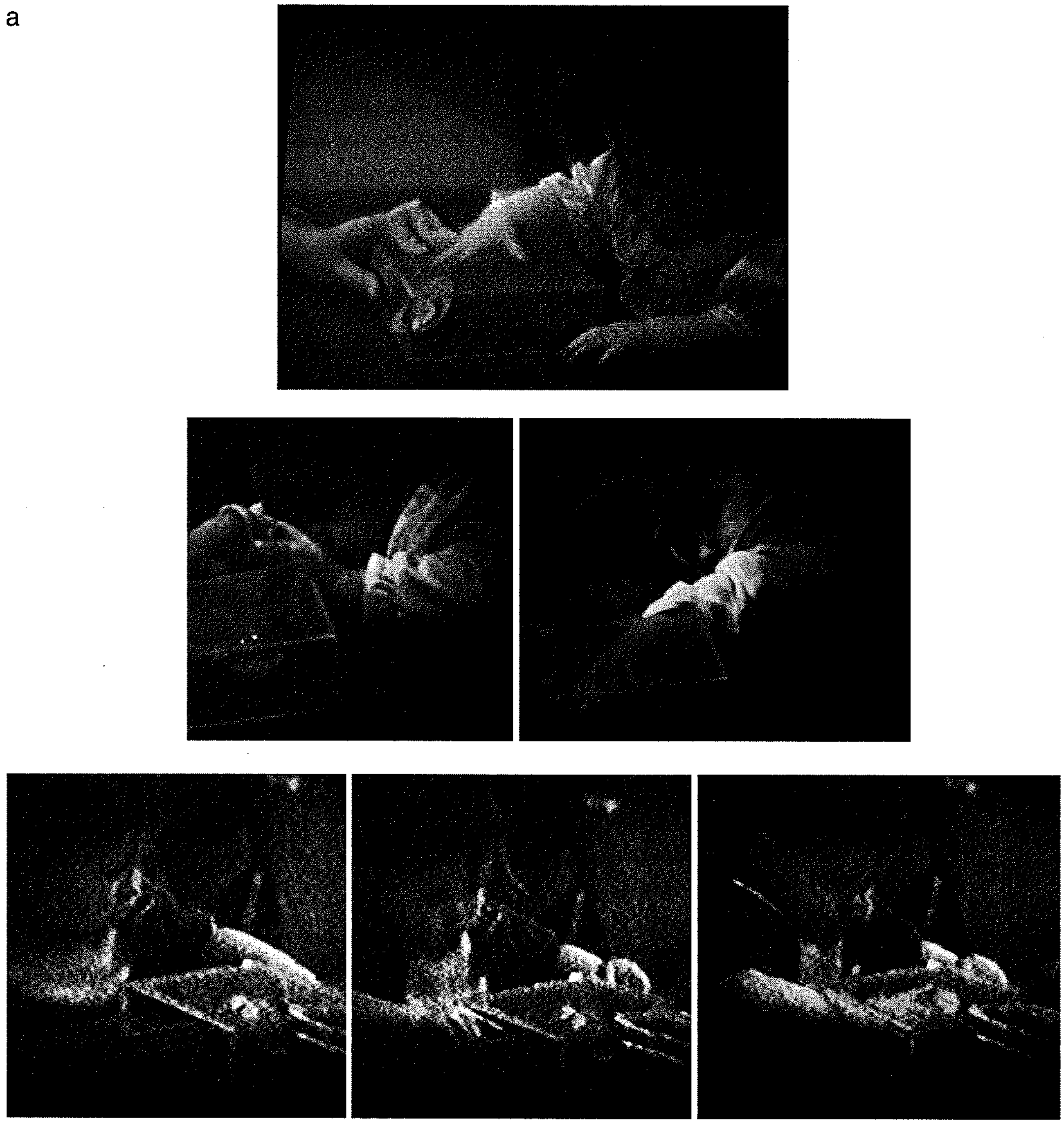
Executive function is not always needed when an action is complex and involves an intricate sequence. Novice dancers or athletes must concentrate hard and rely heavily on executive function, but expert dancers and athletes do not. Indeed, Miller, Verstynen, Raye, Mitchell, Johnson, and D'Esposito (2003) report that disrupting the functioning of dorsolateral prefrontal cortex impairs performance when a task is new and unfamiliar, but it improves performance when a task is familiar; presumably, thinking about what you are doing would get in the way of efficient performance.

THE FIRST YEAR OF LIFE

According to Piaget (1954), the first signs of what we would today call executive function are evident by 8–9 months of age (Sensorimotor Stage 4) and become consolidated over the next few months. When infants reach for a desired object, it is hard to tell if the external stimulus elicited an automatic reach or the intention was internally generated. However, when an infant searches for an object that is not visible, or acts on an object of no particular interest in order to obtain a desired object, then Piaget was willing to infer that intentionality was present and the action sequence had been truly goal-directed (i.e., executively controlled). The emergence of acting on one object to obtain another is also an example of creativity as Piaget pointed out: adapting a behavior (reaching and grasping) for an entirely new end (in order to obtain, not the object of the action, but for the first time as a means to obtaining a hidden or distant object). Piaget also took such means-end behavior to indicate planning, since infants seem to intentionally act on the covering or supporting object with the plan that this will make available the object they want.

My own work suggests that Piaget had this exactly right. Between 8 and 12 months of age, one sees the emergence of detour reaching (first around an opaque barrier and then around a transparent one; Diamond, 1988, 1990a, 1991; see Figure 6.1). Detour reaching requires holding a goal in mind, planning, and inhibiting the strong tendency to reach straight for the goal. Indeed, it requires reaching *away* from the goal object at the outset of the reach. Obviously, a detour reach requires more inhibition when the goal is visible than when it is not, hence detouring around a transparent barrier appears later. To come up with the plan of first reaching to the opening and then to the desired object, infants must grasp the connection between the opening and the desired object, even though these are spatially displaced. Indeed, the farther they are spatially displaced from one another, the later in the first year infants are able to come up with, and execute, the plan of reaching to the opening to obtain what they want.

Also between 8 and 12 months, infants are able to hold in mind for progressively longer periods where a desired object has been hidden, and are able to control their behavior so that they do not repeat a previously correct search that would now be wrong. Instead, they can now override the effects of previous a



(*continued*)

FIGURE 6.1. Emergence of detour reaching around a transparent barrier. (*a*): Infant performing the object retrieval task. Top row: Infant of 6 months is not able to execute any detour reaching. Infants of this age reach exclusively through the side they are looking. Middle row: Infant of 9 months executes a detour reach to the side opening by leaning over to look in the opening and then remaining in that position (continuing to look in the opening) to execute the reach. This behavior is dubbed an "awkward reach" because it looks so awkward. Bottom row: Infant of 12 months executes a detour reach quickly and efficiently. No longer does the infant need to see through the opening before or during reaching there. NOTE: Photographs are screen captures.

reinforcement to change their search behavior when the desired object's hiding place has changed (as shown by the body of work on the A-not-B task; Bell & Adams, 1999; Diamond, 1991; Gratch, 1975; Harris, 1987; Wellman, Cross, & Bartsch, 1987; see Figure 6.2).

What is happening in the brain that helps make possible these cognitive advances in the latter part of the first year? No one knows for sure. Monkeys with lesions of dorsolateral prefrontal cortex (DL-PFC) fail the detour-reaching object retrieval task and the A-not-

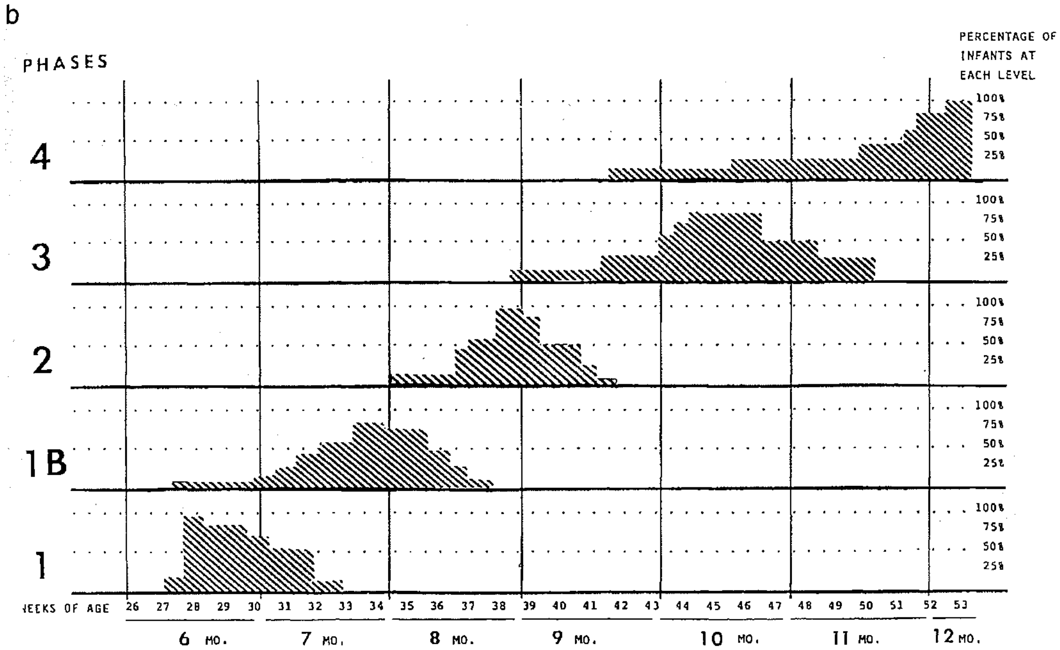


FIGURE 6.1. (*continued*) (*b*): Infants go through a series of well-demarcated phases, which are fairly tightly age-linked, in their ability to detour around a transparent barrier. (Reprinted from Diamond., 1990a.)

