

Knowing in the Context of Acting: The Task Dynamics of the A-Not-B Error

Linda B. Smith, Esther Thelen, Robert Titzer, and Dewey McLin
Indiana University Bloomington

The A-not-B error is one of the most robust and highly studied phenomena in developmental psychology. The traditional Piagetian interpretation is that the error reflects the immaturity of infants' understanding of objects as permanent entities. More recently, the error has been interpreted in terms of changes in representation, in memory, in spatial knowledge, and in inhibitory processes. Each account may be partially right but none offers a unified account of the many accumulated facts about this error. This article presents and tests a new unified explanation. The authors propose that the perseverative reach back to A is the product of the processes that take a hand to a location in visual space: the body-centered nature of the spatial code, memories for previous reaching activity, and the close coupling of looking and reaching. The results from 6 experiments support this explanation. The results are used to challenge the idea of knowledge independent of and distinct from behavior.

In his book, *The Construction of Reality in the Child* (1954), Piaget described many hide-and-seek games he played with his infant children. He invented these games to find out what infants know about the permanence of objects across transformations in space and time. One of these games has become a signature task in the study of infant cognition: the A-not-B task. Here is the classic example: When Laurent was 9½ months old, Piaget placed him on the sofa with “coverlet A on the right and a wool garment B on the left” (p. 58). He placed his watch under A, and observed Laurent lift the coverlet and recover the watch. Piaget repeated this hiding and retrieval game several times. Then Piaget hid the watch at the B location: “Laurent watches this maneuver attentively. But at the moment the watch has disappeared under garment B, he turns back toward coverlet A, and searches for the object under the screen.” From this erroneous reach back to location A, the location at which the watch was first hidden and first found, Piaget concluded that Laurent did not completely understand the independence of objects from his own actions on them.

Linda B. Smith, Esther Thelen, Robert Titzer, and Dewey McLin, Department of Psychology, Indiana University Bloomington.

Portions of Experiments 1 and 2 were submitted by Dewey McLin to Indiana University Bloomington in the form of an honors thesis in partial fulfillment of the requirements for an honor's baccalaureate in psychology. This research was supported by National Institutes of Health Grant R01 HD22830, by Indiana University, and by a National Institute of Mental Health Research Scientist Award to Esther Thelen.

We thank Gerald Edelman, Einar Gall, and the participants at the Workshop on Object Retrieval at the Neurosciences Institute, La Jolla, CA, May 1995; Gregor Schonher, Jay McClelland, Liz Spelke, Marc Jeannerod, Mark Latash, and Giuseppe Pellizzer for their critical discussions of the account and experiments; Elizabeth Bjork for her insightful comments on an earlier version of this article; and Christian Scheier, John Spencer, Fred Diedrich, Melissa Weschler-Clearfield, Jana Iverson, and Dan Robin for discussions throughout the course of this work.

Correspondence concerning this article should be addressed to Linda B. Smith, Department of Psychology, Indiana University, Bloomington, Indiana 47405. Electronic mail may be sent to smith4@indiana.edu.

In the 4 decades since Piaget's report of the A-not-B error, it has been continuously studied and found to be a robust and universal phenomenon in infancy. However, despite the steadfast empirical and theoretical work, it is still unclear what the error means. Do infants actually believe that an object that disappears at location B can be found at location A? Most research on the error has concentrated on this question, on what infants *know* about objects and space.

In this article, we take a different approach. We seek to explain what infants *do* in the A-not-B task. At a surface-level description, what infants do is reach successively to locations in space and they make reaching errors. We start with this surface description of performance and offer an explanation of the A-not-B error in terms of the general processes that underlie goal-directed reaching. Our explanation focuses on performance and in the end raises profound questions about what it means to know. If these errors result from the processes that underlie reaching, what can they tell us about knowing? The idea of knowledge as an enduring mental structure that exists independently of behavior is preeminent in the study of cognitive development. We use the A-not-B error to challenge this idea.

The article is organized as follows: First, we summarize the extant evidence on the A-not-B error and the contexts of its occurrence. The error, although robust in its canonical form, is also highly complex in its context dependency. Second, we briefly summarize post-Piagetian thinking about the A-not-B error. In our view, these competing accounts each capture something quite real about the error, but each falls short of a unified account of the accumulated facts. Third, we propose an alternative account based on general processes of goal-directed reaching. We propose that the reach back to A emerges in the dynamics of goal-directed reaching, that is, in the processes that take a hand to a target in visual space. Fourth, we test predictions from, and find strong support for, this account in six experiments. Finally, in light of this evidence, we return to the question of what the error means for the nature and development of knowing.

A-Not-B Error

In tests of many specific hypotheses, experimenters have manipulated all aspects of the A-not-B task. These include the visual properties of the hiding locations, their transparency, their number, the delay between hiding and search, search for people versus objects, and search in the home versus in the laboratory. What experimenters have found is that nearly all of these conditions matter in one way or another and, if not alone, then in combination. There are several excellent and critical reviews of this extensive literature (Acredolo, 1985; Bremner, 1985; P. L. Harris, 1987; Wellman, Cross, & Bartsch, 1987). A complete theory must explain all these context effects. However, to begin, we summarize the benchmark facts about the canonical task. We return to the context dependency of the error and our explanation of several of these contextual effects in the General Discussion.

In the canonical A-not-B task, an infant sits before two hiding locations that are *highly similar* and separated by a small distance (e.g., two identical cloth covers or two identical lids that are 20 cm apart). While the infant watches, a desired object is hidden in one location, the A location. After a *delay*, the infant is allowed to *reach* and search for the object. This hiding and search at the A location is *repeated several times*. Then, again while the infant *watches*, the object is hidden at B. After the delay, the infant is allowed to reach. In this canonical form of the task, *8- to 10-month-old* infants reliably reach back to location A, making the A-not-B error. The extant evidence suggests that each of the highlighted components is central to the occurrence of the error. In the next sections, we note the relevant evidence.

Visual Distinctiveness of A and B

The error occurs most robustly when the hiding locations are visually similar (e.g., Bremner, 1978; Butterworth, Jarrett, & Hicks, 1982; Carranza, Brito, & Escudero, 1990; Wellman et al., 1987). The error is less likely when the two hiding locations are visually very different (e.g., when the A location is under a blue lid and the B location is under a white lid; Butterworth et al., 1982). In an influential meta-analysis of the many findings in this literature, Wellman et al. (1987) concluded that the distance between hiding locations did not matter. However, in many studies the hiding locations were close (20 to 30 cm from center to center), and the adjacent edges of the covers at the two hiding sites nearly touched (2 to 5 cm apart; see Bremner, 1978; Diamond, 1985; Horobin & Acredolo, 1986; Sophian, 1985; Wellman et al., 1987). In sum, the error occurs in the context of two visually confusable locations.

The Delay Between the Hiding Event and the Reach

The literature also reports that the error requires a delay between the hiding event and the infant's action. The error does not occur reliably at any age if the infant is allowed to search immediately after the object is hidden (Diamond, 1985; Gratch, Appel, Evans, LeCompte, & Wright, 1974; P. L. Harris, 1973; Wellman et al., 1987). This, then, is an error that emerges over time, in the wait between seeing the goal disappear and being allowed to act. Further, the delay necessary for the error increases with age: 8-month-olds require a delay of at least 3 s, whereas 10-month-

olds require a delay of at least 5 s (Wellman et al., 1987; see also Diamond, 1985). Thus, dynamic changes in memories between hiding and searching appear to be central to the error, and these dynamics change with age.

The Act of Reaching

The physical act of reaching also seems crucial to the error. This is the critical fact: In tasks that use the violation-of-expectancy paradigm and the dependent measure of looking time, infants demonstrate mature expectations about the spatial and temporal properties of hidden objects. For example, Baillargeon and Graber (1988) presented 7-month-old infants with a hiding event. The infants watched as an object was hidden behind one of two identical and adjacent screens. Then the infants watched a distractor event. They then watched as the object was retrieved. Infants in one condition saw an expected event: the object was retrieved from behind the screen where it was hidden. Other infants saw an unexpected event: the object was retrieved from behind the adjacent screen. The key result is that infants in this unexpected-event condition looked at the retrieval event longer than those in the expected-event condition. Baillargeon and Graber concluded that the infants looked longer because they were surprised when the object was retrieved from a place other than where it had disappeared. Results from many other violation-of-expectancy studies also suggest that, in these nonreaching tasks, young infants expect an object to be found at the location it disappeared, even after long delays (e.g., Ahmed & Ruffman, 1996; Baillargeon, Graber, Devos, & Black, 1990; Xu & Carey, 1996).

Hofstadter and Reznick (1996) provided a direct comparison between performances in two tasks that differed only in whether the infant reached or not. In their task, objects were first hidden repeatedly at A and then at B. On each trial, after the object was hidden, the infant was required to look to the center. Then, in one condition, infants responded by reaching for the object and, in the other condition, by looking to a hiding location (the experimenter retrieved the object.) Critically, more infants made the error in the reaching task than in the looking task. The idea that the error is inextricably linked to the act of reaching is also supported by experiments on the egocentricity of spatial coding in infants at the age they make the error. Briefly, infants who are moved in the course of a hiding task so that what was on the left becomes on the right commonly maintain the body-centered direction of the reach (see Acredolo, 1985; Acredolo, Adams, & Goodwyn, 1984). Altogether, the results suggest that the error emerges in the processes that take hands to locations in visual space.

Prior Activity at A

The error is a repetition of a once appropriate but now inappropriate act. This means that the prior activity of reaching to a similar and nearby location sets up the error. One unresolved question is just how much prior activity at A is necessary. Some evidence suggests that a single A trial might be sufficient (Piaget, 1954; Diamond, 1985), and several reviews have concluded that the likelihood of the error does not increase with the number of past reaches to A (e.g., Butterworth, 1977; Wellman et al., 1987; but see Landers, 1971). A closer examination of the relevant studies, however, suggests this conclusion may be premature. In particular,

two commonly used procedures make it difficult to determine just how the whole pattern of reaches by an infant in the task may be crucial to the occurrence of the error.

Many studies of the A-not-B error used a pretraining procedure involving several trials of reaching for the uncovered or partially covered object at (or near) the A location (e.g., Bremner, 1978; Bremner & Bryant, 1977; Butterworth, 1976, 1977; Cummings & Bjork, 1983a, 1983b; Bjork & Cummings, 1984; Frye, 1980; P. L. Harris, 1973, 1974; Willats, 1985). Thus, before the first "real" A trial, the infant may have made as many as three or four successive "practice" reaches in the direction of the A location. Such pretraining in and of itself may result in such a strong bias to reach to A that an effect of additional reaches to A may not be discernible.

Other versions of the A-not-B task repeat A trials until the infant meets some criterion number of consecutively correct reaches to A (e.g., Diamond, 1985; Fox, Kagan, & Weiskopf, 1979; Gratch et al., 1974; Horobin & Acredolo, 1986; Landers, 1971; Schubert, Werner, & Lipsitt, 1978). The actual number of A trials and the total number of reaches to A are not reported. A similar problem arises with all studies using multiple reversals (e.g., Appel & Gratch, 1984; Diamond, 1985; Diamond & Goldman-Rakic, 1989; Hofstadter & Reznick, 1996). These are studies in which A trials continue until the infant meets the criterion for (consecutively) correct reaches to A, then the toy is hidden at B and these B trials are continued until the infant again meets the criterion for correct reaches (i.e., the B trials become A trials), and then the hiding location is switched again (and the A location becomes the B location). In this procedure, the meaning of A trials and B trials is ambiguous.

All these procedures—pretraining at A, continuing A trials until some criterion is reached, multiple reversals—make it impossible to determine the complete history of reaches before an error. Thus, we can be confident only that prior activity at A in some as yet unspecified amount is necessary for the error.

Visual Attention

Infants' visual attention to the hiding events has also been implicated as crucial. Infants who look intently at the hiding location are much less likely to make the error than those who do not (Horobin & Acredolo, 1986; Landers, 1971). Moreover, visual distractions during the hiding event increase the likelihood of incorrect search (Diamond, Cruttenden, & Neiderman, 1994; P. L. Harris, 1973). In brief, where infants look influences where they reach.

Diamond, however, (1988, 1990a), suggested that looking and reaching do not always go together. She reported anecdotal evidence that at the same moment infants' hands reach to the wrong location on the critical B trial, their eyes look to the right location. Hofstadter and Reznick (1996) interpreted their (between-subject) finding that the error was less likely in looking-only than in reaching versions of the task as consistent with these anecdotal reports. Overall, then, questions about the relation between where infants look and where they reach remain: The direction of looking and reaching appear coupled, but indirect evidence and anecdotal reports suggests that at certain points in development they may be uncoupled.

Developmental Time Course

The A-not-B task elicits perseverative searching at a particular point in development. Infants younger than 7 months do not make the error; they do not because they do not manually search for hidden objects. Infants older than 12 months do not make the error but instead search successfully where they saw an object last disappear (see Wellman et al., 1987). This time span from 7 to 12 months of age is notably close to two achievements in spatially directed action. The first of these is the development of reaching itself. Infants first reach for objects by 4 months of age. However, they are not immediately skilled reachers. Instead, it takes many months of practice for infant reaches to become smooth, straight, and controlled (Berthier, 1996; Hofsten, 1991; Thelen, Corbetta, & Spencer, 1996). Despite having produced probably thousands of reaches at the time they make the A-not-B error, infant reaches are still jerky and indirect (Thelen et al., 1996), they are just beginning to shape their hands into the pincer grip for grasping (Halverson, 1931), and they make poor online adjustments to changing or difficult targets (Ashmead, McCarty, Lucas, & Belvedere, 1993; Berthier & Robin, 1997). In other words, at the time of the A-not-B error, infants are still in the process of becoming skilled reachers.

The window from 7 to 12 months is also the same time when infants begin to self-locomote. A number of studies have shown that experience at self-locomotion (crawling or walking) is correlated with success in the A-not-B task (Acredolo, 1985; Bell & Fox, 1992; Bertenthal & Campos, 1990; Horobin & Acredolo, 1986; Kermoian & Campos, 1988). Moreover, success on the critical B trial can be experimentally induced by giving infants early experience (through the use of walkers) in self-locomoting (Bertenthal & Campos, 1990). Thus, the error occurs at ages when infants can reach but when they have still limited experience in self-directed action in space.

Data to Be Explained

In summary, the data to be explained are considerable and complicated and contain several unresolved issues. Still, there is much known about the performance—that is the A-not-B error—and the conditions under which it occurs. We know that the error emerges in the dynamics of processes during the wait between seeing the goal object disappear and being allowed to reach. We know that these dynamics are influenced by the recent history of past activity at A such that, given a brief delay, the reach is correctly directed to B but, given a long delay, it is incorrectly directed to A. We know that the likelihood of the error is influenced by the visual distinctiveness of the hiding locations and typically by the direction of visual attention. Finally, the evidence suggests that the act of reaching may itself be crucial.

Current Explanations

We turn now to a brief consideration of explanations of the error in the contemporary literature. The starting question in this literature focuses on the hidden object: Do infants know it exists, do they know where it is, do they remember it? Unfortunately, 30 years of dogged and continuous empirical research addressing these questions has led to neither a consensus on the nature of the error nor on its meaning.

Object Concept

One approach to the error concentrates on infants' ability to represent perceptually absent objects. This approach derives from Piaget's (1954) original claim that infants only gradually become able to represent objects independently of their own actions. In Piaget's theory, the A-not-B error is one developmental step from sensorimotor to symbolic thought. There is contemporary agreement that Piaget's explanation is wrong. However, the development of the object concept still remains an issue. The debate now is what, if anything, the A-not-B error means for the development of object representations.

One side of this debate maintains that the error tells us nothing at all about object representations (e.g., Baillargeon & DeVos, 1991). The A-not-B error is irrelevant in this regard if, as Diamond (1990b, p. 662) suggested, infants in the A-not-B task "really know where the [object] is even when they reach back to where they last found it." In one version of this view, Bertenthal (1996) suggested that knowing and acting form two functionally dissociable systems (or modules). One of these, he posited, is an "object" system that is concerned with the perception and representation of individual objects. He proposed that this is where the object concept resides and that it develops early. He proposed that the A-not-B error arises from a second separate module, from a "perception-action" system that controls directed movement. In Bertenthal's account, the error and the contexts of its occurrence are about perception action, not object representation, and are thus irrelevant to debates about the object concept. This account raises troubling questions about disunities in infant cognition. Either the erroneous reach occurs without thinking (the infant does not access represented knowledge about objects), or the infant thinks "I want the object at B" and sees his or her own hand nonetheless mysteriously reach back to A of its own volition.

The competing side of the object-concept debate interprets the A-not-B error in terms of the weakness of early object representations. In this account, "having" an object concept is not an all-or-none matter but rather is an incremental achievement. More specifically, Munakata, McClelland, Johnson, and Siegler (1997; Munakata, 1998) proposed that infants who demonstrate the object concept in reaching tasks have stronger, longer lasting, and less noisy object representations than those who demonstrate such knowledge only in violation-of-expectancy tasks. This conclusion derives principally from a neural network simulation of both violation-of-expectancy and manual response paradigms. Notice that the direction of growth in this account is just the opposite of what Piaget originally proposed: The object concept is first expressed in expectations without action and then in expectations that organize and motivate action.

Neither side of this debate has generated a full account of the accumulated facts about the A-not-B error. Their focus is not on the behavior that is the error but on the presumed underlying representations. Thus, the empirical and theoretical effort has been concentrated on the contrasting object representations suggested by reaching and nonreaching tasks.

Spatial Concepts

A second class of explanations of the error concentrates on infants' representation of where the hidden object is. One early

idea was that the error resulted from body-centered representations of space, that is, in terms of representations that code locations relative to the body's position. The error disappeared by these accounts when these egocentric representations were replaced by allocentric ones (for reviews of this literature, see Acredolo, 1985; Bremner, 1978; Bremner & Bryant, 1977). The proposal that body-centered spatial coding causes the error and allocentric coding causes correct responding fits the data. In general, task manipulations expected to increase allocentric coding—visually distinct hiding locations, landmarks, familiar surrounds—all increase correct responding. Nonetheless, this egocentric-to-allocentric approach has been all but abandoned in the most recent literature on the A-not-B error. First, the spatial coding account does not fit well into the ongoing debate of what the error means for the development of an object concept. Second, it cannot explain the contrast in spatial competence suggested by reaching and violation-of-expectancy tasks. Finally, it does not explain the dynamics of the error. To work, an egocentric-to-allocentric account must explain why allocentric representations control performance early but not late in the delay between hiding and the allowed manual response (Wellman et al., 1987).

Response Inhibition

The final contemporary account focuses on interfering memories for the hiding events and for the action of reaching back to A. In this account, the reach to A is seen as a strong habit, a prepotent response, that has been rewarded (by finding the toy). Success on the critical B trial thus requires overcoming this strong motor habit (Diamond, 1985; P. L. Harris, 1973). In the most recent version of this account, Diamond (1990a; 1990b) proposed that infants make the error because of a general inability to integrate information over space and time (a memory problem) and a general inability to inhibit prepotent responses. In her account, the error is more likely the longer the delay between hiding and search, because the memory for the most recent hiding event declines and because inhibitory intent can only be maintained over a circumscribed duration. Diamond specifically proposed that the error disappears developmentally as the ability to inhibit increases over longer and longer durations. She placed the locus of this development in the maturation of the dorsolateral prefrontal cortex (see Diamond & Goldman-Rakic, 1989; Diamond, Zola-Morgan, & Squire, 1989).

This account provides a clear explanation of the role of the delay in the error, and sides with the view that the error has nothing to do with the development of object representations. However, it leaves many of the accumulated facts about egocentric responding and allocentric cues unexplained, and does not fit with the role of self-locomotion in the developmental disappearance of the error (see Thelen & Smith, 1994).

A New Approach

This, then, is the state of our understanding of the A-not-B error: There are many robust and systematic experimental facts. Each extant account captures a truth about the error, but only some of it. There is no consensus on the error's meaning or on its developmental importance. Accordingly, we propose to start over. We begin by taking a fresh look at the behavior that constitutes the error. Just what do infants do in this task?

Infants reach to successive locations in visual space, and they make errors by returning to an original location when the goal location has changed.

Reaching to Targets in Visual Space

What is required to accurately reach to a target location? The classic answer is that a reach consists of a series of ordered steps that, as illustrated in Figure 1, begin with cognition (perceiving the target, forming a goal) and end with action (selecting a motor program and forming a reach trajectory). For discussion of this classic view, see Allport (1987), Poulton (1981), and Keele (1981; and also Georgopoulos, 1986; Schönner, 1995).

This classic description of goal-directed reaching shares the same fundamental partition of knowing and acting as do contemporary discussions of the A-not-B error, that is, little connection between the mental events that precede and accompany action and action itself. In addition, it leads to recognizably similar questions about the error: Do infants have the right goal? Do they have trouble incorporating goals into actions? Are their goals formulated in egocentric rather than allocentric terms? Is the problem a habit “run-off” instead of the “right” motor program?

These, however, may not be the right questions in that they do not consider the overlapping temporal reality and continual interaction of the processes involved. The acts of seeing the goal, remembering its location, setting the appropriate movement parameters, forming an actual trajectory, and monitoring the action on-line are not discrete steps but rather processes continuous in time. As these processes coevolve, they may influence each other.

Dynamic Nature of Planning to Move

Georgopoulos et al. (reviewed in Georgopoulos, 1986, 1990, 1991, 1995) recorded the activity of single cells in the premotor and motor cortex of monkeys as the monkeys reached for targets. The monkeys’ task was like the A-not-B task in that the visual target was briefly presented and removed, and then there was a forced delay before the monkey was allowed to reach. Georgopoulos et al. found that the vector sum of the activity of many individual cells predicted the direction of impending movement. Figure 2 shows how the population vector emerged before the reach, in the wait between seeing the target and the beginning of actual movement. Georgopoulos (1990) interpreted the global pattern of activity across many individual cells as a continuously graded memory for target location, a temporally extended memory that takes time to emerge and time to decay. Georgopoulos’s studies indicated further that this is a body-centered memory that codes the location of the target relative to current hand position.

In studies of adult humans, Ghez et al. (Ghez, Hening, & Favilla, 1990; Hening, Favilla, & Ghez, 1988; Hening, Vaccaria,

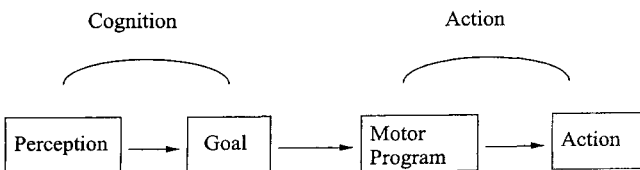


Figure 1. The classic view of reaching: from cognition to action.

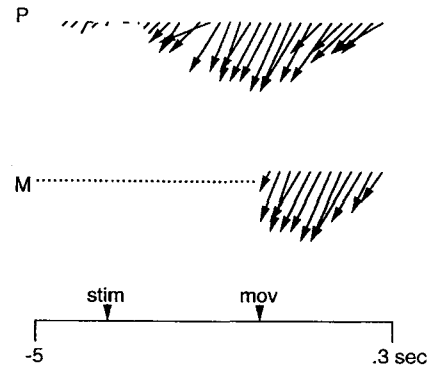


Figure 2. Population vectors (P) of directionally specified cortical neurons in monkeys and movement vectors (M). Adapted from Georgopoulos, Schwartz, & Kettner, 1986. Stim = stimulation; mov = movement.

& Ghez, 1988) designed a task also not unlike the A-not-B experience, with an ambiguous target and a delayed motor response. The task was to match force amplitudes, generated by isometric muscle contractions, to one of three target steps. Participants were given a preparation signal of four tones, but were told to move only on the fourth tone. The critical manipulation was a variable delay between the target force specification and the signal to actually begin the muscle contraction. Ghez et al. found that when the interval between the appearance of the target and the go signal was very short, participants produced motor response amplitudes that were a sort of blend between all three possible targets. As this interval lengthened, the distribution of responses gradually evolved to meet the targets given. Adults, therefore, demonstrated temporally extended processes of motor preparation, processes that began before and lasted longer than the conventionally measured reaction times. Given an uncertain goal to start, participants prepared a default amplitude based on what they expected from previous experience. After the appearance of the true target, they gradually modified this default value toward the desired one. The initial default plan for a reach was a summary memory for previous reaches.

Coupling of Looking and Reaching

Most of the contexts in which infants reach for objects in their daily lives are ones in which the target of the reach is an individually distinct object that is continuously present from the moment the sight of the object instigates the desire to reach until the hand makes contact with it. A continuously present and individually distinct target might be expected to help guide the reach by capturing and holding visual attention at a specific location. Considerable research on adult reaching suggests the direction of visual attention and the direction of a reach are closely and continuously coupled. First, momentary shifts in the direction of gaze, even after a reach has started, produce shifts in the path of the reach (e.g., Enright, 1995; Ghez, Hening, Favilla, 1990; Goodale, Péllisson, & Prablanc, 1986; Jackson, Jackson, & Rosicky, 1995). Second, in the absence of a continuously present visual target, adult reaches are biased by starting hand position and posture (Biguer, Jeannerod, & Prablanc, 1982; Fisk & Goodale, 1985; Ghilardi, Gordon, & Ghez, 1995). Finally, adult reaches are

perturbed by the presence of irrelevant visual distractors, including those added after a reach has started (Castiello, 1996; Tipper, Lortie, & Baylis, 1992). In sum, adult reaches depend crucially on the direction of visual attention and the visual information available to guide a reach. Apparently, the internal activity that codes the direction of an adult reach is not rigidly fixed by the original sight of the goal but is fluidly shaped, kept on target or pulled away, by the continuing visual input. Recent studies of infant reaching suggest the same conclusion. Infant reaches, like adult reaches, are perturbed when the target object shifts or disappears, even after a reach has started (Ashmead et al., 1993; Berthier & Robin, 1997).

From this perspective, it is not surprising that infants find the A-not-B task difficult. The toy presents what could be an easy reaching target, a unique and perceptually well-segregated object; but the toy is hidden. The reaching target, the continuously available visual cue to guide motor planning, is instead a flat object (lid or cloth) that rises slightly from the background and sits next to a highly similar distractor object (the other hiding cover). From the perspective of the processes that take a hand to a location in space, this is a context in which errorful and biased reaching seems likely.

Memories for Previous Reaches

Finally, the evidence suggests that repeated reaches over and over to the same location—what infants do in the A-not-B task and what monkeys did for the Georgopoulos group—alter the internal activity that signals a reach and the directional bias of a movement. In particular, the evidence from monkeys suggests that repeated reaches lead to more finely timed and more finely tuned population vectors (Georgopoulos, Crutcher, & Schwartz, 1989). Other studies suggest that such repeated activity also leads to an increased tendency for the system to repeat the immediately preceding activity (Racazone, Merzenich, & Schreiner, 1992; Roby-Brami & Burnod, 1995). Indeed, rapidly repeated movements by adults have been shown to be biased in the direction of past activity (Hening, Vaccaria, & Ghez, 1988; Jeannerod, 1988; Lackner & DiZio, 1994; Shadmehr & Mussa-Ivaldi, 1994). Memories for the last reaches seem most likely to interfere when the new reaching target is not perceptually salient or is similar to the previous reaching target. This is the A-not-B task.

Reaching Account of the A-Not-B Error

In view of the extant evidence on reaching to visual targets, we propose that a reach emerges from a continually evolving and self-organizing system, a flow of information better illustrated by Figure 3 than by Figure 1. In this new depiction, the visual input, most critically, where one is looking, defines and continuously influences the reach goal and the movement. However, the goal and the movement also influence where one looks. The momentary activity of the system is the joint product of all these and also of their recent history. In this way, the goal of an action and the action itself are inseparable. We propose that the A-not-B error emerges as a direct consequence of this system and its unskilled form in infancy. Specifically, we propose that the error is created by the in-task dynamics, by the emergence of each reach out of memories for preceding reaches, and by the continuous coupling and co-employment of reaching and looking.

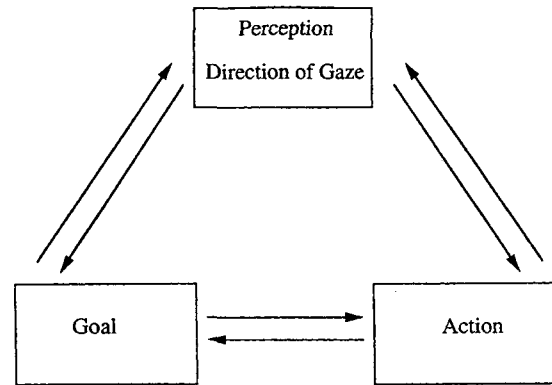


Figure 3. Multidirectional influences in a continually evolving reaching system.

The extant evidence on reaching reviewed in the previous section suggests that the activity at any moment in the components of the system shown in Figure 3 are determined in part by the immediately preceding activity of the system. This means that the internal patterns of activation that arise from seeing a target will change over the course of the task. For example, the internal activation on trial n will be a function of the moment-to-moment pattern of where the infant looks on that trial and the specific events of looking and reaching that occurred on trials 1 to $n - 1$. We propose, then, that the A-not-B error is a reaching error, emerging because the history of looking and reaching in the task creates a directional bias and because the visual input continuously available to guide the hand to the target location is insufficient to overcome this bias. The visually available reaching target—the cover—is insufficient to overcome this bias because the cover is nonsalient and sits next to a similar distractor and because 8- to 10-month-old infants are not skilled reachers.