B task in the same ways and under the same conditions as do human infants (Diamond, 1991; Diamond & Goldman-Rakic, 1989). In the human brain, dendrites of pyramidal neurons in layer III of DL-PFC undergo their most dramatic expansion between the ages of 7½ and 12 months (Koenderink, Ulyings, & Mrzljiak, 1994), exactly coinciding with the period of marked improvement on the A-not-B and object retrieval tasks. Pyramidal neurons in DL-PFC have relatively short dendritic extents at 7½ months, but reach their full mature extent by 12 months. The surface of the cell bodies of these pyramidal neurons also increases between 7½ and 12 months (Koenderink et al., 1994). The level of glucose metabolism in DL-PFC increases during this period as well, approximating adult levels by 1 year of age (Chugani & Phelps, 1986; Chugani, Phelps, & Mazziotta, 1987). One particularly important developmental change during this period might be increased levels of dopamine in DL-PFC. Dopamine is a particularly important neurotransmitter in prefrontal cortex and reducing dopamine in prefrontal cortex impairs performance on executive function tasks (Brozoski, Brown, Rosvold, & Goldman, 1979; Diamond, 2001; Sawaguchi & Goldman-Rakic, 1991). During the period that infant rhesus macaques are improving on the A-not-B and object retrieval tasks, dopamine levels are increasing in their brain (Brown, Crane, & Goldman, 1976; Brown & Goldman, 1977), the density of dopamine receptors in prefrontal cortex is increasing (Lidow & Rakic, 1992), and the distribution within DL-PFC of axons containing the enzyme critical for the production of dopamine (tyrosine hydroxylase) is markedly changing (Lewis & Harris, 1991; Rosenberg & Lewis, 1995).

THE SECOND YEAR OF LIFE

Not until almost 2 years of age (20–21 months; Diamond, 1990b; Diamond, Towle, & Boyer, 1994; Overman, Bachevalier, Turner, & Peuster, 1992) can infants succeed at a task called "delayed nonmatching to sample" (DNMS). First, a sample object is presented, which the child displaces to retrieve a small reward in the depression (or "well") beneath it. After a delay of 5–10 seconds, the sample and a novel object are presented, with the reward now in the well

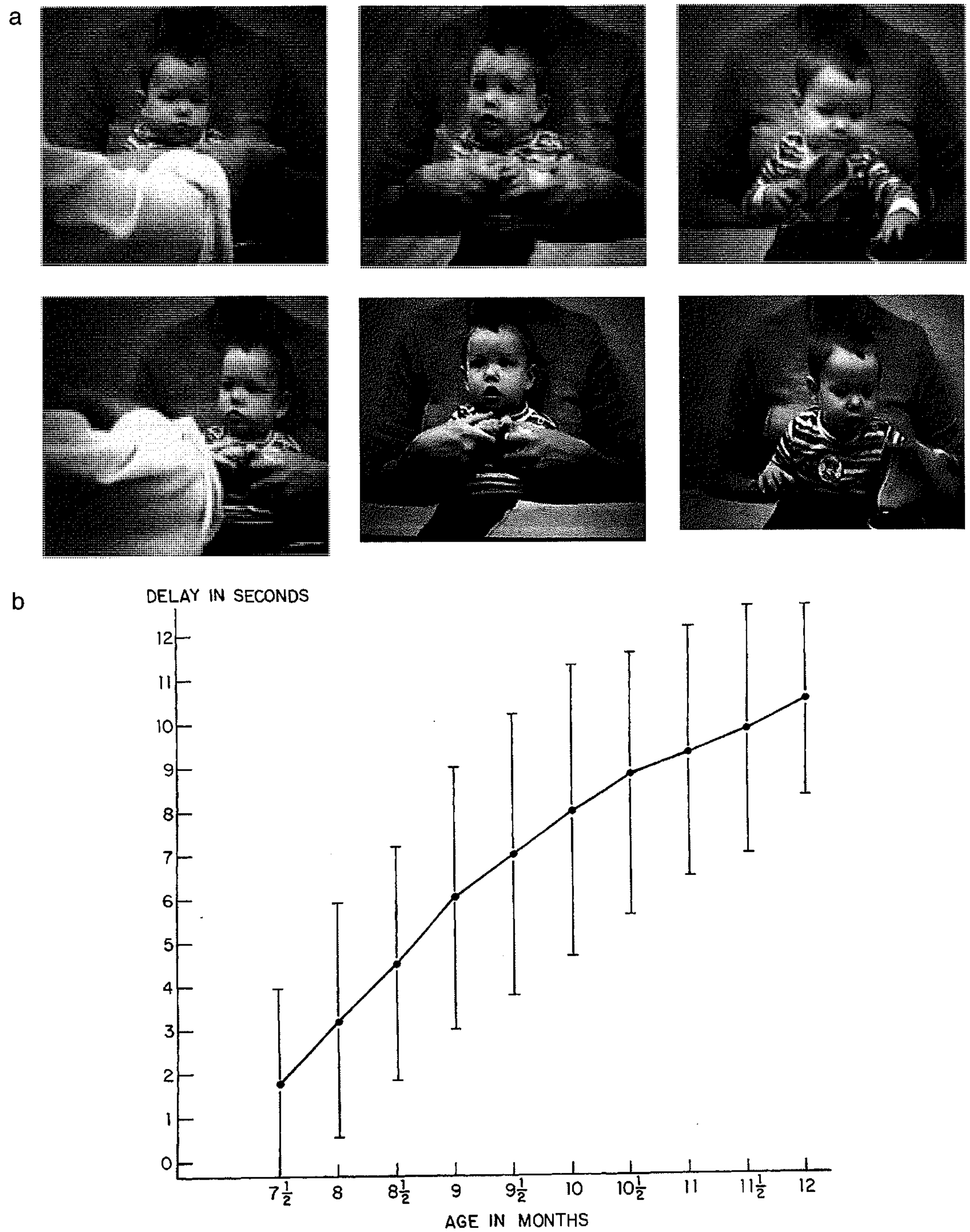


FIGURE 6.2. The A-not-B error in infants. *(a)*: Infant performing the A-not-B task devised by Jean Piaget.Top row: Trial at Well A: Infant watches as a desired object is hidden and both wells are covered simultaneously by identical covers. A brief delay of only seconds is imposed, during which the infant is restrained and distracted and not allowed to look toward the correct well. Then the infant is allowed to reach for the reward. The infant reaches correctly.Bottom row: Trial at Well B. The procedure is repeated but with the object hidden on the opposite side. Again the infant watches the hiding and the simultaneous covering. The same delay procedure is used. Then the infant is allowed to reach. The A-not-B error consists of the infant reaching correctly on the initial A trials, but erring on the B trial by going back to where the infant had previously been successful. *(b)*: Infants show a clear developmental progression in the length of the delay they can withstand on the A-not-B task. (Reprinted from Diamond, 1988 with the permission of Blackwell Publishing.) Note: Photographs are screen captures.

under the novel object. Thus, displacing the novel (nonmatching) object is rewarded. Many trials follow, each with a new sample and another novel object. Reaching to the novel stimulus is consistently rewarded, whether it is on the right or the left, is taller or shorter, or is more or less colorful than the sample. Once a child succeeds at the brief training delay, the delay is increased.

One might think that, since this task is a classic behavioral assay of the functions of the medial temporal lobe (Murray & Mishkin, 1998; Zola et al., 2000), and since success on it does not appear until late in infancy, the medial temporal lobe memory system must be late maturing. However, the problem for infants on this task is in "acquisition"—that is, understanding what correct performance entails, not retention at long delays (which is the problem for monkeys and adults with medial temporal lobe damage). Robust recognition memory at long delays is present well before 20–21 months (Brown, 1975; Dempster, 1985; Fagan, 1973). It is another ability required by the DNMS task that matures late.