We use Figure 4 to depict the theoretical activity in the goal component of Figure 3 to make our theoretical claims clearer. On the very first trial of the task, as the experimenter directs attention to Location A by putting the toy under the A cover, the infant's intended movement to A will be internally signaled by increasing activation in the A direction. We depict this activation at the top of Figure 4, which shows the theoretical activity in the goal component over the delay as a result of seeing the toy hidden at A. We draw a weak and temporally blurred activation curve because infants are not skilled reachers and because the visually available reaching target is a poor attentional guide. The prediction is that seeing the object disappear at the A location for the very first time will bias all the components in the system—the goal, looking, reaching—toward A. However, it will not be a strong or long-lasting bias. Indeed, by our analysis, the initial hiding event might not even yield an activation level that exceeds threshold to yield a reach. That is, after seeing one toy disappear, a novice reacher might not reach at all. This, we assume, is the reason past researchers used either a pretraining procedure to induce an initially correct reach to A or continued A trials until some criterion number of reaches to A had been achieved.

As the middle panel of Figure 4 illustrates, each time the experimenter pulls the infant's visual attention in the direction of the A location and each time the infant reaches to A, the activation

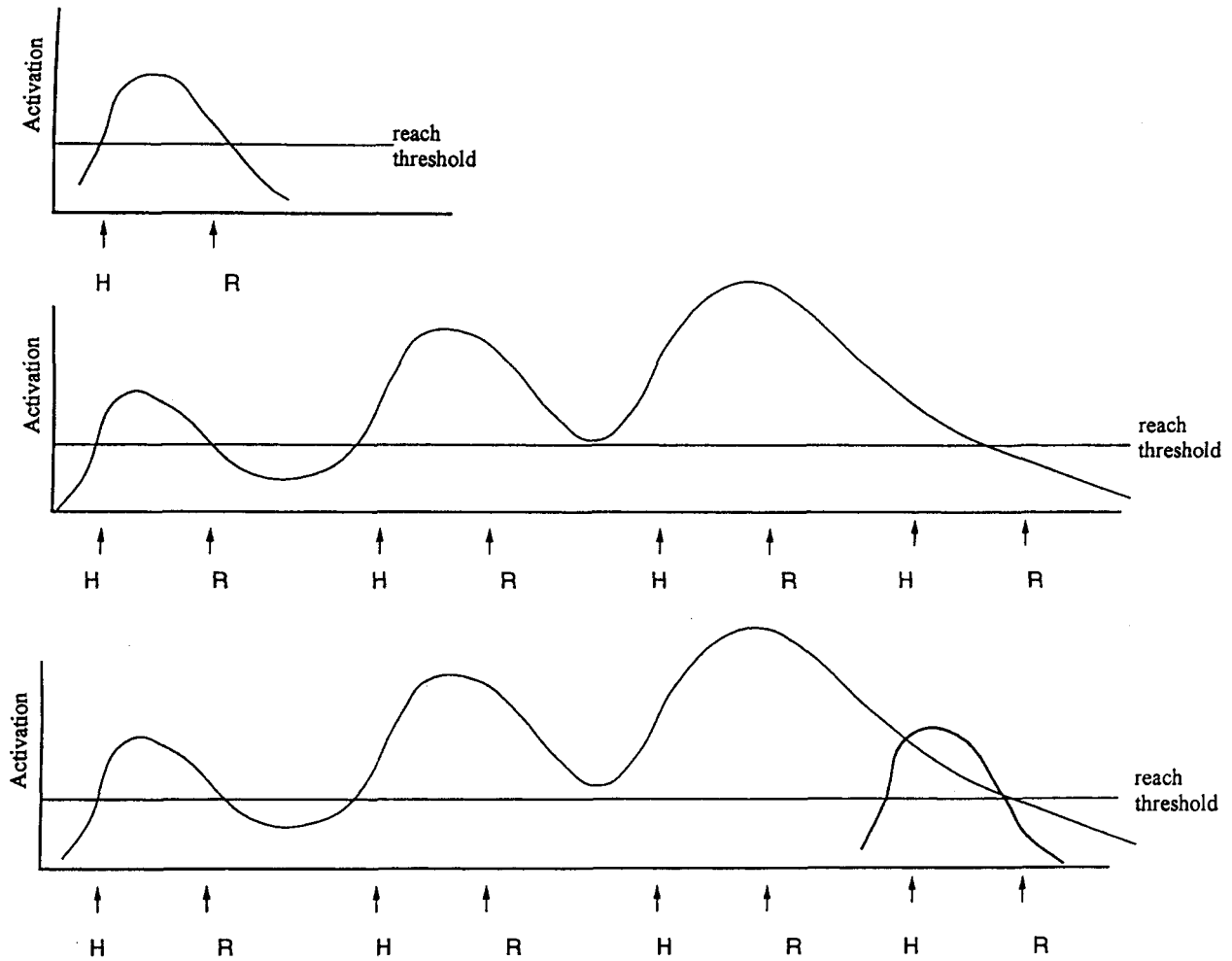


Figure 4. Theoretical activity in the goal component as a result of (top) seeing the toy hidden at Location A once, (middle) several successive hidings and searches at A, and (bottom) seeing the toy hidden at B. H = time of hiding event; R = time when infant is allowed to reach.

triggered by seeing the toy disappear at A will change. More specifically, the internal activation triggered by the visual events at A will build. Further, an actual reach to A may strengthen and tune the pattern such that after several reaches the internal activity more tightly specifies the direction and onset of the reach. In these ways, the memory for the direction of preceding looking and reaching endures to bias subsequent reaches.

What will happen when ultimately the experimenter directs the infant's attention to Location B by hiding the object there? The experimenter's actions at the B location should activate an intended direction of movement toward B. However, that pull to B must be laid on the remaining activation from previous trials, combined with the bias to A. We illustrate the possible time course of activation in the third panel of Figure 4. Immediately after the hiding event, internal activity may be more strongly in the B direction than A direction; thus, the infant may reach correctly. However, as the activity engendered by the visual events at B decline in the absence of a continuing and visually unique reaching target, it will become increasingly likely that

the combined activity—the residual activation from successive reaches to A and the residual activation from seeing the object hidden at B—will signal a reach to A. Thus, we will observe the A-not-B error.

Crucial to this account of the error is the idea that these patterns of internal activations reflect the continuous interaction of looking, reaching, and memory in the system for its own previous activation. It matters that there are two potential reaching targets on the table that are similar. It matters that infants repeatedly reach to A before they reach to B. Thus, by our account infants do not make (at least not noticeably) perseverative errors in their everyday reaches to real objects. In the everyday world, the bias to reach in the direction of past activity will be weak because infants are not required to reach repeatedly to one location, and any memory for a just preceding reach is also likely to be swamped by the unique and continuing visual input presented by the desired object.

Our account yields a number of testable predictions and empirical questions. We outline these here in an overview of the six experiments that follow:

Experiment 1: Previous Activity

Our account makes three predictions that run counter to some characterizations of the phenomenon. These three predictions are (a) without pretraining, reaches to A on the initial A trials should be fragile because there is not a compelling and unique reaching target; (b) the likelihood of a reach to A on the first B trial is an increasing function of the number of past reaches to A; and (c) reaching and looking are coupled such that infants reach where they look. We test these predictions in Experiment 1 using the standard version of the A-not-B task, that is, search for a hidden object.

Experiment 2: No Hidden Object

Our account explains the error in terms of the visual information present at the time of the reach—the reach target—not in terms of a representation of a hidden object. Experiment 2 tests the prediction that infants make perseverative errors in reaching tasks identical to the A-not-B task even when there is no object to represent. We use what we call a lids-only version of the task in which the reaching targets and distractors are the same as in the hidden object task of Experiment 1.

Experiment 3: Spontaneous Reaching

Our account predicts that reaches should become strongly perseverative in the absence of visual input that specifies a new reaching target. Moreover, the likelihood that a visual cue disrupts perseverative behavior should decrease with each perseverative act. We test these predictions in a spontaneous reaching task.

Experiments 4 and 5: The On-Line Influence of Where One Looks

These two experiments test the prediction that the direction of a reach is directly influenced by the direction of gaze. We experimentally manipulate the direction of gaze just as the reach begins and ask how it combines with a history of reaching to A to

influence a reach to a target at A (Experiment 4) or a target at B (Experiment 5). The task is the standard A-not-B task in which an object is hidden.

Experiment 6: Posture and a Body-Centered Code

By our account, the error emerges because of the dynamics of the internal code specifying a reaching direction. Using the standard version of the A-not-B task in which a toy is hidden, this experiment tests the idea that this code is body centered in that it specifies the location of an object relative to body position. If this is so, memories for previous reaches should be disrupted by changing posture.

Experiment 1: Previous Activity

The main task in this experiment consisted of just four trials: An object was hidden twice at Location A and then twice at Location B. The three experimental conditions were defined by pretraining procedures that preceded this main task. The structure of the three conditions is illustrated in Figure 5.

In the no-pretraining condition, infants received just the four experimental trials, A1, A2, B1, and B2. We predict poor performance in this condition, especially on Trial A1, because the reaching target (a brown lid on a brown box) is not salient and sits next to a similar distractor.

In the pretrain at A condition, infants are given four training trials just before the experimental task. Our training procedure in this condition was modeled on that used by P. L. Harris (1987) and Butterworth (1977). On the first training trial, T1, a desirable toy is placed in clear view in front of the A well. Infants should readily reach for this object because it is distinct and closer to the infants than the distractor object (the B lid). On the remaining training trials, the toy is progressively hidden, in the uncovered A well on T2, in the partially covered A well on T3, and in the completely covered A well on T4. On this last training trial, the continuously available reaching target, the A lid, is adjacent to the B lid, just as in the main task. Thus, during pretraining, the infant proceeds

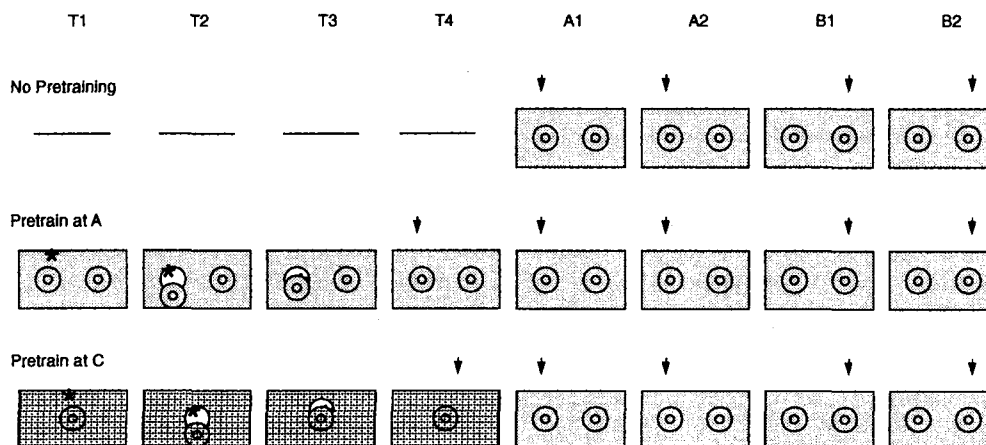


Figure 5. Structure of the three conditions in Experiment 1 depicted in terms of what the infant sees at the moment the infant is allowed to reach on the pretraining trials (T1, T2, T3, T4) and the four experimental trials (A1, A2, B1, B2). The toy is indicated by the *; the arrows indicate the location of the completely hidden toy.

progressively from reaching for a target that is unique to a less salient target next to an identical distractor. However, the infant always reaches in the same direction: toward A. If each reach by an infant builds on the preceding one, this pretraining procedure should create a strong bias to reach in the A direction that is evident on Trial A1. Moreover, the directional bias toward A should become so strong that it overwhelms the transient visual signal at B when the object is hidden there. In brief, this condition should yield a robust A-not-B error.

In the Pretrain at C condition, infants are also progressively taken from a salient reaching target to a less salient one. However, in this condition, pretraining occurs at a third location with no distractor target in view during pretraining. As illustrated at the bottom of Figure 5, the infant is pretrained with a single hiding well at midline. The infant's reaches to center in this pretraining task should not create a directional bias to A or B. Thus, we predict that, in the main experimental task, infants will be less likely than infants in the Pretrain-at-A condition to reach to A on both the A and B trials.

The pretrain-at-A condition has been used in many studies (e.g., Bjork & Cummings, 1984; Bremner, 1978; Bremner & Bryant, 1977; Butterworth, 1976; Munakata, 1998; Frye, 1980). Versions of the train-at-C condition have also been used in past studies (Benson & Uzgiris, 1985; Gratch et al., 1974; Hofstadter & Reznick, 1996; Horobin & Acredolo, 1986). We know of no direct comparisons of the these two procedures and only rare and inconsistent reporting of the first A trial performance after pretraining. We are aware of only one study that used no pretraining (or criterion correct responding at A) and reported the first A-trial performance. Without pretraining, Webb, Massar, and Nardolny (1972) found that one third of the infants erred or did not respond at all on the first A trial.

Thus, the new empirical contribution of Experiment 1 is the direct comparison of no pretraining, pretraining at a neutral location, and pretraining at A. Additionally, we provide a trial-by-trial accounting of infant reaches during pretraining, on A trials, and on B trials. All these reaches, and not just those on the B trials, are essential to understand the error, because by our account the same processes that create a reach during pretraining also create a reach on A trials and on B trials, and where the infant reaches at any moment depends on the events that instigate a goal to reach, the visually available reaching target, and the moment-to-moment reaching history in the task.

Method

Participants. The participants were 57 infants: 30 infants within 2 weeks of their 8-month birthday and 27 infants within 2 weeks of their 10-month birthday. Infants were randomly assigned to the three conditions. Ten infants at each age level participated in the pretrain-at-C and the pretrain-at-A conditions. Ten 8-month-old and seven 10-month-old infants participated in the no-pretraining condition. An approximately equal number of boys and girls participated at each age level in each condition. Six additional children were tested and replaced either because of experimenter error, parents not following instructions, or failure of the video equipment. Infants were recruited from birth announcements and advertisements in the local newspaper and received a small gift (T-shirt) for participation.

Materials. The hiding box for the main task in all conditions and for pretraining in the pretrain-at-A condition was 30 cm × 23 cm × 5.5 cm. It was painted brown and contained two circular hiding wells, each with a

radius of 4.5 cm and depth of 4.5 cm. The centers of the wells were 12.5 cm apart. The wells had identical brown circular covers made from thin (0.25 cm) wood. The radius of each cover was 4.7 cm. Each had an hourglass-shaped wood knob, which served as a handle. The knobs were 1.8 cm tall with a radius of 1.3 cm at the widest point. All sessions were conducted on a 60.5 cm × 122 cm table. The table contained wood tracks to ensure the hiding box was presented to and withdrawn from the infant in the same way and by the same amount on each trial. The hiding box for pretraining in the pretrain-at-C condition was identical to the box described previously except there was one well located in the center of the box and the box and lid were painted orange. Small brightly colored toys (keys, small figures, small vehicles) served as objects to be hidden. All were approximately 3.5 cm along their longest dimension. Each participant's session was recorded by video camera.

Procedure. The infant sat on the parent's lap centered in front of the hiding box across from the experimenter. The parent was told that this was a memory and reaching task in which infants sometimes did not reach and often made errors and that they should not coax, encourage, or correct the infant's actions. The infant was then presented with four to five small toys. The first toy the infant picked up was used as the toy to be hidden. In the few cases in which an infant did not choose a toy, the experimenter chose one. At this point, infants in the no-pretraining condition were presented with the first trial of the main task, A1. At the start of the trial, the hiding box was on the experimenter's side of the table and out of reach of the infant. The experimenter removed the A lid from over the A well and held the toy up to draw the infant's attention to it. Care was taken to ensure that the infant was watching as the experimenter put the toy in the open well and covered it with the lid. The experimenter imposed a delay of 3 s for 8-month-olds or 5 s for 10-month-olds. Timing of the delay interval began from the moment the lid was placed on the well to the moment the hiding box was pushed forward. Three- and 5-s delays were based on previous research that indicates that these are the delays at which 8- and 10-month-old infants, respectively, reliably make the error (Diamond, 1990a; Wellman et al., 1987).

After the delay, the box was slid toward the infant until it came to rest directly in front of the infant. The experimenter waited 15 s for a response by the infant. If the infant had not found the toy at that point, the experimenter removed it from the well and gave it to the infant. The box was pulled back out of the infant's reach, the toy was taken from the infant, and the next trial begun. This procedure was repeated once more with the toy hidden in A and then twice more with the toy hidden in B, resulting in a total of two A trials followed by two B trials.

The procedures for the train-at-A and train-at-C conditions were identical except the four trials of the main task were preceded with four training trials, as illustrated in Figure 5. The first training trial began with the hiding box close to the experimenter and out of reach of the infant. The participant's attention was drawn to the toy that was placed on the edge of the box, in front of the A well in the train-at-A condition and in front of the single center well in the train-at-C condition. Then the box was immediately pushed forward so that toy came within the infant's reach. On the second training trial, the box was pulled back out of the infant's reach, and the toy was placed in the A or C well uncovered. The box was immediately pushed forward to within the infant's reach. The third and fourth training trials were identically structured except that on the third trial the toy was in the well partially covered by the lid, and on the fourth trial the toy was in the well completely covered by the lid.

The right-left assignment of the A and B locations was counterbalanced across participants at each age level in each condition.

Coding. Infant responses were coded from videotapes by scorers unaware of our specific hypotheses. A reach was defined as an action that ended in contact with the lid. The first reach (first lid manually contacted) on each trial was counted as the response. For each of these responses, the scorers determined the direction of the infant's gaze at the moment the hand first made contact with the lid. Scorers judged the infant's gaze at the

moment of contact to be either in the A or B direction. Two scorers independently judged 25% of the infants tested. Reliability was 100% for first reach on each trial and for direction of gaze at the moment of manual contact with the lid. In brief, these were not ambiguous behaviors.

The scorers also measured the time of the delay between when the experimenter placed the lid over the well and when the experimenter pushed the box forward. Validation of the delay is important because the experimenter's behavior is not automatically controlled and is likely to vary at least somewhat with individual infant's behaviors. The mean delay was 3.25 s ($SD = .47$ s) for 8-month-olds and 4.90 s ($SD = .62$ s) for 10-month-olds. One-way analyses of variance conducted separately at each age level indicated no reliable differences among the three conditions in the mean delay imposed by the experimenter, $F(2, 27) < 1.00$ and $F(2, 24) < 1.00$, respectively.

The scorers also coded parent behavior to ensure all complied with our instructions not to influence infants' reaching. The data reported all derive from infants whose parents complied with these instructions.

Results and Discussion

Table 1 shows the proportion of all children who reached to A on the four trials of the main task. There were no differences in the frequency with which 8- and 10-month-olds reached to A, a fact that is not surprising because we selected delays designed to yield comparable performance at the two age levels. There are, however, clear differences in performances among infants in the three conditions.

Refusals to reach. Five of the 17 infants in the no-pretraining condition refused to reach on the first A trial (A1), and 4 of these 5 refused to reach on all four trials. No infant in the other two pretraining conditions ever refused to reach. Only in the no-pretraining condition did infants begin with the hard reaching task of a nonsalient reaching target and a nearby and similar distractor.

Reaches on A trials. As predicted, infants in the three pretraining conditions were not equally likely to reach to A on the first A trial, $\chi^2(2, N = 57) = 10.86, p < .01$. Infants pretrained at either A or C were much more likely to find the hidden object on Trial A1 than were those who received no pretraining. In both the pretrain at A and pretrain at C conditions, infants reached to A on Trial A1 reliably more often than expected by chance (binomial, $p < .05$, chance estimated as .50). The frequency with which infants in the three conditions reached to A on Trial A2 also

differed reliably, $\chi^2(2, N = 57) = 4.29, p < .05$. However, only infants who were pretrained to reach to A did so on Trial A2 at levels greater than expected by chance (binomial, $p < .05$). Overall, then, infants in the pretrain-at-C condition were less successful on the A trials than were infants in the pretrain-at-A condition. In addition, infants in both of these conditions were more successful than those in the no-pretraining condition.

The chief conclusion from these results is that the initial goal-directed reach to the A lid is itself fragile. The common textbook description of the A-not-B error is wrong. Infants do not easily find the object where it is first hidden and then paradoxically search back to that place when the object is hidden in a new location. Rather, without training, infants do not easily reach to A on Trial A1.

B trial performance. As can be seen in Table 1, the proportion of infants who make the error and reach back to A differs reliably among the three conditions on trial B1: $\chi^2(2, N = 52) = 6.79, p < .05$. Indeed, only infants who were pretrained at A continue to reach to A at levels reliably greater than chance on B1 (binomial, $p < .05$). These group differences on Trial B1 are exactly what one would expect if a reach back to A is highly dependent on the number of previous reaches to A: On Trial B1, the mean number of prior reaches to A was 5.35 for infants in the pretrain-at-A condition, 1.35 for infants in the pretrain-at-C condition, and .92 for infants (who reached at all) in the no-pretraining condition. Thus, only infants in the condition that had elicited many prior reaches to A reliably made the A-not-B error.

These differences among conditions remained, indeed were increased, on Trial B2, $\chi^2(2, N = 52) = 15.04, p < .01$. Again, only infants in the pretrain-at-A condition reached to A reliably more often than expected by chance on B2 (binomial, $p < .05$). That the differences among conditions increases over the course of the experiment makes sense by our account: Different initial conditions create different behaviors that then push subsequent behavior in increasingly different directions.

Conditional probabilities. To examine more closely how the in-task history of reaches biases the next reach, we calculated the conditional probabilities of a reach in one direction given the number of previous reaches in that or the opposing direction. For these analyses, unlike those reported previously, we counted *all* reaches: the first reach that ended in contact with a lid (the reach counted in the prior analyses) as well as any subsequent reaches. For example, if an infant in the no-training condition on Trial A1 reached first to the A lid and secured the toy and then reached and touched the B lid, the infant on Trial A2 would be counted as having one prior reach to A and one prior reach to B. We include all reaches throughout the training and test trials in this analysis because by our account it is the continuous dynamics of the system—real behaviors in real time and not the remembered outcomes of discrete trials—that creates the bias to reach to A. Overall, infants reached first to one lid and then another on 38% of all pretraining and main task trials. Interestingly, a second reach was not more likely given an erroneous first reach, $\chi^2(2, N = 52) < 1.00$.

Figure 6 shows the probability of a reach to A as a function of the number of previous reaches to A or B on A trials and on B trials. Consider first the conditional probabilities on the A trials, the trials on which the infant has just seen the toy disappear at A. Even on these trials, the likelihood of a reach to A increases as a

Table 1
Proportion of Children Reaching to the A Lid on the Four Experimental Trials

Group	A1	A2	B1	B2
No pretraining	.35 ^a	.45	.30	.20
8 mo	.50	.60	.30	.20
10 mo	.10	.30	.30	.20
Pretrain at C	.70	.60	.45	.55
8 mo	.80	.60	.40	.50
10 mo	.60	.60	.50	.60
Pretrain at A	.85	.80	.70	.75
8 mo	.90	.80	.70	.70
10 mo	.80	.80	.70	.80

Note. Proportions of 8- and 10-month-olds considered separately are given below each group. mo = months old.

^a Recall that in the no-pretraining condition, there are unequal numbers of 8- and 10-month-olds.

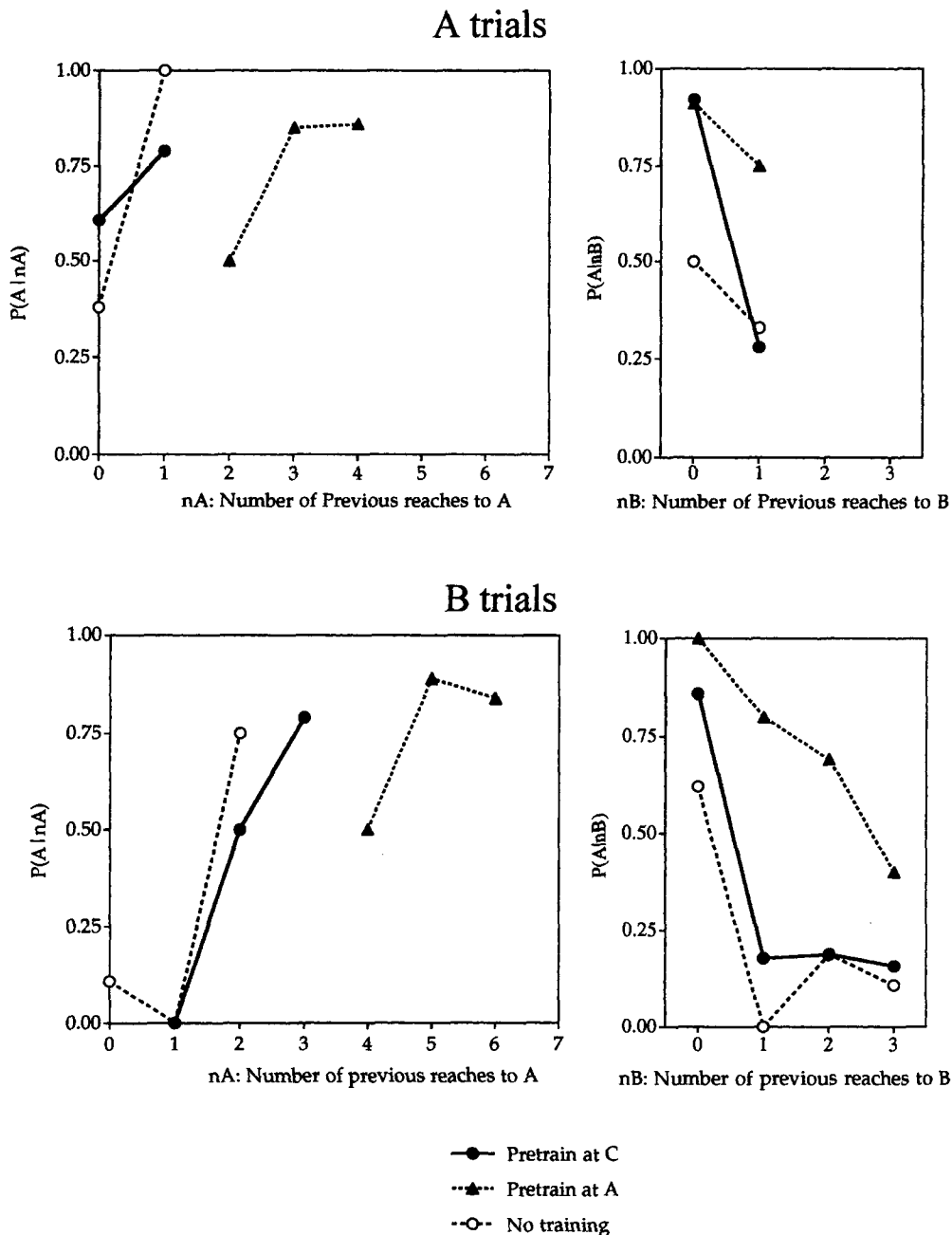


Figure 6. Conditional probabilities of a reach to A on A trials and B trials as a function of the number of prior reaches by the infant to A or to B in the three conditions of Experiment 1.

function of the number of prior reaches to A and decreases if the infant has made even one reach to B. Notice especially the no-pretraining condition. These infants who are not given a strong visual cue to A on their very first trial of the experiment are not highly likely to reach to A. However, given just one prior reach to A, a subsequent reach to A is certain. Thus, a single reach to A is enough to create a bias in the A direction. This fact fits with past suggestions that under some circumstances a single A trial on which the infant reaches to A might be sufficient to yield a

perseverative error (see Butterworth, 1976; Landers, 1971). However, as is evident in the figure, the strength of the bias clearly increases with the number of reaches. Performances on the B trials show the same pattern. The likelihood of a reach to A increases as a function of the number of previous reaches to A and decreases as a function of the number of previous reaches to B.

Coupling of looking and reaching. Infants overwhelmingly looked and reached in the same direction on A trials and B trials. Only 2 infants of the total 57, 1 on an A trial and 1 on a B trial,

were looking at the other lid when they made manual contact with the lid. In other words, of the 208 trials on which these infants reached, looking and reaching coincided on 206 of them.

We further examined the coupling of reaching and looking by continuously coding the direction of gaze throughout the experiment for four randomly selected infants who made the error. The left side of Figure 7 shows the total amount of time 2 infants in the pretrain-at-A condition looked in each direction on each trial. The right side of the figure shows the moment-by-moment direction of gaze on Trials B1 and B2. Both infants watched the object disappear at B and then before the reach shifted their direction of gaze to A. As shown in Figure 8, a similar pattern of results, both in total looking on each trial and for the moment-to-moment direction of gaze on B1 and B2, was obtained for the 2 infants continuously coded in the pretrain-at-C condition.

In brief, infants look where they reach. We return to this point in Experiments 4 and 5, in which we attempt to manipulate the direction of reach by manipulating the direction of gaze.

Summary of Experiment 1. This experiment tested and found support for three predictions derived from our reaching account of the A-not-B error, three predictions that run counter to lore about the A-not-B error. First, we found that reaches on the initial A trials were themselves fragile unless they were preceded by a recent history of reaching to A. Second, we found that the likelihood of a reach back to A on B trials was an increasing function of the number of past reaches to A. This was true in the group differences among pretraining conditions and in the performances of individuals measured in terms of the conditional probability of a reach in one direction given the number and direction of previous reaches. Finally, we found that looking and reaching are tightly coupled behaviors. All these aspects fit our view that the A-not-B error arises out of the processes underlying goal-directed reaching.

Experiment 2: No Hidden Toy

Our account explains the A-not-B error in terms of reaching rather than in terms of infants' representation of the hidden object. If the error is caused by the processes that take a reach to a location in visual space, then the error should occur in any analogous reaching task, including tasks in which there is no hidden object. We test this prediction in Experiment 2 by repeating the procedure used in the pretrain-at-A condition except there is no hidden toy. Instead, on each trial, the experimenter directs the infant's attention to one of the two lids by picking it up and waving it.

Method

Participants. The participants were 20 infants: 10 infants within 1 week of their 8-month birthday and 10 infants within 2 weeks of their 10 month birthday. Five boys and 5 girls participated at each age level.

Materials. The brown box and lids used in the pretrain-at-A condition of Experiment 1 were used for all participants in this experiment.