The critical competence required for success on DNMS that young infants appear to lack is the ability to grasp the abstract rule-based relation between the stimulus and reward when there is no obvious physical connection between stimulus and reward. When there is a physical connection, infants of only 9–12 months easily succeed. For instance, they succeed when the reward is "Velcroed" to the base of the stimulus (attached to , though detachable from, the stimulus), and still hidden beneath the stimulus when the stimulus is atop its well (Diamond, Churchland, Cruess, & Kirkham, 1999). They also succeed when the stimuli and rewards are attached to the same piece of apparatus and in the same visual field, even though not directly attached to one another and not spatially close together. Indeed, when the stimuli and rewards are parts of a single apparatus, even when the stimuli and rewards are several inches apart and the close temporal connection between pulling the stimulus and appearance of the reward is broken, infants succeed (Diamond, Lee, & Hayden, 2003). In the absence of the perception that the stimulus and reward are components of a single thing, even close spatial *and* temporal proximity are insufficient for infants of 12 months to succeed at DNMS (Shutts, Ross, Hayden, & Diamond, 2001; Diamond et al., 2003). For instance, infants fail even if the stimulus is directly in front or on top of the reward, and the reward pops up the instant the infant grasps the stimulus (see Figure 6.3). Physical connectedness appears to be necessary and sufficient for infants of 9–12 months to grasp the abstract principle connecting the stimuli and the rewards in the

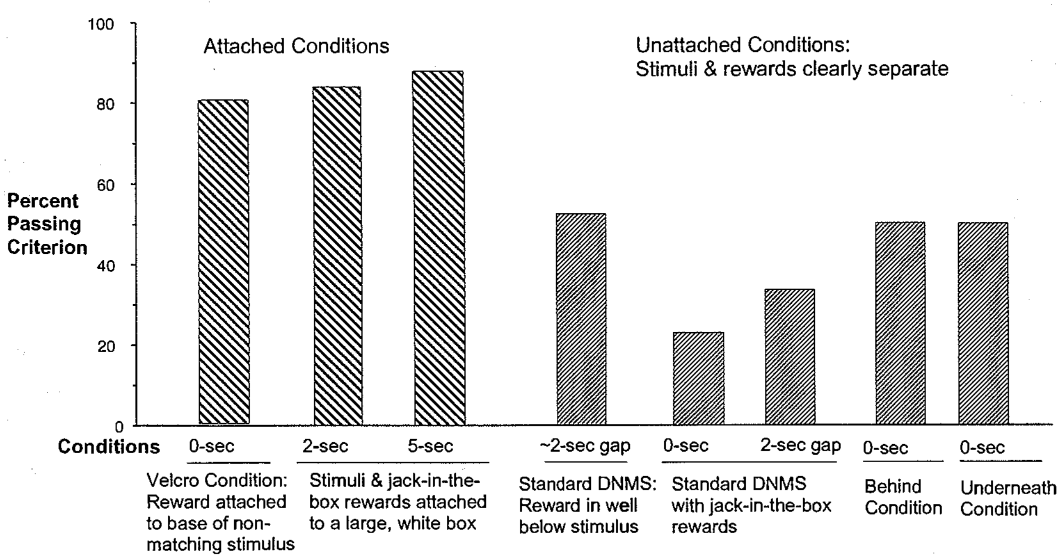


FIGURE 6.3. Delayed nonmatching to sample performance in infants as a function of physical connection, and temporal proximity, between stimulus and reward. (Based on data from Shutts, Ross, Hayden, & Diamond, 2001; Diamond et al., 2003.)

DNMS task. In its presence, neither close spatial or temporal proximity is needed. In its absence, even close spatial and temporal proximity are insufficient.

Physical connectedness also appears to be central to infants' ability to grasp conceptual connectedness. Aguiar and Baillargeon (2000) placed two cloths, one twice as long as the other, in front of 9-month-old infants. On the longer cloth, near its far end, sat a desired toy. Pulling the cloth brought the toy within reach. Equally far from the infant sat an identical toy behind the shorter cloth; pulling that cloth would not bring the toy within reach. After infants' initial success, if the locations of the shorter and longer cloths were reversed, 9-month-olds continued to succeed *if* the toy was attached to the longer cloth, but not if toy and cloth were not physically attached, though the toy was still on top of the cloth and spatially contiguous to it. In the former case (physical connection), infants correctly switched from pulling the cloth on side A to pulling the cloth on side B. In the latter case, 9-month-olds continued to the pull the cloth on side A. Evidently, physical attachment made a huge difference to the infants. Perhaps when the objects were attached, their synchrony of movement was exact, whereas when one was on top of the other unattached, the correlation was less precise. Synchrony of movement has long been known to be a powerful cue for infants in determining whether two things are part of one whole or are separate objects (Spelke, 1985; Vishton & Badger, 2003).

It may seem odd that physical attachment made such a big difference, but Jarvik (1953) found parallel results in rhesus macaques. When monkeys are trained on a color discrimination using two wells, one covered by a blue plaque and one by a red plaque, it can take a rhesus monkey 100 trials to learn the color discrimination. When Jarvik trained rhesus monkeys using bread as the reward (one slice injected with something that did not smell but tasted awful), the monkeys learned the color discrimination in one trial *if* there was a physical connection between stimulus and reward (the stimuli of red and green transparent celluloids pasted on top of the bread), but performed as poorly as in the standard procedure when the same stimuli were placed on top of the bread but were not attached.

DeLoache (1986) varied whether a reward was hidden in one of four distinctive containers, or whether the distinctive containers were mounted on top of plain boxes in which the rewards were placed. For infants of 27 months, it did not matter. For 21-month-olds, however, it made a great difference. When the boxes were scrambled, 21-month-olds were 80% correct when the rewards were *in* the distinctive containers but only 35% correct when the distinctive containers *marked* where the rewards were hidden (the reward being in the box underneath). "[W]hen the same distinctive visual information was a less integral aspect of the hiding location, age differences appeared" (DeLoache, 1986, p. 123). Similarly, DeLoache and Brown (1983) found that infants of 18–22 months performed significantly better when a reward was hidden *in* a piece of furniture rather than *near* it. By 24–30 months, infants performed equally well in both conditions.

Thus, during the second year or year and a half of life, an important advance in executive function appears to be an improvement in the ability to grasp connections between physically connected things. Grasping such connections, and using them to deduce abstract rules, has been linked to the region of frontal cortex known as the *periarcuate region* in the monkey brain and the *inferior frontal junction* (IFJ) in the human brain (Derfuss, Brass, Neumann, & von Cramon, 2005). This region overlaps (a) the posterior portion of BA 44/45 (called *ventrolateral PFC* in monkeys and *inferior PFC* in humans) and (b) the anterior, ventral portion of BA8 (premotor cortex). This area is also called F5, includes Broca's area, and is where Rizzolatti and colleagues have identified mirror neurons (e.g., Rizzolatti & Fadiga, 1998).Wallis & Miller (2003) report that more cells in this periarcuate region than in any other frontal subregion encode the abstract delayed nonmatching and delayed matching rules. Such abstract rules were encoded earliest and most strongly in anterior premotor cortex invading the periarcuate. Indeed, earlier Kowalska, Bachevalier, & Mishkin (1991) and Rushworth, Nixon, Eacott, and Passingham (1997) had found that monkeys in whom ventrolateral PFC had been removed (as long as the lesions invaded the periarcuate, but not otherwise) were profoundly impaired at relearning the delayed matching or nonmatching to sample rule (even with no delay), needing over 10 times more trials post-operatively as pre-operatively or as controls; but once they grasped the rule, their performance showed no decline at longer and longer delays (i.e., the same profile as human infants: great difficulty abstracting the general rule, but no memory problem and therefore no delay-dependent deficits). Matsumoto, Suzuki, & Tanaka (2003) found that periarcuate neurons show higher activity during the phase when a monkey is learning the rule for correct performance on a task, whereas neurons in DL-PFC show less activity during learning. Bunge, Kahn, Wallis, Miller, & Wagner (2003) report that functional magnetic resonance imaging (fMRI) in human adults reveals that the posterior portion of inferior PFC extending into the IFJ appears to encode specific abstract rules, such as matching and non-matching. In an fMRI study of DNMS, Elliott & Dolan (1999) found increased activation in left anterior, ventral premotor cortex. In positron emission tomography (PET) studies, too, performance of delayed matching to sample has been shown to increase activation in right, posterior inferior PFC (Grady *et al.*, 1998) and selecting between actions on the basis of visual associative rules has been shown to increase activation of the IFJ (Brass & von Cramon, 2002; Toni et al, 2001).

THE PRESCHOOL PERIOD: 3–5 YEARS OF AGE

Between the ages of 3 and 7 years, and especially between 3 and 5 years, there are marked improvements in inhibition and cognitive flexibility, especially the flexibility to change perspectives. These cognitive advances are expressed in social cognition (theory of mind; Wimmer & Perner, 1983), moral development (Kohlberg, 1963), and on diverse cognitive tasks, such as the dimensional change card sort task (DCCS; Zelazo, Reznick, & Piñon, 1995), ambiguous figures (Gopnik & Rosati, 2001), appearance-reality (Flavell, Green & Flavell, 1986), false belief (Perner, Leekam, & Wimmer, 1987), Luria's tapping and hand tasks (Diamond & Taylor, 1996; Hughes, 1998), the day-night Stroop-like task (Gerstadt, Hong, & Diamond, 1994), conservation of liquid or number (Inhelder & Piaget, 1958), and go/no-go (Livesey & Morgan, 1991).