Procedure. The procedure was identical in all aspects to that in the pretrain-at-A condition of Experiment 1 except that on no trial was a toy hidden. The experiment begins with the A lid over the A well and the B lid over the B well. On the first pretraining trial, the experimenter lifted the A lid, waved it until the infant looked at it, placed the lid on the edge of the box in front of the A well, and then pushed the box to within the infant's reach. This first pretraining trial thus presents a salient reaching goal and target; the A lid is both waved and pushed forward to rest on the edge of

the box so that it is nearer to the infant than the distractor (B) lid. Our expectation was that infants would reach for the A lid. On successive training trials, the lid was moved further back on the box until the last training trial when the lid covered the A well and thus sat next to the B lid. On the first A trial proper, the experimenter lifted and waved the A lid and put it on the A well; the B lid remained in place over the B well. The experimenter waited for the delay (3 s for the 8-month-olds, 5 s for the 10-month-olds) and then pushed the box to within the infant's reach. The experimenter waited 15 s for a response by the infant before beginning the next trial. This A trial was repeated a second time. The two following B trials were identical to the A trials, except the experimenter waved the B lid and then put it back on the B well. All sessions were videotaped and coded by individuals unaware of our specific hypothesis as in Experiment 1. Two scorers independently judged 25% of the infants tested. Reliability was 100% for first reach on each trial. The mean delay between the time the experimenter placed a lid down and moved the box to within the infant's reach was 3.19 s ($SD = 0.35$ s) for 8-month-olds and 5.11 s ($SD = .86$ s) for 10-month-olds.

Results and Discussion

All infants reached for a lid on all trials in this experiment, not a surprising result given a first pretraining trial that presented an easy reaching target. Table 2 shows the proportion of all children who reached to A on the four experimental trials. More infants than expected by chance reached to A on the A trials, and more infants than expected by chance reached back to A on the B trials (binomial, $p < .05$ for all trials, chance estimated as .50). Further, on none of the four trials does the number of reaches to A differ reliably from those made by the infants in the pretrain-at-A condition of Experiment 1, $\chi^2(2, N = 40), p < 1.00$ in all cases. These results provide strong support for the idea that it is the processes of reaching, not the processes of remembering hidden objects, that creates the perseverative error.

The conditional probabilities of a reach to A or B as a function of the number and direction of previous reaches was calculated as in Experiment 1. Figure 9 shows the probability of a reach to A as a function of the number of previous reaches to A or to B. By the first experimental trial, all infants had reached to A many times; thus, the probability of a reach in that same direction was high on all subsequent trials, both A and B. Notice, however, that even one or two previous reaches to B considerably lessens the likelihood of reaching to A. Where and how often an infant has reached in the immediate past determines the likelihood of a perseverative reach. Notice further that the pattern is nearly identical to that observed in the pretrain-at-A condition of Experiment 1. The correspondence between the patterns of conditional probabilities with and without a hidden object provide further support for the idea that it is the processes of reaching to a visual target that create the error.

Experiment 3: Spontaneous Perseveration

By our account, where an infant reaches is the blended product of the strength of the transient signal that instigates a goal to reach (e.g., a toy being hidden, a waved lid) and the lingering activity from, or memories for, previous reaches. The relative strength of these determines the direction of the reach. We test this idea in a spontaneous reaching task.

In one condition, we presented the transient input to instigate a directional reach before the first reach. That is, the experimenter waved one lid and with no delay pushed the box forward so that

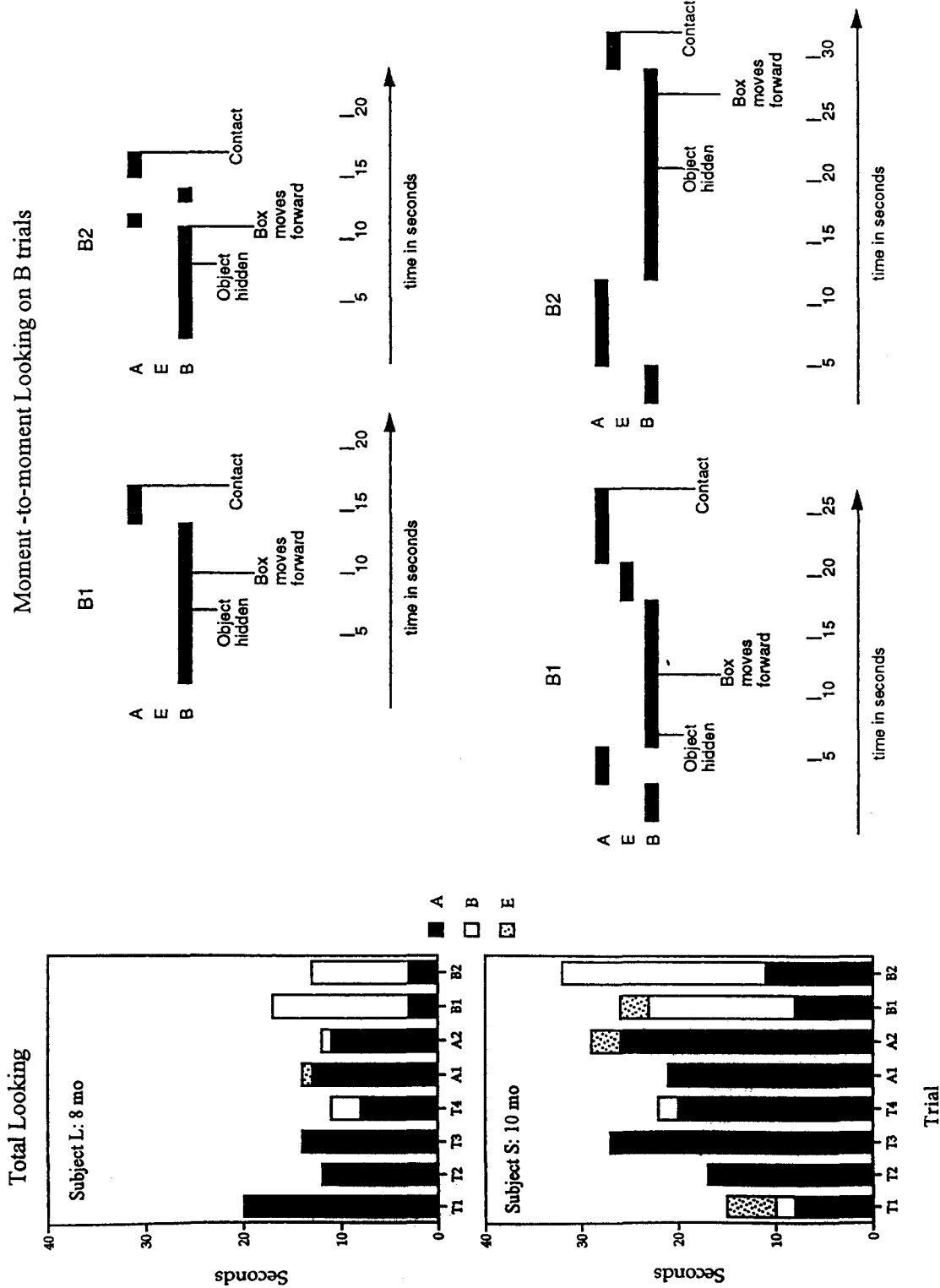


Figure 7. Looking behavior by two infants in the pretrain-at-A condition of Experiment 1. Left: amount of looking in the direction of A, B, or the Experimenter (E) on training and experimental trials. Right: moment-to-moment looking on the two B trials. mo = months old.

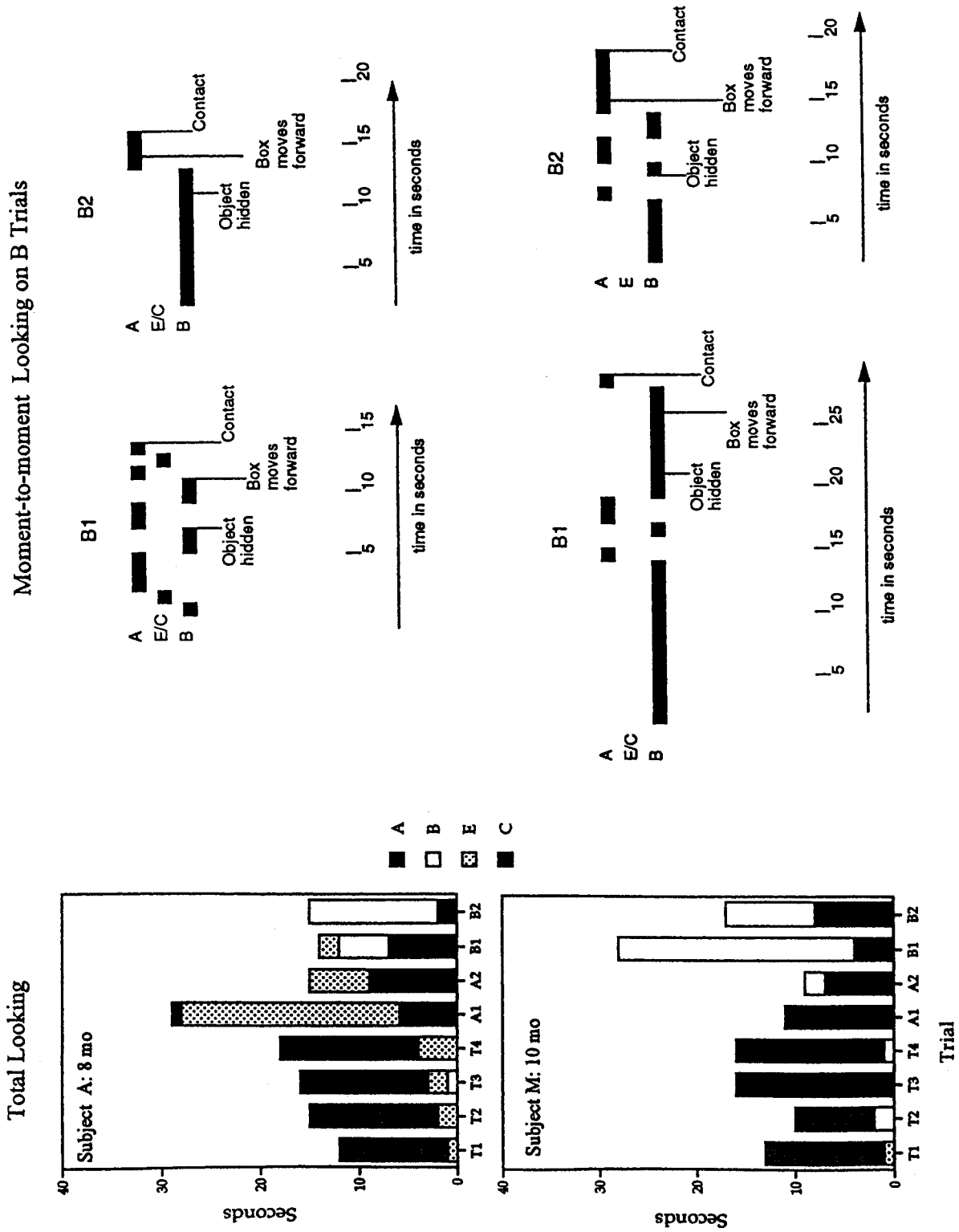


Figure 8. Looking behavior by 2 infants in the pretrain-at-C condition of Experiment 1. Left: amount of looking in the direction of A, B, C, or the Experimenter (E) on training and experimental trials. Right: moment-to-moment looking on the two B trials. mo = months old.

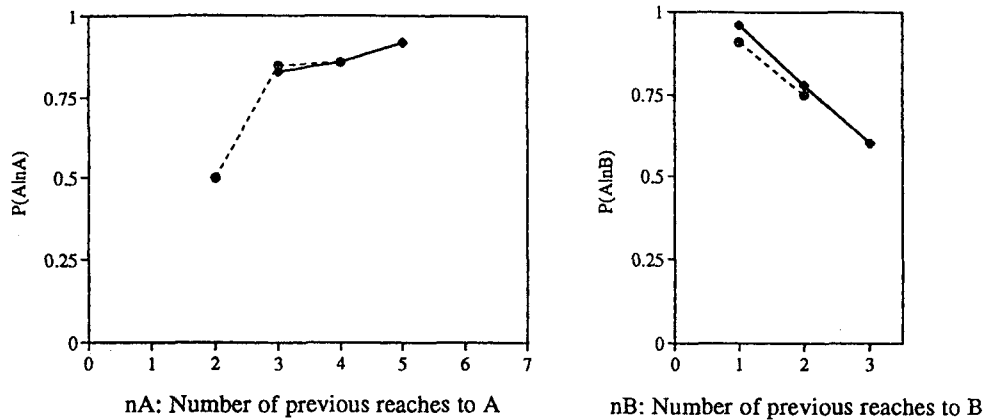
Table 2
Proportion of Children Reaching to the A Lid on the Four Experimental Trials of Experiment 2: Lids Only With Pretraining at A

Age group	A1	A2	B1	B2
Total	.85	.90	.85	.70
8 mo	.90	.80	.80	.80
10 mo	.80	1.00	.90	.60

Note. Proportions for 8- and 10-month-olds considered separately are given. mo = months old.

the infant could reach. With no history in the task and with identical A and B lids, the waved lid presents the only directional bias. Given that there was no delay between placing the lid on the well and allowing the infant to reach, we expected that this transient signal of the waved lid and the direction of looking it elicited would be sufficient to evoke a reach to that lid. After this first biasing trial, we then presented no biasing input—no waved lids—on the subsequent trial. We merely pushed the box forward and observed where infants reached. By our account, on this second trial, the only directional bias present is the memory for the previous reach. Thus, we predict that on Trial 2, the infant, unprompted by any directional cue, should again reach to A. Indeed, if our account is right, after one directional signal and with

A trials



B trials

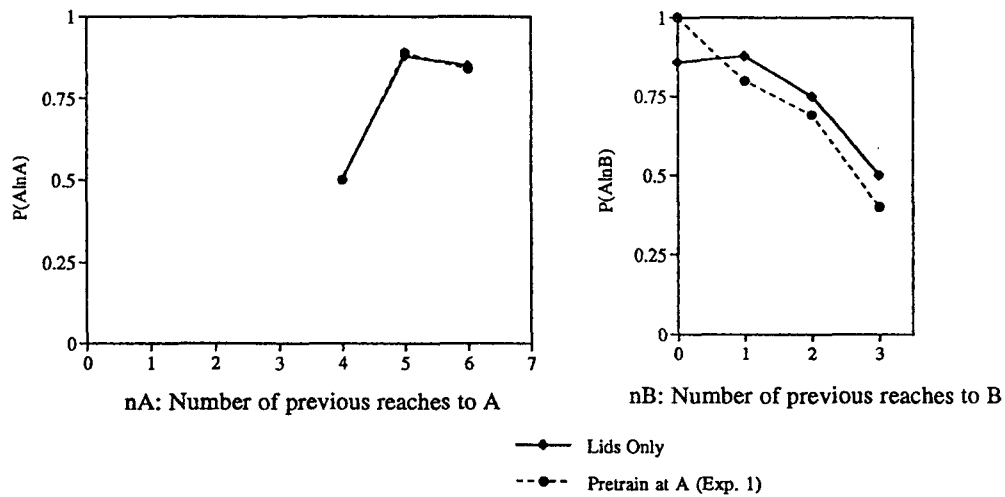


Figure 9. Conditional probabilities of a reach to A on A trials and B trials as a function of the number of prior reaches by the infant to A or to B in the lids-only procedure of Experiment 2 and for comparison from the hidden toy task, pretrain-at-A procedure, from Experiment (Exp.) 1.

no further input, infants should reach repeatedly in the same direction, each subsequent reach guided by the increasingly strong directional memories from reaching in that same direction.