If one has "theory of mind," one is said to be able to infer what another person might know, think, believe, or want (another person's "mental state"), and to use that to accurately predict what the other person might do (Premack & Woodruff, 1978). Tasks that assess theory of mind generally require holding two things in mind about the same situation (the true state of affairs and the false belief of another person) and inhibiting the impulse to give the veridical answer. That impulse likely comes from children's desire to show how smart they are (they followed everything that happened and know where the hidden object really is) and children's desire for the nice other person (or puppet) to succeed in finding the hidden object. Children must keep in mind where a hidden object has been moved to while the other person was not watching and where that other person last saw the object placed, and inhibit the inclination to say where the object really is, reporting the mistaken belief instead (see Figure 6.4). Children of 3 years typically fail such tests, but children of 4–5 years typically succeed (Wimmer & Perner, 1983; Flavell, 1999). Birch and Bloom (2003) propose that the errors of 3-year-olds on theory-of-mind tasks have their remnants in the "curse of knowledge" tendency seen in adults—the tendency to be biased by one's own knowledge and thus assume that another person, not privy to such knowledge, would still act in accord with it (e.g., Hinds, 1999; Kelley & Jacoby, 1996). Manipulations that reduce the perceptual salience of the true state of affairs (and hence the inhibitory demands) aid children of 3–4 years; for example, by telling children where the object has been moved to but not actually showing them (Zaitchik, 1991). So do manipulations that reduce inhibitory demand in other ways (see e.g., Carlson, Moses, & Hix,1998; Rice, Koinis, Sullivan, Tager-Flusberg, & Winner, 1997).

Success on theory-of-mind tasks emerges at roughly the same time as success on many cognitive tasks that assess executive functions, and performances on the latter and the former are correlated. This is true for performance on theory-of-mind tasks and (1) the DCCS task (Carlson & Moses, 2001; Perner, Lang, & Kloo, 2002), (2) the day-night Stroop-like task (Carlson & Moses, 2001; Hala, Hug, & Henderson, 2003), and (3) Luria's tapping (Hala et al., 2003) and hands (Hughes, 1998) tasks. Success on the day-night and similar tasks appears to precede and predict theory-of-mind success (Carlson, Mandell, & Williams, 2004; Flynn, O'Malley, & Wood, 2004; Hughes, 1998). Further, Kloo and Perner (2003) report that training on theory of mind improves performance on that and on the DCCS task, and training on the DCCS task improves performance on that and on theory of mind.

The moral reasoning of preschoolers of 2–4 years also reflects a seeming inability to consider two perspectives as potentially both having validity. Instead,

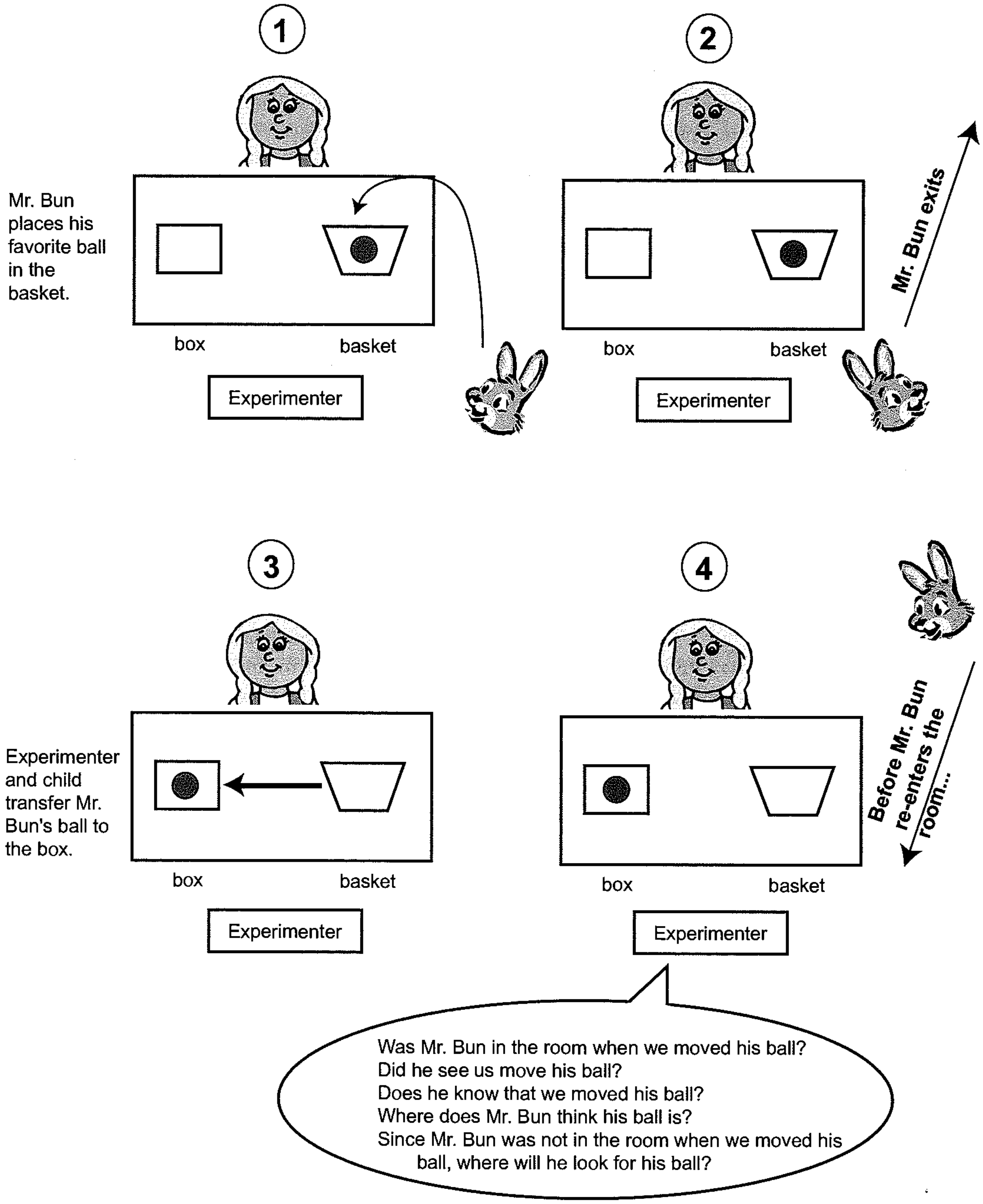
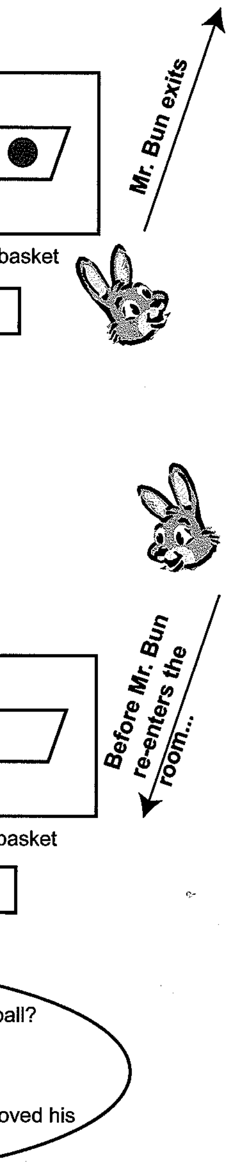


FIGURE 6.4. Illustration of a typical theory-of-mind task. Normal development of prefrontal cortex from birth to young adulthood: cognitive functions, anatomy, and biochemistry (Reprinted from Diamond, 2002 with the permission of Oxford University Press).