By this same reasoning, we should see perseverative biases emerge even when we do not present an instigating directional bias. That is, in the remaining conditions, we did not present a transient input to signal a target on Trial 1. Instead, we handed the infant one lid to play with at midline so that they would know the lid was a reachable object. Then, in a manner designed not to pull visual attention to one lid or the other, we put the two lids side by side on the box and immediately pushed it forward for the infant to reach. We expected that the direction of reach would vary from infant to infant determined by noise in the system or by biases intrinsic to the infant. Critically, however, to whatever side an infant initially reaches, the memory for that reach should bias reaching on the next trial. This ever-strengthening bias should prevail unless a transient input pulls visual attention to the other direction. We tested this second idea by waiting until the infant had spontaneously reached some prespecified number of times, and then, just before pushing the lids to within reaching distance, we waved the lid opposite to the one to that the infant first reached. Our prediction is that the relative power of this visual bias will decline as a function of the number of spontaneous reaches in the opposing direction.

In total, the experiment includes four conditions determined by when the transient input of a waved lid is offered in a series of spontaneous reaches: before the very first reach or before the second, fourth, and sixth reaches.

Method

Participants. The participants were 40 infants (22 girls, 18 boys) who ranged in age from 8 to 10 months (M age = 9.7 months). Ten infants were randomly assigned to each of the four experimental conditions.

Apparatus. The brown box and lids used Experiment 2 were used in this experiment.

Procedure. The session began with a familiarization procedure designed to show infants that there was a reachable object (the lid) but without biasing a reach in any direction. It worked like this: The infant was seated across the table from the experimenter with the hiding box pulled out of the infant's sight. One lid was placed on the contrasting light-tan table, and the infant was encouraged to play with it. After several seconds of play, the experimenter took that infant's lid, pulled out the identical second lid and, in imitation of the classic shell game, rapidly switched the two lids back and forth several times on the table top. Then the experimenter simultaneously put the two lids over their respective wells on the box and pushed the box forward for the child to reach. The experimenter waited 10 s for the infant to respond and then began the next trial. Each trial began with the switching around of the two lids on the table (the one the infant had and the second identical one) and the simultaneous placement of the two lids on their respective wells. This procedure was repeated on five of the six trials. The deviating trial was the one on which the experimenter directed the infant's attention to one lid.

Specifically, the four conditions were defined by when the transient input of a waved lid in the series of spontaneous reaches occurred: (a) before Trial 1 (i.e., before the infant has reached at all in this experiment), (b) before Trial 2, (c) before Trial 4, or (d) before Trial 6. On each of these cued trials, the shell game was not played; instead, the one lid was waved and put over its well while the other lid remained in placed over its well. The box was immediately pushed forward within the infant's reach. For half the infants in the Trial 1 condition, the experimenter waved the right lid and for the other half, he waved the left lid. In the remaining conditions,

the experimenter waved the lid opposite to the one to that the infant had spontaneously reached on Trial 1.

Results

All infants reached six times in the experiment. Table 3 shows the number of infants switching the direction of their reach after each trial in the four conditions. As is apparent, infants who were biased by a waved lid before the very first reach (Trial 1 condition) continued to reach in that initially biased direction across the six trials, repeating the first reach despite the lack of any further biasing input. The infants in the other conditions maintained the direction of their first spontaneous reach until the experimenter offered the countering transient input of a waved lid. At this point, infants tended to switch and reach to the waved lid if they had not already made many reaches to the other lid. Thus, infants in the Trial 6 conditions could not be pulled from the direction of their first reach, but infants in the Trial 2 condition could be pulled in a new direction.

These conclusions are supported by the data in Table 4, which gives the mean number of reaches in the same direction and the mean number of switches in reach direction. There are reliable differences among conditions by both measures: in the number of reaches in one direction, $F(3, 36) = 7.158, p < .04$, and in the number of switches, $F(3, 36) = 4.092, p < .006$. Further by both measures, infants in the Trial 1 and Trial 6 conditions reached in the same direction more often than infants in the other two conditions (Neuman-Keuls, $p < .05$).

These results from this experiment support the idea that the bias from the direction of visual attention and the bias from the memory for previous reaches combine to determine the direction of reach.

Experiment 4: Perturbing Visual Attention on A Trials

In this experiment and the next, we test that direction of gaze provides a direct pull on the direction of reaching. We use the standard hidden object A-not-B task. In this experiment, we attempted to alter the direction of a reach by altering the direction of gaze on the A trials. In Experiment 5, we attempted to alter the direction of reach on the B trials.

Method

Participants. Twenty infants (13 girls and 7 boys) who were within 2 weeks of their 10-month birthday participated. Ten infants were randomly assigned to the two conditions: A side tap or B side tap.

Table 3
Number of Infants Shifting Direction of Reach on Each of the Six Trials in the Four Conditions of Experiment 3

Trial	Trial 1 Cue	Trial 2 Cue	Trial 4 Cue	Trial 6 Cue
2	0	6	1	2
3	1	4	0	1
4	1	2	5	1
5	0	1	2	0
6	1	4	2	1

Note. The four conditions differed in terms of when the experimenter visually cued direction.

Table 4
Number of Reaches in the Same Direction and Number of Switches in Direction of Reach in the Four Conditions of Experiment 3

Variable	Trial 1 cue	Trial 2 cue	Trial 4 cue	Trial 5 cue
Reaches in same direction				
No.	5.30	3.70	4.00	5.30
SD	1.49	1.04	1.70	1.25
Switches				
No.	0.20	1.70	1.00	0.60
SD	0.42	1.06	0.94	1.07

Note. The four conditions differed in terms of when the experimenter visually cued direction. The number of trials in each condition is six.

Apparatus and procedure. The base structure of the task was identical to that used in the pretrain-at-A condition of Experiment 1 for 10-month-olds: There were four training trials in which the toy was progressively hidden in the A well, followed by the four experimental trials (two A trials and then the two B trials). A delay of 5 s between the hiding of the toy and movement of the box to within the infants' reach was imposed on the four experimental trials.

The new additions to the task were two: First, throughout the task, a 13-cm tall blue rod was attached to the table by a suction cup 30 cm to the right or left from midline and 4 cm back from the edge of the table closest to the infant. This rod was thus within easy reach of the infant. However, the experimenter made no notice of the rod until the first A trial. Second, on (and only on) the two A trials, the experimenter looked at, reached out, and tapped three times the top of the rod; the experimenter did so at the end of the delay period just as the box began to move forward. The experimental set up is illustrated in Figure 10.

For half the children in each condition, the A side was on the right and for half it was on the left. For half the children, the rod was on the A side and for half it was on the B side. The sessions were videotaped and scored by scorers naive to the specific hypotheses. According to the scorers, tapping the rod on A trials and movement of the box forward occurred within 3 frames on the videotape (within 0.1 s) on all A trials. The mean time between hiding the toy (lid on) and movement of the box forward on experimental trials was 5.14 s (*SD* = 0.86 s).

The purpose of the experimenter's tapping was to pull visual attention just before the reach. Accordingly, the scorers also coded (yes–no) whether infants looked to the rod as the experimenter tapped. Reliability for this measure was 100% for a randomly selected 5 infants. By this measure 19 of 20 infants looked to the tap on Trial A1 and 17 of 20 looked to the tap

on Trial A2. The infants who did not look to the tap were four different infants, 2 in the A side tap condition and 2 in the B side tap condition.

Results and Discussion

Figure 11 shows the proportion of infants in the two conditions who reached to the A lid on the four training trials and the four experimental trials. As is apparent, on the training trials, the two groups of infants performed equivalently: All infants reached to the A side on at least three of the four training trials. However, the performances of the two groups diverged on the A trials; across all four experimental trials, infants in the A side tap condition reached to the A side (*M* = 3.6) more than did those in the B side tap condition (*M* = 1.4), $t(8) = 4.88, p < .01$. The effect of pulling visual attention just before the reach is clearly seen on the two A trials; many more infants in the A side tap condition reached to A than did infants in the B side tap condition (Fisher exact probability, $p < .005$ for Trial A1 and $p < .05$ for Trial A2). The effect of pulling visual attention and reaching in the direction of A on the A trials also affected B trial performance, even though the experimenter did not tap the rod on these trials. Reliably more infants in the A side tap condition reached to A on Trial B2 than did infants in the B side tap condition (Fisher exact probability, $p < .01$). The difference in the number of infants in the two conditions reaching to A on Trial B1 is not statistically reliable.

The results of this experiment provide strong support for two claims made by the present account. First, where infants look influences where they reach. We pulled the direction of looking just before a reach on A trials, and we pulled the direction of the reach in the direction of the look. Second, where infants have just looked and have just reached influences where they reach next. Infants in the B side condition who did not as a group reach to A on the A trials were also less likely to reach to A, and thus more likely to find the toy on B trials.

Experiment 5: Perturbing Visual Attention on B Trials

In this experiment, we asked whether a directional pull of visual attention on the B trials will pull the direction of the reach. Here, the momentary direction of visual attention at the time of the reach must combine with the transient visual input of an object hidden at B and the strong memory for the many immediately preceding reaches to A.

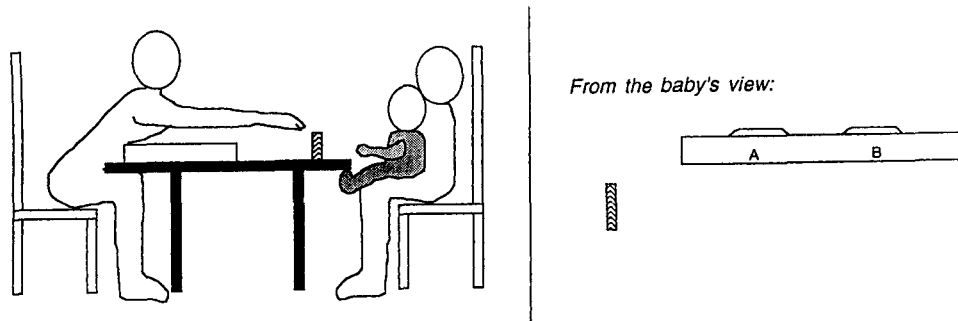


Figure 10. The task setup for Experiments 4 and 5 (see text for more information).

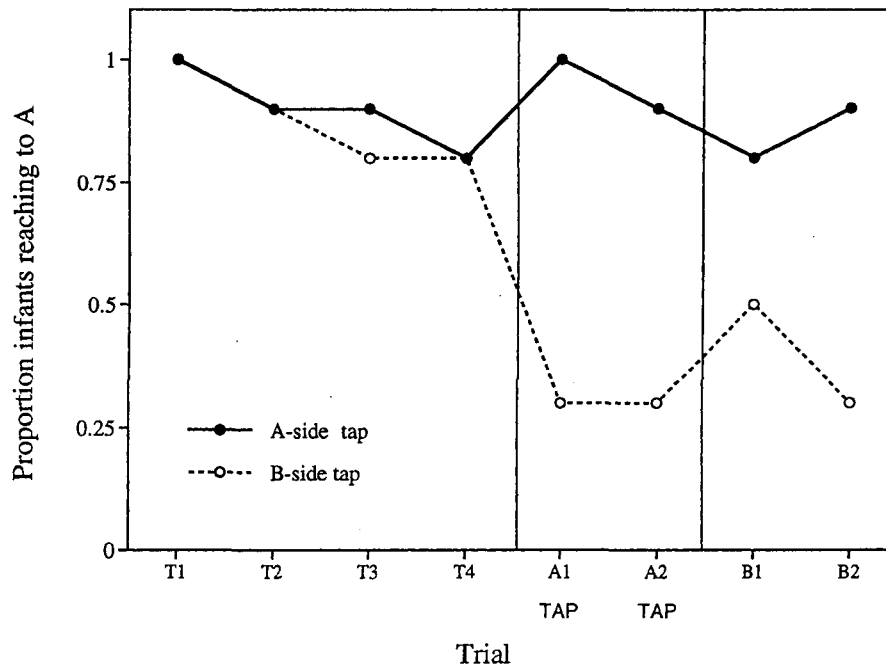


Figure 11. Proportion of infants reaching to A on the four training trials, the two A trials, and the two B trials when the experimenter taps a marker on the A side or on the B side just before the infant's reach on the two A trials.

Method

Participants. Twenty infants (11 girls and 9 boys) who were within 2 weeks of their 10-month birthday participated. Ten infants were randomly assigned to the two conditions: A side tap or B side tap.

Apparatus and procedure. The procedure is identical to that in Experiment 4 except that the experimenter ignored the marker until the first B trial. On that trial, the experimenter looked at, reached out, and tapped three times the top of the rod at the end of the delay period just as the box began to move forward. For half the children in each condition, the A side was on the right and for half it was on the left. The sessions were videotaped and scored by scorers naive to the specific hypotheses. According to the scorers, tapping the rod on B trials and movement of the box forward occurred within three frames on the videotape (within 0.1 s) on all B trials. The mean time between hiding the toy (lid on) and movement of the box forward on experimental trials was 5.04 s ($SD = 1.12$ s). All 20 infants looked to the tap on Trial B1, and 18 of 20 looked to the tap on Trial B2. Reliability for this measure was 100% for a randomly selected 5 infants.

Results and Discussion

Figure 12 shows the proportion of infants in the two conditions who reached to the A lid on the four training trials and the four experimental trials. As is apparent, on the training trials and the two A trials, the two groups of infants performed equivalently: Infants reached predominantly to the A side. However, the performances of the two groups diverged dramatically on the B trials. On both Trials B1 and B2, infants in the A side tap condition continued to reach to the A side and thus did not find the toy there; in contrast, infants in the B side condition reached correctly to the B ($p < .01$, Fisher exact probability for both B1 and B2).

The results of this experiment provide further support for the coupling of visual attention and goal-directed reaching. We pulled the direction of looking in the direction of B just before the reach, and despite the strong perseverative pull of many past reaches to A, the infants reached to B. The similarities of these effects of tapping on B trial performance in this experiment to those on A trial performance in Experiment 4 suggest again that the processes that create the typically correct performance on A trials are the same as those that create the error on B trials.

Experiment 6: Posture and a Body-Centered Code

The work of Georgopoulos (1990, 1991) suggests that the neural events that code the direction of reach are posture specific in that they code the location of the target to current hand position. If our account is right and the A-not-B error is the emergent product of the processes that code directional reaches, then shifts in posture—just like shifts in visual attention—should alter the internal activity that signals a directed reach. More specifically, if we shift the infant's posture between the A and B trials, then we should disrupt the biased internal code that has accrued from the previous reaches to A. A postural shift that resets the internal code should cause reach direction to be more strongly determined by the immediate input than by the past activity, and perseveration should be less likely.