of prefrontal cortex
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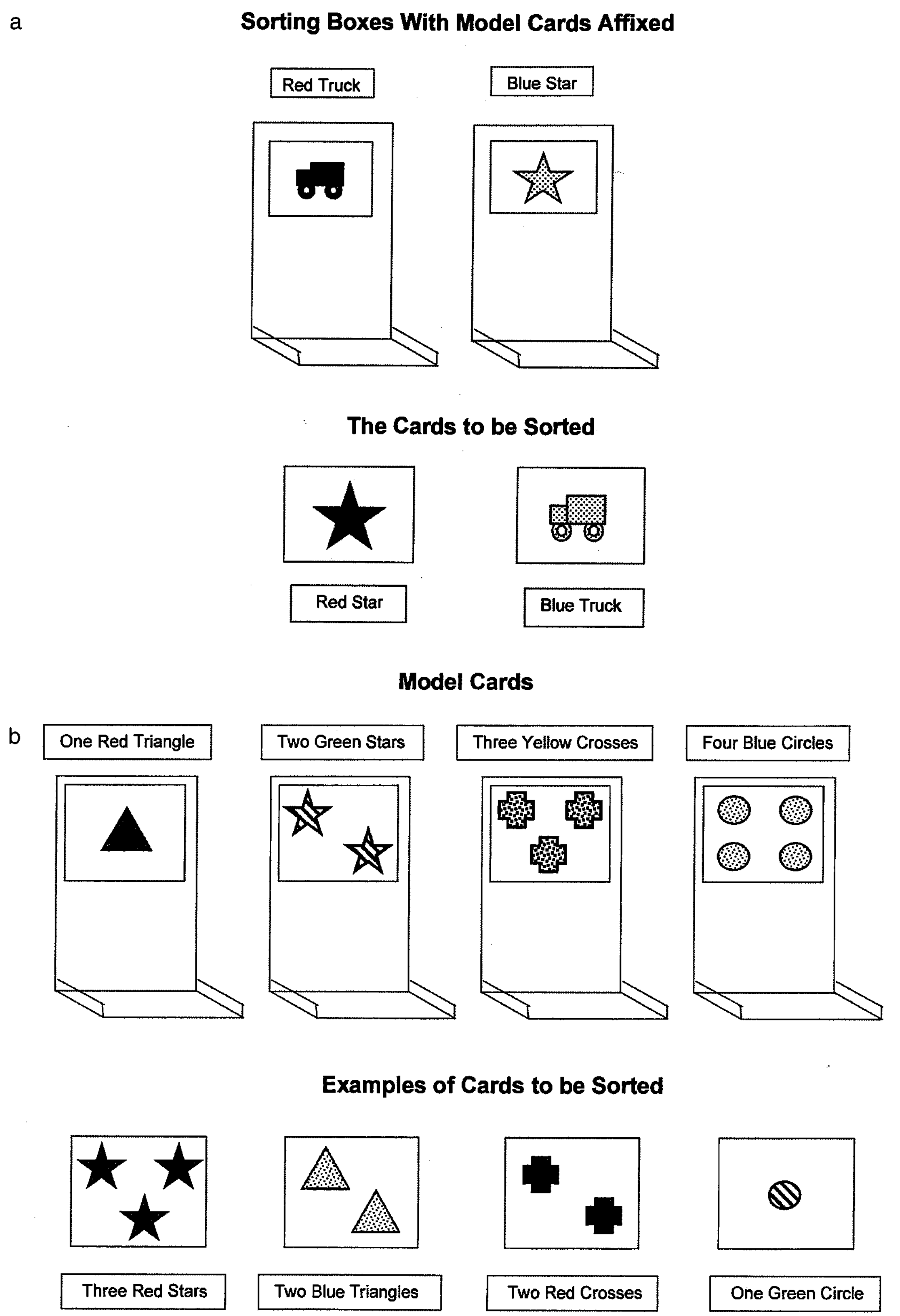
things are clearly right or wrong, and people are either good or bad. A parent or respected authority figure can do no wrong and therefore one should obey what the individual says and conform to the rules. Only very gradually do children begin to understand that even wise people can be wrong sometimes, good people can do things they are ashamed of, a person who does many bad things may still have good qualities, and different people may hold differing, yet reasonable opinions about the moral course of action in a given situation. Gilligan (1982) suggests that female moral development may differ from that of boys, but girls still need to overcome the tendency to see things as black or white: although it is right to help and care for others and wrong to be selfish, according to Gilligan, girls need to come to the realization that they will endanger the very relationships they are trying to preserve if they always deny their own needs in their attempt to be unselfish.

An ambiguous figure appears to be one thing (e.g., a duck or an old woman) from one perspective and something quite different from another perspective (e.g., a rabbit or a young woman). Even when informed of the alternatives in an ambiguous figure, children of 3 years remain stuck in their initial way of perceiving the figure; they cannot see the image from the other perspective (Gopnik & Rosati, 2001). Children of 3 years also have difficulty on appearance-reality tasks where, for example, they are presented with a sponge that looks like a rock. They typically report that it looks like a rock and really is a rock; children of 4–5 years correctly answer that it looks like a rock but really is a sponge (Flavell et al., 1986, 1993). The problem for the younger children appears to be in relating two conflicting identities of the same object (e.g., Rice et al., 1997) and in inhibiting the response that matches their perception. Manipulations that reduce perceptual salience on appearance-reality tasks, by removing the object during questioning, enable many more children of 3–4 years to succeed (e.g., Heberle, Clune, & Kelly, 1999).

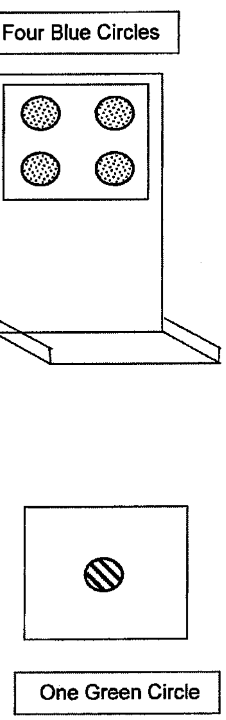
In a second type of false-belief task, the true state of affairs (e.g., that pennies rather than M&M's are in an M&M's box) is at odds with the child's original belief that M&M's would be in the M&M's box. Once 3-year-olds see what is in the box, they insist that the answer to what is actually in the box and what they had earlier guessed is the same: they had thought all along that pennies were in the box (Perner et al., 1987).

Although adults typically succeed on these tasks, the difficulty in holding in mind two conflicting perspectives on the same thing and discomfort with ambiguity never completely disappear. Even adults often have difficulty accepting that good people (or good nations) sometimes act wrongly or that people who disagree with them might have a point (Van Hiel & Mervielde, 2003; Webster & Kruglanski, 1994). Even adults have difficulty representing more than one interpretation of an ambiguous figure at a time (Chambers & Reisberg, 1992). While adults do not claim that they earlier said that pennies were in an M&M's box, in analogous situations they claim that they earlier rated similarly unlikely outcomes as more probable than they actually had. This was named the "knew it all along" effect by Fischhoff (1977; Fischhoff, & Beyth, 1975); see also Hoffrage, Hertwig, and Gigerenzer (2000). I do not know of studies of the "curse of knowledge" or "knew it all along" in older adults, but if older adults have problems with inhibition, as some have claimed, then the prediction would be that they might be disproportionately prone to show these biases as they would be less able to inhibit them.

In the DCCS task, children are asked to sort a deck of cards first by one dimension (e.g., color) and then to switch and sort the same cards by another dimension (e.g., shape). No sorting card matches either model card on both color and shape; hence the correct sorting response for one dimension is necessarily the wrong response when sorting by the other dimension (see Figure 6.5). For example, a blue-truck stimulus card goes with a blue-star model card when sorting by color but goes with the red-truck model card when sorting by shape. By 3 years of age, children can sort the cards correctly by color or shape. However, when asked to switch sorting dimensions, 3-year-olds tend to continue to sort by the initially correct dimension, even though they can correctly indicate on each trial what the current sorting dimension is and how to sort according to it (Zelazo et al., 1995; Zelazo, Frye, & Rapus, 1996). By 4–5 years of age, that error disappears. This task, unlike the Wisconsin Card Sort Test (WCST), does not require participants to deduce which sorting criterion is currently correct because they are told, nor do they need to remember that over trials because they are reminded at the start of each trial, and when the sorting criterion changes, that change and the newly correct sorting dimension are pointed out to the participant and emphasized.


a
Sorting Boxes With Model Cards Affixed
Red Truck
Blue Star
The Cards to be Sorted
Red Star
Blue Truck
Model Cards
b
One Red Triangle
Two Green Stars
Three Yellow Crosses
Four Blue Circles
Examples of Cards to be Sorted
Three Red Stars
Two Blue Triangles
Two Red Crosses
One Green Circle

(continued)



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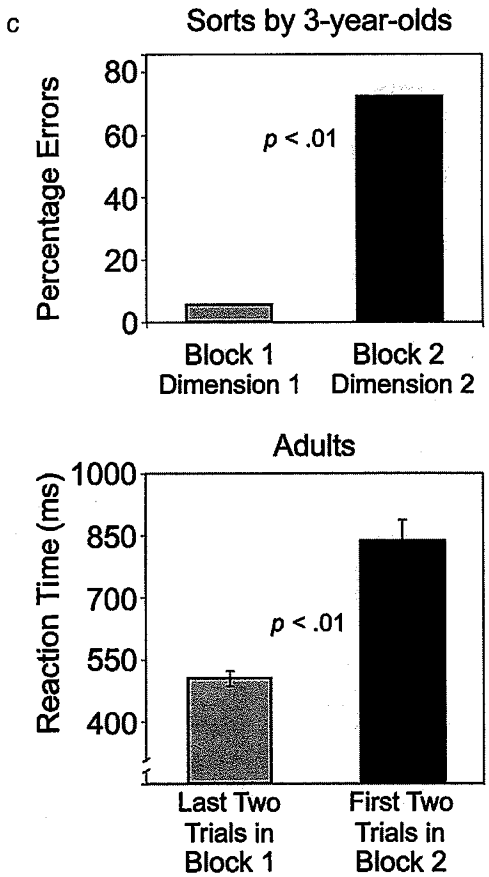

FIGURE 6.5. *(a)*: Illustration of the Dimensional Card Sort Task for preschoolers. There are 2 dimensions and 2 values per dimension. *(b)*: Illustration of the Wisconsin Card Sort test for adults. There are 3 dimensions and 4 values per dimension. (Reprinted from Diamond, 2002 with the permission of Oxford University Press.) *(c)*: Cost in switching from sorting by color or shape in Block 1 to sorting by the other dimension in Block 2. Three-year-olds can sort by either color or shape initially, but typically cannot switch to sort by the other dimensions. Adults can switch, but they are slower at sorting by the second dimension. Top: Percentage of 3-year-old children who sort incorrectly in Block 1 versus Block 2. Bottom: Reaction times for adults on the last 2 trials in Block 1 versus the first 2 trials in Block 2. (Reprinted from Diamond. & Kirkham, 2005 with permission of Blackwell Publishing.)

I think the problem for 3-year-olds on the DCCS task is in overcoming an inertial tendency—what Kirkham, Cruess, & Diamond (2003) have termed *attentional inertia*. Once a child of 3 years has focused on the "redness" of a red truck, it is difficult for the child to switch mindsets and focus on its "truckness." The child is not yet able to inhibit the inertial tendency to continue to focus on, and respond on the basis of, what had been relevant. Three-year-olds, who correctly point to where the trucks should go at the outset of a trial, run into a problem when they are handed a stimulus that is not only a truck but red, though the experimenter labels it along the relevant dimension only ("Here's a truck"). Sometimes 3-year-olds look at the stimulus and say, "But it's red"; typically they sort it with the red stars (the previously correct answer, but now the wrong response). Exactly analogous results obtain if the order is shape first and then color.

Increasing the perceptual salience of the previous dimension (and hence the inhibitory demand) impairs performance. For example, cards are normally sorted face down in the DCCS task. If they are sorted face up, the previously relevant dimension is visible on the sorted cards under each target when the rule changes, emphasizing the salience of the obsolete dimension. While almost all 4-year-olds succeed in the standard face-down condition, almost 50% of 4-year-olds fail the face-up condition (Kirkham et al., 2003).

Manipulations that reduce the inhibitory demand can dramatically increase the number of 3-year-olds who are able to successfully switch sorting dimensions. For example, redirecting attention to the currently relevant dimension by asking the child, rather than the experimenter, to label the card to be sorted according to the currently relevant dimension enables most 3-year-olds to succeed in switching (Kirkham et al., 2003; Towse, Redbond, Houston-Price, & Cook, 2000). Similarly, if the same color and shape are still present, but are not properties of the same object, the tendency to conceive of that object according to the previously correct perspective is no longer relevant and therefore does not need to be inhibited. Over 90% of 3-year-olds succeed if the sorting cards and model cards display the outline of a shape alongside a patch of color, even though each sorting card still matches one model card along one dimension and the other model card along the other dimension (Kloo & Perner, 2005). If shape outlines are used and the switch is a reversal (switch to sorting trucks with stars and stars with trucks), that does not require inhibiting attention to the previous relevant dimension and children of 3 years succeed (Brooks, Hanauer, Padowska, & Rosman, 2003; Perner & Lang, 2002).

The inertial tendency never completely disappears. Traces of it can be seen in the heightened reaction times of adults when asked to switch criteria and respond on the basis of another dimension (e.g., Monsell & Driver, 2000; Diamond & Kirkham, 2005). No matter how much warning adults are given about which dimension will be relevant on the upcoming trial, and no matter how long the time between the warning and when the stimulus appears, or how long the period between trials, adults are still slower to respond on trials where the relevant dimension switches than when it does not (Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). Moreover, throughout a testing session of scores of trials, adults continue to sort faster by whichever criterion had been relevant first in their testing session (Diamond & Kirkham,2005).

Luria's tapping test (Luria, 1966) requires remembering the rules, "Tap once when the experimenter taps twice, and tap twice when the experimenter taps once," and inhibiting the tendency to mimic what the experimenter does, making the opposite response instead. The greatest improvement in correct responding on this task occurs between 3½ and 4 years of age, and the greatest improvement in response speed occurs between 4½ and 5 years (Becker, Isaac, & Hynd, 1987; Diamond & Taylor, 1996; Passler, Isaac, & Hynd, 1985). Luria's hands test (used with children by Hughes, 1996, 1998) is quite similar (when the experimenter makes a fist, the child is to hold his or her pointer finger out straight; when the experimenter points that finger, the child is to make a fist) and that too is sensitive to developmental improvements between 3 and 5 years of age.

The day-night task has somewhat similar requirements. It requires remembering two rules (say "night" to a depiction of the sun, and "day" to the moon and stars) and inhibiting saying what the stimuli really represent. Children 3½ to 4½ years of age find the task very difficult; by the age of 6–7 years it is trivially easy. Improvement in the percentage of correct responses is relatively continuous from 3½ to 7 years of age, while improvement in response speed occurs primarily from 3½ to 4½ years (Gerstadt et al., 1994). However, children at least as young as 4 years *can* inhibit saying what these stimuli represent as long as the response to be inhibited is not related to the response to be activated. They can successfully say "dog" to a picture of the sun (or moon) and "pig" or "cat" to the other picture (Diamond, Kirkham, & Amso, 2002). The dog-pig manipulation teaches us that 4-year-olds *can* inhibit saying what a stimulus represents. The relation between the response to be activated and the response to be suppressed is key. It does not have to be a semantic relation either (contrary to what Diamond et al. [2002] had proposed). Simpson and Riggs (*submitted*) have shown that what matters is whether the prepotent response to Stimulus A (or B) is related to the correct response for Stimulus B (or A). For instance, if the stimuli are book and car (words *not* semantically related) and the correct responses are to say "car" when shown a picture of a book and to say "book" when shown a picture of a car, children show the same pattern of errors as on the "classic" day-night task (Gerstadt *et al.*, 1994).

Many of the advances of Piaget's "concrete operational" child of 5–7 years over a "preoperational" child of 3–4 years also reflect the development of the abilities to relate one thing to another and inhibit the strongest response of the moment. For example, children of 3 or 4 years fail tests of liquid conservation (they do not attend to both height and width, attending only to the most perceptually salient of the two dimensions) and they fail tests of perspective-taking where they must mentally manipulate a scene to indicate what it would look like from another perspective and must inhibit the tendency to give the most salient response (their current perspective). By 5 or 6 years, they can do these things (Flavell, 1963). Part of the difficulty posed by Piaget's liquid conservation task is the salience of the visual perception that the tall, thin container contains more liquid. Thus, placing an opaque screen between the child and the containers before the child answers enables younger children to perform better (Bruner, 1964).

A final example of a task on which dramatic improvements are seen between 3 and 5 years of age is go/no-go. Here, the child is to respond to one stimulus but withhold responding when another appears. Children 3–4 years old can correctly state the instructions, but they cannot inhibit responding to the no-go stimulus. Not until roughly 4½ years of age can they begin to curb errors of commission to the no-go stimulus (Livesey & Morgan, 1991; Tikhomirov, 1978; van der Meere & Stemerdink, 1999). This is not to say that continued improvements cannot be seen with age, especially when more rapid responding is required and/or the ratio of go to no-go responses is increased (Casey et al., 1997; van der Meere & Stemerdink, 1999). Even adults are rarely at ceiling. Conversely, with a slightly easier variant of the task, children of 3¾–4 years have been reported to perform at better than 90% correct (Jones, Rothbart, & Posner, 2003).

THE GRADE SCHOOL YEARS: EARLY CHILDHOOD

Between the ages of 5 and 11 years, improvements are evident in *cognitive flexibility* (especially flexibly switching back and forth), *working memory* (the ability to hold information in mind and work with it, manipulating, monitoring, or transforming it), and *speed.* (For a more extended discussion of developmental changes in working memory than provided here, see Chapter 8, this volume.) Tasks on which children show sharp improvements over this age period include the anti-saccade task, the Wisconsin Card Sort Test (WCST), the directional Stroop task, and span tasks. On the anti-saccade task, as soon as a target appears, participants are to look in the opposite direction (but matching the distance and angle). This requires inhibiting the strong tendency to look toward a target when it appears, the response that is correct on the pro-saccade trials. Children can barely do this at all until they are 6–7 years old and improve dramatically over the next few years, but do not reach peak performance until their early 20s (Luna et al., 2001; Munoz, Broughton, Goldring, & Armstrong, 1998). The WCST is one of the classic tests of prefrontal cortex function in adults (Stuss et al., 2000). The participant must deduce the sorting criterion, which can be color, shape, or number, and must flexibly switch sorting rules without warning on the basis of feedback (the sorting dimension changes unannounced after every 6 or 10 consecutively correct sorts). Children show great improvements on this between 5 and 11 years but may still not reach adult levels until perhaps 20 years of age (Chelune & Thompson, 1987; Rosselli & Ardila, 1993; Welsh, Pennington, & Groisser, 1991).

Task-switching paradigms require that a participant flexibly switch back and forth between two rule sets and two sets of response mappings. In a paradigm devised by Meiran (1996), participants must indicate whether a cue is in the left or right half of a square or the top or bottom half of the square, one key being used to indicate left or top and the other to indicate right or down. On this task, by 4 years, children can begin to switch back and forth, but only poorly. The cost of having to switch back and forth was greatest for the youngest children and declined continuously through at least age 11. Even at the oldest age tested (11 years), children showed more of a reduction in speed and accuracy when they had to switch back and forth (compared to single-task blocks) than did adults (Cohen, Bixenman, Meiran, & Diamond, 2001). Another task-switching paradigm that has been used with children requires that they switch between identifying whether the stimulus display contains a 1 or a 3 (task A) and whether the number of digits displayed is 1 or 3 (task B). Hence, for task A, the correct response to a stimulus display of "1 1 1" is 1, but for task B for the same display the correct response is 3. As on Meiran's task, participants are cued on each trial. Cepeda, Kramer, and Gonzalez de Sather (2001) found that performance was better at 10–12 years than at 7–9 years, but did not reach peak levels until the early 20s. Development of the ability to flexibly switch starts early but continues for almost two decades.