We tested this prediction in the final experiment. Infants in the postural shift condition participated in a standard version of the A-not-B task. For the four training trials and Trials A1 and A2, the infant sat on the mother's lap; but then between Trials A2 and B1, we stood the infant up (on the mother's lap) so that he or she had

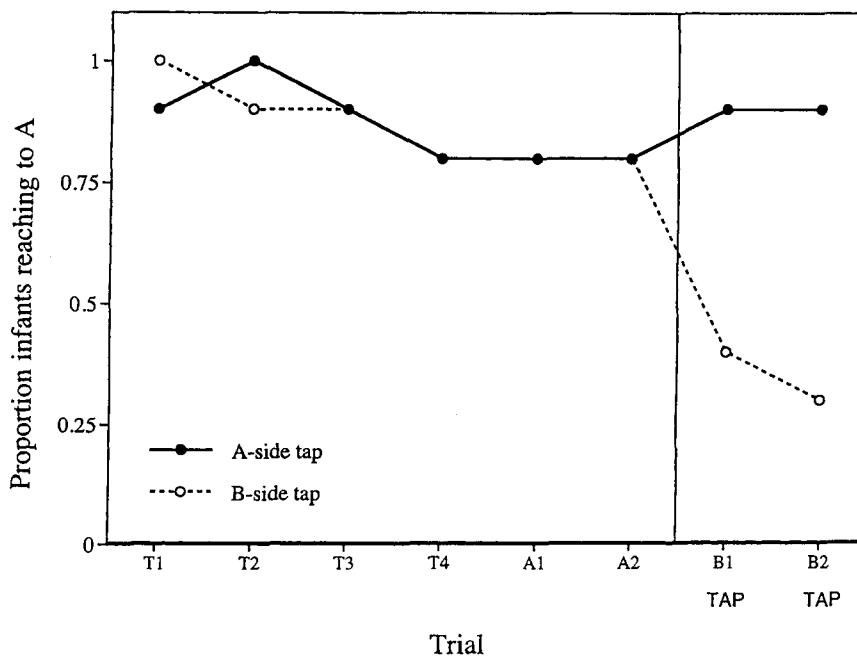


Figure 12. Proportion of infants reaching to A on the four training trials, the two A trials, and the two B trials when the experimenter taps a marker on the A side or on the B side just before the infant's reach on the two B trials.

to reach down to the lids. We hypothesized that this postural shift should disrupt the perseverative pull to A and that these infant should reach correctly to B.

Method

Participants. Twenty infants (10 girls and 10 boys) who were within 2 weeks of their 10-month birthday participated. Ten infants were randomly assigned to the two conditions: posture shift and the visual distraction control condition.

Apparatus and procedure. The testing situation is identical to the pretrain-at-A condition of Experiment 1: There were four training trials in which the object was progressively hidden in the A well, followed by two A trials on which the object was hidden in the A well and the infant was allowed to search after a 5-s delay and then finally two B trials on which the object was hidden in the B well and, after a 5-s delay, the infant was allowed to search. All infants sat on their mother's lap for the four training trials and two A trials. In the posture shift condition, infants were stood up on their mother's lap before the start of Trial B1 and were held in that posture for the remainder of the experiment. Pilot testing suggested that this shift in posture took between 1 to 3 s to accomplish. Accordingly, in the visual distraction control condition, infants remained in a sitting posture on their mother's lap throughout the experiment, but between Trials A2 and B1 a colorful, noisy wooden clown puppet with multiple moving parts was shown to them (and shaken) at midline for approximately 3 s.

The sessions were videotaped and scored by scorers naive to the specific hypotheses. According to the scorers, the time to shift the infant's posture from sitting to standing averaged 2.4 s ($SD = 2.1$ s), and the time the distracting puppet was shaken averaged 3.1 s ($SD = 0.85$ s). The mean time between hiding the toy (lid on) and movement of the box forward on experimental trials was 5.23 s ($SD = 0.98$ s).

Results and Discussion

Figure 13 shows the proportion of infants in the two conditions who reached to the A lid on the four training trials and the four experimental trials. As is apparent, on the training trials and the two A trials, the two groups of infants performed comparably: Infants reached predominantly to the A side. The total number of reaches to the A side across these six trials does not differ reliably for the two groups of infants, $t(19) < 1.00$. However, the performances of the two groups diverged dramatically on the B trials ($p < .001$, Fisher exact probabilities). On both Trials B1 and B2, infants who reached from a standing position tended to reach correctly (i.e., to the location of the last visual event). Indeed, of the 20 reaches of these 10 infants on the two B trials, only 3 were in the A direction. This is a level of correct performance that has no equal in the previous experiments, nor in the visual distraction control condition of this experiment. Despite the distracting visual events between the A and B trials, infants in the visual distraction control condition continued to reach to the A side.

These results suggest that the biasing memory that builds over reaches is in some way posture specific or disrupted by the vestibular and proprioceptive changes engendered by movement. It is not disrupted, however, by watching a moving event.

General Discussion

The six studies show how a goal-directed reach by an infant emerges in the complex interactions of visual input, direction of gaze, posture, and memory. The system that creates a reach remembers its own previous activity, and so reach direction is

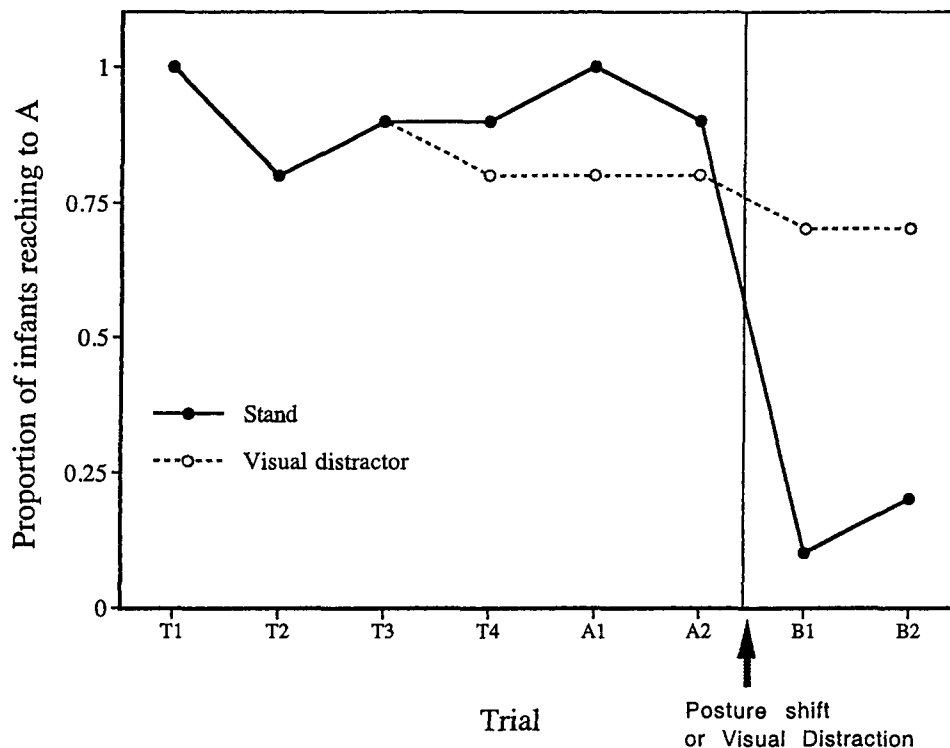


Figure 13. Proportion of infants reaching to A on the four training trials, the two A trials, and the two B trials when the experimenter shifts the infants' posture (by standing the infants up) or visually distracts the infants before the hiding of the object on the first B trial.

always a combination of the current input and memories of just previous reaches. This is a system, then, that is biased toward perseveration. This bias will prevail whenever the input specifying a new reach direction is weak or highly similar to that which gave rise to previous reaches and whenever the system's memory for previous reaches is strong. The six studies show further that the processes that make a goal-directed reach are the processes that make the A-not-B error.

These findings and the theoretical framework that generated them have implications for the development of reaching, for explanations of the A-not-B error, and more fundamentally for how we understand knowledge and knowing.

What Develops?

Multiple processes. Our account explains the A-not-B error in terms of general processes of goal-directed reaching, processes that are not specific to a particular moment in development. If this is right, then why do only infants 8 to 12 months old make this error? We predict that infants will not be the only ones who make the error. If, as we suspect, the general processes that create a directional reach change only quantitatively, then there should be circumstances in which older children and adults make a similar perseverative error. These key circumstances should be a weak and brief visual input that specifies the current goal, a memory delay, a B location highly similar to and confusable with the A location, and many recent reaches to A before the cue to B.

Spencer, Smith, and Thelen (1997) tested this prediction with 2-

and 3-year-old children in an A-not-B task in which a toy was hidden. The hiding medium (sand) presented a large and uniform field, providing no continuing visual cues to guide direction of gaze and the reach. Given six prior reaches to A, a 10-s delay between hiding and search, and a 34-cm separation between the A and B locations, virtually all children reached back to A on the first B trial. In sum, when there were no continuously available visual cues, the strong bias created by many previous reaches to one location prevailed, even though the children were two to three times the age of typical participants in A-not-B experiments.

We predict that even adults will make the error under the right task circumstances. Although this prediction has not been tested, the literature on goal-directed reaching is replete with what would seem to be related phenomena: reaches biased by past activity and posture (e.g., Ghilardi, Gordon, & Ghez, 1995), reaches pulled in the direction of visual attention (e.g., Enright, 1995), and reaches pulled toward distractor objects in the visual field (e.g., Tipper et al., 1992). Thus, we are confident that the task specifics can be arranged to create an A-not-B error in adults. The error is not peculiar to infants because it reflects much more general truths about the dynamics of reaching.

Nonetheless, it is infants and not older children and not adults who make the error under the special circumstances of the standard task. What develops, then, such that an infant will perseverate in this particular task and then several months later will not? In a neural field model of goal-directed reaching, Thelen, Schoner, Scheier, and Smith (1999) simulated development by the self-

sustaining representation of the transient cue that signals A or B as the target on that trial. Munakata's (1998; Munakata et al., 1997) connectionist model similarly simulates the developmental decline of the error by self-sustaining transient memories for the cuing event. The causes of these longer memories, however, may reside in the processes of perceiving and acting. Here we point to two such developmental changes that we suspect are crucial to the developmental decline of the error in the canonical task.

One likely contributor is infants' increasing ability to discriminate among perceptually similar locations. A considerable number of empirical studies motivated by the idea of an egocentric-to-allothetic shift have examined the effects of landmarks and distinguishing cues to hiding locations; and in general, these studies found that the frequency of the error decreased with the addition of such cues (Acredolo, 1985; Bremner, 1978). Other evidence from toddlers in hiding tasks indicates considerable development in the metric representation of space, with those representations becoming increasingly finer grained with age (Huttenlocher, Newcombe, & Sandberg, 1994). One of the forces that may drive the early development of finer grained spatial discrimination is self-locomotion. Past research shows that when infants are experimentally given early experience in self-movement, they make the perseverative error less often and for not as long as infants not given this early extra experience (see Bertenthal & Campos, 1990). Self-locomotion seems likely to both demand and set up the contingencies that teach detailed spatial discriminations.

A second relevant change is increasing skill in reaching. More specifically, the fact that infants are just becoming skilled reachers may be crucial to the formation of strong motor memories and thus perseveration. We hypothesize that in difficult and novel reaching tasks reachers try to control their reaches, that is, limit the degrees of freedom in the movement. Increased control will lead to the repetition of highly similar motor patterns. These repetitions, in turn, will create strong motor memories. These strong motor memories will make perseveration more likely when the task requires a different direction of movement.

This hypothesis was suggested by Diedrich, Thelen, Corbetta, and Smith (1998) in an A-not-B-like reaching task. The infants in that study, 9-month-olds, were unskilled reachers in the sense that the path that the hand followed to the target was not direct, and the movement consisted of many increases and decreases in velocity. These jerky paths contrast with the straight paths and single acceleration and deceleration of adult reaches. The Diedrich task required the infants to reach repeatedly to a target, A, next to a similar distractor, B. Individual infants solved this task by reproducing over the A trials highly similar reaches with highly similar path and velocity profiles. Such similarity in successive reaches by an individual is rare. Indeed, in the Diedrich et al. study, infants did not reproduce the same path and velocity profiles in an easier task in which they reached to a single target without a nearby distractor. Apparently, when faced with the hard task of reaching to a target next to a distractor, the infants were not skilled enough to reach flexibly on each trial but were just skilled enough to control their reaches tightly. Diedrich et al. further showed that infants who solved the initial reaching task by reproducing the same velocity profiles were the ones most likely to perseverate, repeating that same reach pattern to the A target again when a new target, B, was cued. We speculate that there is a curvilinear trend in infants' tendency to perseverate in the A-not-B task; very young

infants may be too disorganized and variable in their reaches, and older children may be too fluid and flexible in their reaches to create strong motor memories. The idea of a curvilinear trend fits our intuitions about the general course of skilled actions; it seems to be the moderately skilled golfer who is most likely to repeat a problematic swing consistently.

This analysis also suggests another way to demonstrate the generality of the processes that create the A-not-B error across development. That is, adults should perseverate in reaching tasks that require considerable control to execute and are repeated. We have been told that there is a common game in Macedonia that creates this situation on purpose with the expected outcome. In this game, a matchbox is set on its side. The player starts with the hand close to the body, an arm's length from the box, and rapidly brings it as near as possible to the box and then flicks the fingers. However, this flick must be off to side of the box so that the box is not hit and does not move. This is a movement that requires considerable control; the degrees of freedom in the movement must be strictly limited so that the box is not hit. The player repeats this highly controlled movement nine times and then on the 10th attempt alters the action slightly so as to now flick the box off the table. However, the typical player fails by repeating the pattern from the nine trials before and thus missing the box.

These hypotheses about spatial discrimination, reaching skill, and motor control place the cause of development in perception-action experience. Reaching, crawling, cruising, walking—big changes in perceptual-motor behavior in the second half of the first year—seem likely to create new experiences that cause parameter changes in the multiple contributing processes that compose a goal-directed reach, creating first the confluence of skills that leads to a perseverative error in this special task and then the confluence of skills that leads to success in that same task.

Context effects. The results of the present experiments, combined with the evidence on adult reaching and on the neurophysiology of reaching, implicate a complex dynamic system in which visual input, direction of gaze, posture, and previous activity interact. This description also fits the extant evidence on the context dependency of the A-not-B error in infancy. The lack of a unified explanation of these effects is one failing of past explanations. Our reaching account promises a comprehensive explanation of the many varied findings. We illustrate this promise here by considering two results that have posed problems for previous accounts: transparent covers and multiple hiding locations.