Marked developmental advances between 5 and 11 years of age are consistently found on complex span tasks that require transforming information held in mind under high-interference conditions requiring inhibition (Dempster, 1985). For example, consider the counting span and spatial span tasks. On each trial of the counting span task (Case, Kurland, & Goldberg, 1982), a participant is asked to count a set of blue dots embedded in a field of yellow dots, touching each blue dot and enumerating it (see Figure 6.6a). Immediately thereafter, the participant is to give the answer for that display and the answers for all preceding displays in correct serial order. This requires (1) selective attention (inhibiting attention to the yellow dots); (2) holding information in mind while executing another mental operation (counting); (3) updating the information held in mind; and (4) temporal order memory (keeping track of the order of the totals computed across trials). In the spatial span task (Case, 1992) a participant inspects a 4 x 4 matrix on each trial, noting which cell is shaded (see Figure 6.6b). A filler pattern is then shown, and then a second 4 x 4 grid. The second grid is empty; the participant is to point to the cell that had been shaded on that trial. Over several blocks of trials, the number of shaded cells gradually increases. Interference from prior trials and from the filler pattern is high. A meta-analysis by Case (1992) of 12 cross-sectional studies showed remarkably similar developmental progressions on both of these tasks (see Figure 6.6c). (Note also the remarkably similar developmental degradation during aging across letter, reading, and computation span tasks as illustrated in Figure 9.1a. Continuous and marked improvements are seen from 4½ to 8 years of age,

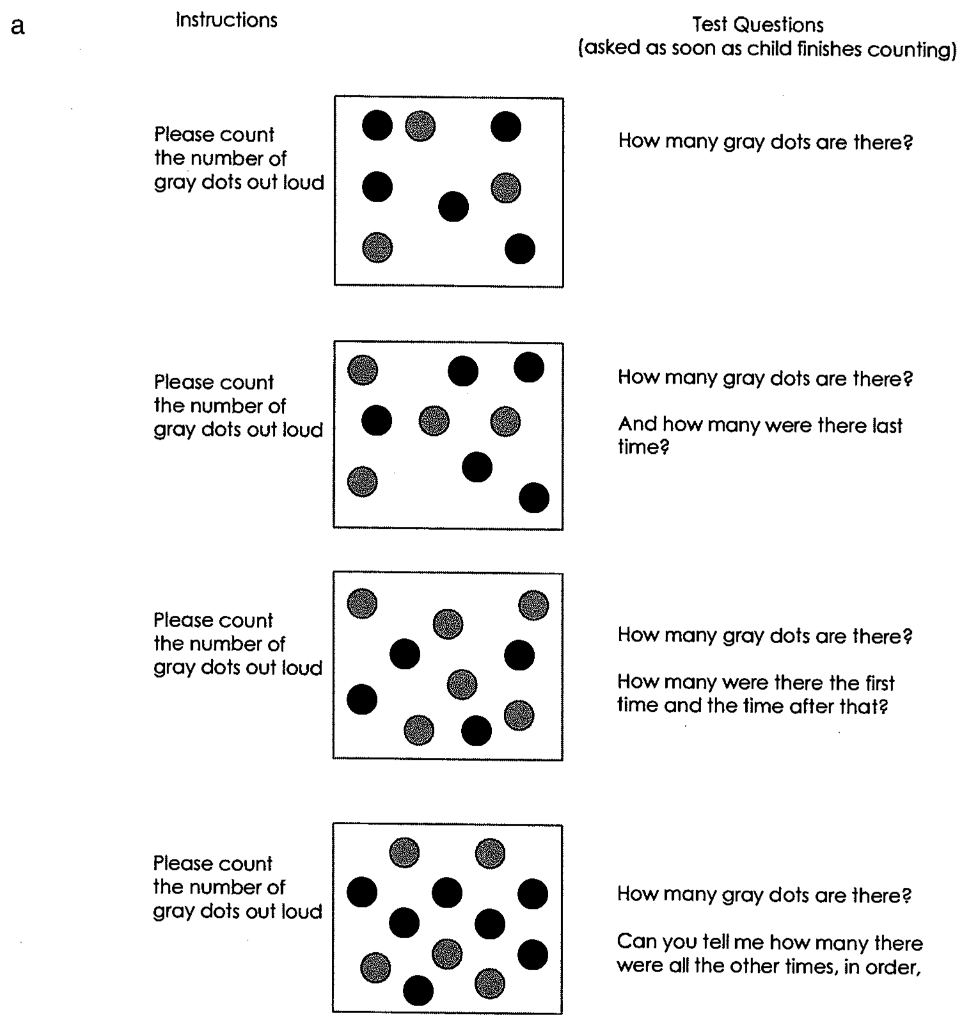

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FIGURE 6.6. Two complex span tasks. (*a*): Sample of the kinds of trials presented on the counting span task. (Case et al., 1982.) (*b*): Sample of the kinds of trials presented in the spatial span task. (Stuss & Knight, 2002.) (*c*): Developmental progression in the number of items that can be held in mind on the two tasks. (Data from Crammond et al.,1992, for the counting span and Menna, 1989, for the spatial span.) (Reprinted from Diamond, 2002 with the permission of Oxford University Press.)

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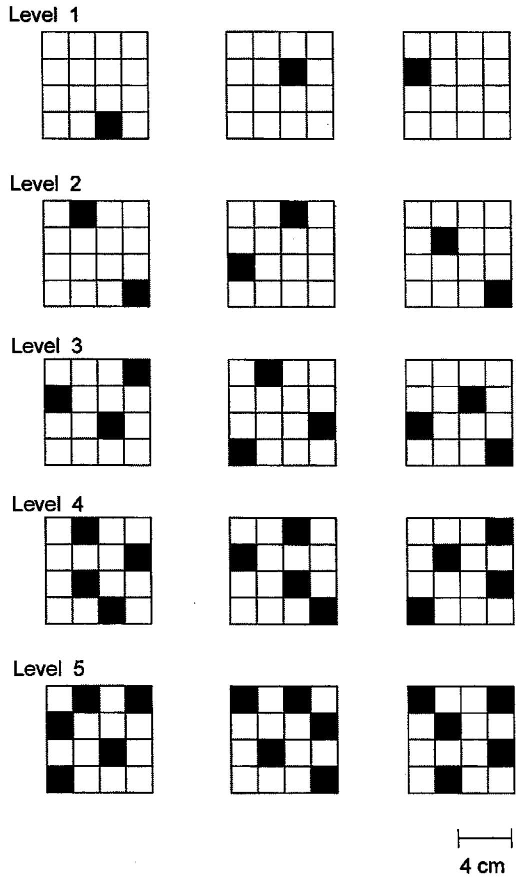

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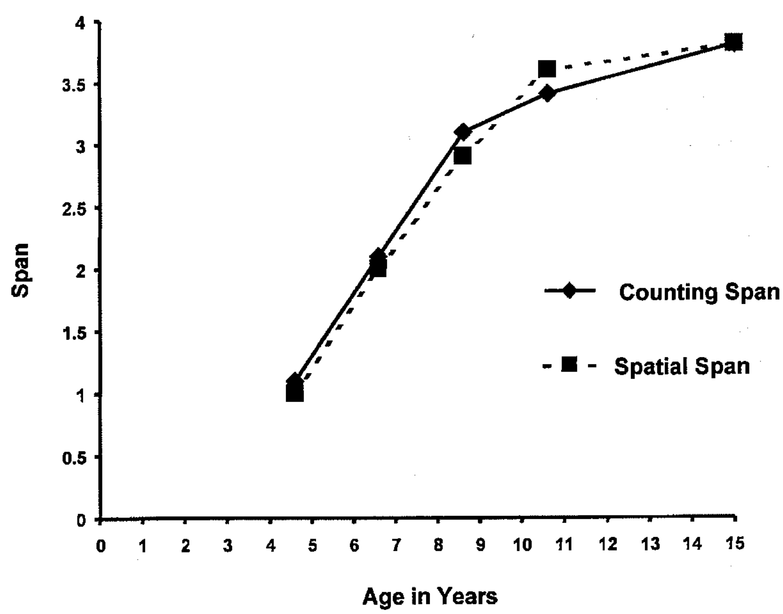

FIGURE 6.6. (*continued*)

continued, more gradual improvement until 10–11 years of age, and then much more gradual improvement thereafter.

The pattern span task is similar to the spatial span task except that several cells are shaded. First, the participant gets a quick look at the pattern. At test, one of the cells that had been shaded is now unshaded and the participant must point to that cell. The number of shaded cells increases until the participant's accuracy falls below criterion. Performance on this task also improves greatly between 5 and 11 years of age, when it starts to asymptote (Miles, Morgan, Milne, & Morris, 1996; Wilson, Scott, & Power, 1987). Finally, the listening span task (Daneman & Carpenter, 1980) requires processing of incoming information (auditorially presented sentences) while retaining, in correct temporal order, the final words of each preceding sentence. Performance on this improves from 6 years until at least 15 years and probably until the early 20s (Siegel, 1994).

Speed of processing is not considered an executive function, yet for reasons not fully understood, age-related improvements in the speed of processing account for a great deal of the age-related improvements on span tasks (Case et al., 1982; Hitch et al., 2001; Kail, 1992) and there is a strong, well-replicated relation between speed of processing and performance on executive function measures (Duncan, Burgess, & Emslie, 1995; Fry & Hale, 1996; Kail & Salthouse, 1994). Processing speed increases markedly until the early teens and continues improving, though more gradually, until early adulthood (Fry & Hale, 1996; Kail, 1991; Miller & Vernon, 1997). It might also be noted that processing speed slows markedly during aging and the decline in the speed of processing from early through late adulthood is highly correlated with the age-related decline in executive function performance (Salthouse, 1993; Salthouse & Meinz, 1995).

When I say that improvements in speed account for a large percentage of the variance in age-related improvements on span tasks, I am referring to findings such as the following: the faster people can repeat back the word they just heard, the more words they can hold in mind. As the speed of word repetition improves, so too does word-span memory. When the speed at which adults and 6-year-olds can repeat back words is equated by presenting adults with unfamiliar words, children and adults show equivalent word-span memory (Case et al., 1982). Similarly, when the speed at which adults and children can count is equated by requiring adults to count in a foreign language, equivalent counting-span memory is found in adults and 6-year-olds.

Item recognition speed also improves with age (Chi, 1977; Samuels, Begy, & Chen, 1975–1976), and the speed of item identification is related to the number of items (span) that can be held in mind and retrieved (Dempster, 1981). Individuals who have shorter naming times (within and between ages) have larger memory spans. People can generally name a digit faster than a word, and people generally have larger spans for digits than for words. Similarly, words can usually be identified faster than pictures, and people generally have larger spans for words than pictures (Mackworth, 1963). Chi (1977) found that when adults were allowed to view picture stimuli for only half as long as 5-year-olds (to offset the faster encoding speed of adults), the age difference in the number of pictures that could be held in mind was dramatically reduced.

The empirical relation between performance on complex span tasks and generalized speed of processing might be due to any number of reasons. Faster processing would mean that items do not need to be held in mind as long, for example. Faster processing and improved executive function performance may co-vary not because they are causally related but because they both reflect another factor, such as more efficient neural processing or improved signal-to-noise ratios; the latter could be either because of system-wide improvements in the nervous system (such as greater myelination) or because a better functioning prefrontal cortex improves signal-to-noise ratios for diverse neural regions, permitting faster and more efficient cognitive processing. It could be that both speed measures and complex span measures are sensitive to distraction and interference, so the relation between the two sets of measures is due to their common requirement for the exercise of inhibition. In any case, while a great deal of the variance in performance on complex span tasks can be accounted for by processing speed, controlling for speed does not eliminate all age-related differences in complex span performance (Hitch et al., 2001), so even if speed is a large part of the story, it is not the entire story.

TERMINOLOGY UNPACKED

Above, I have used the terms *executive function* and *working memory*—terms discussed in other chapters in this volume and widely used elsewhere, but sometimes used to mean quite different things. It might be helpful in closing to remind readers of the way in which those terms are used in this chapter and how that differs from the ways those terms are sometimes used by others.

Executive function, as I use the term, refers to occasions when conscious, cognitive control is required, and is the antithesis of occasions when going "on automatic" would suffice. The epitome of when executive control is required is when one's automatic inclinations provide no guidance or would lead one astray, as in novel situations or when things change. Executive function often involves inhibiting an automatic tendency and acting on information held in mind (what I have referred to as the conjunction of working memory and inhibition). Exercising executive function is not always beneficial; it can get in the way when acting "on automatic" is exactly what is required (e.g., "The Zen of Archery"; early in training disrupting lateral prefrontal function impairs performance, but disrupting lateral prefrontal function after a task is familiar can *improve* performance [Miller et al., 2003]).

In Chapter 7, (this volume), Daniels, Toth, and Jacoby discuss planning and problem solving as executive functions, whereas I am inclined to think of those as activities that require executive functions but not in themselves executive functions. Daniels et al. discuss the gambling task pioneered by Bechara and Damasio (Bechara, Damasio, Tranel, & Damasio, 1997; Bechara, Tranel, & Damasio, 2000) as an executive function measure. While it is true that the gambling task is a sensitive measure of the functions of orbital (ventromedial) prefrontal cortex, not all functions dependent on prefrontal cortex are executive, and the gambling task seems to me a prime example of that. When slower-operating, older systems can subserve gradually improved performance (as in the gambling task), executive function is not required. Orbital prefrontal cortex is the oldest area of prefrontal cortex and the most tied to the limbic system. Extinction has for years been held up as the epitome of a nonexecutive function, and extinction too is impaired by damage to orbital prefrontal cortex. There is general agreement, however, that executive function (or functions) is an umbrella term that covers a family of cognitive functions rather than a single function such as selective attention.

The term *working memory* has been used in even more varied senses than has executive function. Goldman-Rakic (1988) used the term to refer to holding information in mind, and I have generally focused on that aspect of working memory as well. Baddeley (1992; Baddeley & Hitch, 1994) defined *working memory* as both holding information in mind and simultaneously manipulating or transforming it (maintenance + manipulation, or temporary storage + processing). Chapters 8 and 9 (this volume) rely heavily on this definition of working memory. Baddeley's perspective shares in common with my own that simply holding information in mind is not that taxing (unless the number of items becomes very large) and does not generally require involvement of dorsolateral prefrontal cortex. It is when holding information in mind must be combined with another operation, such as manipulation (which Baddeley has emphasized) or inhibition (which I have emphasized), that cognitive capacity is truly taxed and dorsolateral prefrontal cortex is required.

Another prominent model of working memory is that offered by Engle, who defines working memory as the ability to (1) maintain selected information in an active, easily retrievable form while (2) blocking or inhibiting other information from entering that active state (i.e., maintenance + inhibition; Conway & Engle, 1994; Kane & Engle, 2000, 2002). This shares much in common with the influential thinking of Hasher and Zacks (1988; Chapter 11, this volume), who have emphasized the inhibitory requirements of gating out irrelevant information from the mental workspace of working memory and deleting no-longer-relevant information from that limited-capacity workspace. Note that, to a large extent, the functions of holding information in mind and exercising inhibitory control, which I separate into working memory and inhibition components, are integrated in Engle's model under the term *working memory*.

While some, such as Engle, myself, and Gernsbacher and Faust (1991), discuss holding information (activating relevant information) and inhibitory control (suppressing irrelevant information and disadvantageous action tendencies) as separate processes, others argue that activating the relevant information alone is sufficient. Computation models, in particular, have tended to support the latter perspective (Cohen, Dunbar, & McClelland, 1990; Kimberg & Farah, 1993; Munakata, 2001).

When people discuss individual differences, or age-related differences, in working memory, they are often referring to differences in performance on complex span tasks (see, e.g., Chapters 8 and 9 on working memory, this volume). As pointed out above, however, complex span tasks (including counting, spatial, or reading span tasks) require a great many abilities, such as holding information in mind, updating, temporally ordering the information held in mind, resisting attention to distractors, and performing operations such as counting or reading. They are not simple measures of working memory, unless working memory is so broadly defined as to include almost every mental operation. There is no question that these tasks tap executive functions. They are less informative, however, about which of the component functions required by the task are critical to the observed individual or age-related differences in performance. For example, although complex span tasks are generally interpreted as indices of working memory, individuals who are better at blocking out, or inhibiting, distracting information perform better on complex span tasks (Conway & Engle, 1994; Conway, Tuholski, Shisler, & Engle, 1999; Gernsbacher, 1993; Hasher & Zacks, 1988) as do individuals who perform better on tasks (such as the anti-saccade task) that impose minimal demands on memory (Kane, Bleckley, Conway, & Engle, 2001). Could the inhibitory requirement of complex span tasks be what is critical?

Jacoby's processing dissociation method (1991) and Posner's subtraction method (Posner, Petersen, Fox, & Raichle, 1988) are powerful approaches to understanding which of the component abilities required by a task is critical to observed performance differences or to observed neural correlates. Even tasks far simpler than complex span tasks require multiple abilities, and it is critical to establish which of those component abilities is the reason for someone's difficulty with the task (see the discussion above on the differences between the reason amnesic patients or monkeys with medial temporal lobe lesions fail the delayed nonmatching to sample task, and the reason infants fail the task). However, it is also critical to bear in mind that adding an additional cognitive requirement may also change the intensity or nature of the requirement(s) it is being added to. Take, for example, the Eriksen Flanker task, where you are to attend to the centrally presented stimulus, ignoring the flankers around it. When the flanking stimuli are irrelevant to the task, no response inhibition is required because no response is associated with the flankers and demands on attentional inhibition are minimal. When the flanking stimuli are relevant to the task and mapped to the opposite response from the center stimulus (i.e., incompatible flankers), not only has a demand on response inhibition now been added, but the demand on attentional inhibition has also been increased.

Finally, distinctions between attentional control and working memory may be arbitrary and perhaps meaningless. Certainly, focusing on information held in mind for several seconds might as easily be called *focused* or *sustained attention* as working memory. The same prefrontal system that enables us to selectively remain focused on the information we want to hold in mind also helps us selectively attend to stimuli in our environment, tuning out irrelevant stimuli (e.g., Awh & Jonides, 2001; Barnes, Nelson, & Reuter-Lorenz, 2001; Casey et al., 2001). Individual differences in working memory capacity (using the Engle definition of working memory) correspond to individual differences in selective attention (Bleckley et al., 2003; Conway et al., 1999).

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