The manipulation of "hiding" the toy under transparent covers is perplexing because, although the perseverative error decreases in this version of the task, it still occurs (e.g., Butterworth, 1977; P. L. Harris, 1974; Yates & Bremner, 1988). If infants' problems in this task are due to an inability to represent the hidden object or to remember it, they should not make errors when the object is seeable under a transparent cover. These findings, like our no hidden toy condition of Experiment 2, raise doubts about the centrality of object representation to the error. We explain the transparent cover results as follows: The error still occurs with transparent covers because reaching is a fragile skill dependent on the continuous visual availability of a reaching target and because the perceptual cues afforded by side-by-side transparent covers are unusual and perceptually confusable to infants. Errors decrease with transparent rather than opaque covers because the reaching target (cover with the object underneath) and the distractor (cover

with nothing underneath) are more perceptually different in the case of two transparent covers than two opaque covers. Finally, Yates and Bremner (1988) have showed that extra experience with transparent covers before hiding events leads to a further decrease in reaching errors. Prior play with transparent covers should help infants detect the perceptual difference between a transparent cover with a toy underneath from a transparent cover over an empty well. In brief, the same processes that explain goal-directed reaching and perseveration more generally can explain the performance when the hiding covers are transparent.

The effect of multiple hiding locations also presents a perplexing effect (e.g., Bjork & Cummings, 1984; Cummings & Bjork, 1983a, 1983b). These multiple location tasks are like the standard A-not-B task in that an object is hidden repeatedly at one location A and then at a second B. However, in these multilocation tasks, several other irrelevant locations are marked by covers on the table. These extra locations decrease the likelihood of the perseverative error. One likely reason for this decline is that the multilocation task offers opportunities for errors other than a reach back to A. In the two-location task, there is only one kind of error possible: Infants can only reach "correctly" to B or reach "perseveratively" back to A. In the multilocation task, infants can reach correctly to B, err by reaching to A, or err by reaching to the other locations. The most common error in the multilocation task is a reach near B (Bjork & Cummings, 1984; Cummings & Bjork, 1983a, 1983b). In tasks in which there are distractors on both sides of B, errors tend to be in the A direction (Diamond et al., 1994).

Our reaching explanation of the error works in three ways. First, more hiding covers on the table means more distractors to perturb reaching on A trials. Spontaneous errors to nearby covers on A trials is predicted because reaching is a fragile skill at this age and is likely to be challenged by many distractors in the field. This prediction fits Cummings and Bjork's (1983a, 1983b; see also Diamond et al., 1994) report that errors clustered near the A location occur on the A trials. Such variability in the direction of reaches on A trials should lead to a weak and broadly tuned biasing memory. This weaker bias should lead to a weaker pull in the A direction and thus, given the visual events of hiding at B, reaches in the B direction. By our dynamic account, then, there is nothing paradoxical about reaches near B on B trials given multiple distractors. Multiple distractors result in more errors on A trials, and more errors on A trials, whatever their cause, should lead to less perseveration on B trials.

Second, more covers on the table mean potentially more discriminable A and B locations (see Bjork & Cummings, 1984; Smith & Thelen, 1993). In the multilocation task, the A location is not as confusable with the B location as in the two-location task: In the multilocation task, the B location does not sit "next to" the A location, there are other locations more similar (nearer) to the A location than the B location, and typically, the B location is farther from the A location in the multilocation than two-choice versions of the task. All this means that the cue to B should be less likely to remind and be blended with the memory for reaches to A in the multilocation than in the two-location task, and thus there should be a weaker pull to A.

Finally, the greater spatial separation of the A and B locations in multilocation than in two-location tasks may create postural effects. When infants watch and reach for objects at the A location in the multilocation task, they will look and reach farther to the left

or right than they do in the two-location task. The greater postural difference may dampen perseveration just as a shift in standing to sitting did in Experiment 6.

We suspect that each of these explanations is at least partially correct, part of the ensemble that creates an individual behavioral act. Indeed, it is because real behavior in real time is multiply determined that the context effects that challenge previous accounts comprise, in our view, the core of the phenomenon to be explained. A reach—be it perseveratively back to A or correctly to B—emerges out of the immediate sensory input, the ongoing and immediately preceding activity of the system, and the longer term history of the system. Changes in any of these will alter the complex interactions that make a single behavioral act. Thus, it is by understanding context effects that we will understand the processes that make behavior.

Explaining the A-Not-B Error

Softly assembled competence. The erroneous reach back to A is the behavioral product of many graded processes, including those involved in looking, in discriminating locations, in posture control, and in motor planning. All these processes are brought together and self-organized by the task of reaching for a particular object in a particular context. The A-not-B error is theoretically important in this view because it provides a window on how these processes interact, how they change themselves through their own activity, and how seemingly qualitative changes in behavior may emerge from quantitative changes in a complex dynamic system. If one accepts this performance-based framework, then one must reject the more usual idea that an act of reaching can be used to diagnose a task-independent competence. This is a hard but fundamental point. We attempt to clarify it by considering Diamond's (1990a, 1990b) memory plus inhibition explanation of the A-not-B error.

Diamond's explanation is similar to the present one in that she explained the error in terms of the dynamics of underlying processes. In her account, the processes are memory for the hiding event and the inhibition of a prepotent response. Diamond's explanation is profoundly unlike the present one in that the A-not-B task is seen as diagnostic of competencies that are tied to maturation and are independent of the specific task and the specific experiences of the individual. In particular, the infant's failure to inhibit a prepotent response is seen as resulting from the immaturity of the dorsolateral prefrontal cortex. Perseveration in the A-not-B task is seen as diagnostic of the maturity and health of that brain region.

By Diamond's account, infants' cortical immaturity should be apparent in more tasks than the A-not-B. Thus, Diamond predicted that 8- to 10-month-old infants would have trouble retrieving objects from transparent containers because doing so requires the inhibition of a direct-line-of-sight reach to the goal. Consistent with her prediction, infants failed by trying to reach directly for the object through the transparent surface. Moreover, and fitting with the idea of task-independent competencies, Diamond reported that infants' performances in the object retrieval task were correlated with performances in the A-not-B task. Both tasks, she concluded, tap the maturity of the prefrontal cortex to inhibit a prepotent response.

This idea of a task-transcendent inhibitory failure is directly

contrary to our explanation. We posit no unitary or localized inhibitory process. Indeed, nothing is inhibited by our account. Instead, the direction of a reach is the blend of multiple directional pulls, each of which depends on the specific task input, the infant's current posture, direction of gaze, immediately preceding activity, and longer term experiences in similar tasks.

In the standard A-not-B task, the pull from the memory of immediately preceding and repeated reaches typically dominates, but it does not have to. As in Experiments 4, 5, and 6, we can cause the error to both increase and decrease, even to disappear, by manipulating the relative strengths of the multiple and interacting forces on reaching and looking. Infants reach correctly to B not when a prepotent habit to reach to A is inhibited but when the immediate perceptual input biasing the system in the B direction is stronger than the biasing internal activity from the previous reaches to A. There is no "failure to inhibit" that causes the A-not-B error, just a particular mix of activation from current perceptual input, posture, direction of gaze, and remembered activity from previous reaches. By implication, there is no "failure to inhibit" that causes infants to try to reach through transparent surfaces either.

We explain infant performance in the object-retrieval task in the same general way that we explain the A-not-B error: many graded processes self-organized by the specific task and by the individual's history of perceiving and acting in the world. Indeed, experience with transparent containers may be essential to successful object retrieval in this task because the perceptual cues that mark the openings of transparent containers are unique. Titzer, Thelen, and Smith (1998) tested this idea in a training study: 8-month-old infants were given transparent containers of various shapes and sizes to play with for 2 months; control infants were given opaque containers for the same period. Subsequent testing showed that infants who had played with transparent boxes knew how to retrieve objects rapidly from transparent boxes. Two months of perceiving and acting on transparent containers taught infants the unique perceptual cues for openings in transparent things. In sum, success does not require inhibition of a prepotent response, but requires instead immediate perceptual cues familiar enough to generate the right action given those cues.

The larger point is this: A single behavioral act—a reach to B or a reach through the opening in a container—is made in real time from many real causes. The competency of a single act can reside in no one place; it is distributed across the triggering stimulus events and across the sensory, perceptual, motor, and cognitive processes internal to the individual. These internal processes, in turn, change over the shorter term of the task and over the longer term as a result of their own activity. Neither the A-not-B task nor the object-retrieval task can be diagnostic of any one competence that resides in the child independent of task and developmental history. In addition, there can be no necessary association in performance in the two tasks. Pertinent to this point, Bell and Fox (1992) and Matthews, Ellis, and Nelson (1996) reported evidence indicating that the association between the A-not-B error and failure to retrieve an object from a transparent container is considerably less than Diamond (1990a) initially reported.

We do not see our analysis as contrary to the facts from animals and neurological patients showing that the dorsolateral prefrontal cortex is closely associated with perseveration (e.g., Diamond, Zola-Morgan, & Squire, 1989). The evidence that this cortical

region plays a role in the A-not-B error is clear and uncontested. Less clear and contested is the nature of that role, the causes of developmental change in those cortical processes, and the uniqueness of the prefrontal cortex to success in the A-not-B task (see Thelen, Schonner, Scheier, & Smith, 1999; Thelen & Smith, 1994).

Embodiment. The present account sees a reach emerging from a continually evolving and self-organizing closed flow of information, as illustrated in Figure 3. This contrasts with the classic view of a one-way causality from goal to motor plan to act. The present findings strongly challenge any account that separates mind and cognition from body and action. We consider Munakata's (1998) connectionist simulation of the A-not-B error to illustrate this challenge.

Munakata's (1998) most recent model is more successful than any prior model in simulating context effects on the A-not-B error (e.g., Cohen, Dunbar, & McClelland, 1990; Dehaene & Changeux, 1989). In the new account, the error derives from the interaction of two types of memory mechanisms: active and latent. The model consists of a six-layer architecture. Three input layers encode information about the object location, cover type, and toy type. The one hidden and two output layers contain units representing locations A, B, and C. The output is mapped onto both a reaching layer and a gaze or expectancy layer, which can differ in histories because infants can look without reaching. The hidden and output layers have both inhibitory connections between units and self-recurrent excitatory connections back to each unit.

Starting with a small initial bias toward correct responding, the network develops an association between the input location and the motor response by Hebbian learning adjustments to the connection weights. As in other models, the repeated presentation at the A location strengthens the mapping to the A response. Because the B response stimulus shares input representation, when B is cued, the more potent A networks respond and the error occurs. The developmental change is modeled by changing the degree of recurrence in the network. With more recurrence, the activation of the units changes more gradually over time, and the active memory can be maintained longer over the delay. This leads to a decrease of the influence of the A latent memory and an increase of relative strength of the B active memory. Likewise, the B representation fades more rapidly than the latent A memory, accounting for the delay effect. Finally, Munakata (1998) can simulate the effects of multiple and distinctive covers by reducing the degree to which the sensory representations overlap in the network, that is, by increasing the fineness of spatial discrimination.

Despite the progress in this model, the results from the present experiments require changes in it. At present, Munakata's (1998) model is a connectionist version of Figure 1: a one-way causal path from sensory input to internal representation to output. What the body does—where the hands are, where the eyes are directed—are outputs only with no influence on the internal activations of the system. Thus, the model as it presently stands cannot simulate how looking pulls reaching and why posture matters. To be fair, Munakata's current model was specifically designed to explain a dissociation of looking and reaching, the idea that infants correctly expect the object to be at B and thus sometimes even look to B while erroneously reaching to A. The present results suggest a model is needed that, instead of separating looking for reaching, simulates their interaction and the coevolution of looking, reaching, goals, and expectations.

Knowing in the Context of Acting

We believe that the present explanation of the A-not-B error has far-reaching implications. For all of Piaget's genius in discovering the error, he was likely wrong about what the error means. For Piaget, success in searching for a displaced hidden object indexed an "object concept," an enduring knowledge structure about the spatial and temporal constancies of objects. Our studies, as well as scores of others, have demonstrated, however, that performance in this task itself is far too fluid, too context dependent, too easily derailed by even seemingly minor changes in conditions to be a reliable indicator of some enduring structure of mind.

In view of these facts and evidence that the A-not-B error is the product of the task dynamics of goal-directed reaching, one possibility is to retain the idea of an object concept but dismiss infants' perseverative reaches as irrelevant to the nature and development of that concept. By this argument, the object concept actually does exist at least by some point in development, but this is the wrong task to reveal it. We believe this is a fundamentally wrong idea. Our evidence shows that both correct and perseverative reaches arise from the coupled dynamics of looking, reaching, and remembering, and that we can understand the error and its disappearance completely in terms of the time-dependent interactions of these processes. The construct of an object concept is neither necessary nor supported. What then is the evidence that demands a theoretical construct such as an object concept?

We suggest that there is not and cannot be any such evidence. Just as a reach is an event that emerges from dynamic processes, so must all other behaviors be events that emerge from dynamic processes, and so must the moments of knowing—the expectations, the goals—that underlie those real-time acts. Consider current proposals in the literature that looking is a better index of infants' object concept than reaching. We do not see how this could possibly be. Both reaching and looking are behaviors, events made in time by perceiving, acting, and remembering. The moment of knowing that is made in violation-of-expectancy paradigms is emergent in real time and in real processes just as is the reach in the A-not-B task. In addition, the repeated presentation of the stimuli that set up the expectations in these tasks just like the training trials in the A-not-B tasks are not neutral events. These immediately preceding experiences create the dynamics from which the critical behavior on the test trial emerges. Because a great many experiments in infant cognition use some type of habituation, repetition, or saturation of looking, it is critical to understand the real-time processes by which a memory of one event influences performance on succeeding trials, and how those memories are affected by the relative familiarity and novelty of the objects and events presented, and the infants' past experiences (see also Schilling & Clifton, 1998; Thelen & Smith, 1994; Bogartz, Shinsky, & Speaker, in press).

What does all this mean for what knowledge is and where knowledge is? Do adults at least "have" an object concept when they act as if they know objects persist in time and space, when they think that objects persist in time and space? By our account, the processes that make a goal-directed action interact as illustrated in Figure 3. For adults as for infants, the goal of a spatially directed action is coupled to looking and reaching and depends both on the immediate perceptual input, the immediately preceding activity of all the components in this system, and the internal

dynamics, which have evolved over a lifetime of perceiving and acting. The moment of knowing that coincides with a behavioral act—or a moment of knowing, a thought, that occurs without an overt act—will be made through many interacting processes that cannot be separated from the specifics of the task or the specifics of the individual's ongoing and immediately preceding activity. The real-time causes of a real-time moment of knowing include the specifics of the here and now.

The radical conclusion that follows is that there is no such thing as an "object concept," at least not in the sense of a causal mechanism that generates a thought or a behavior. It is merely convenient to say that adults "have" an object concept because there is great regularity and stability across individual moments of knowing, across individual acts of reaching, looking, thinking, and talking about objects. However, stability in these moments of knowing, just as in the apparent variability in the infants' moments of knowing, is a summary statement over many individual moments, each individually made in a complex system of interacting processes of perceiving, acting, and remembering. What we commonly and casually call knowledge and concepts are distributed across and embedded in all these processes (see also Jones & Smith, 1993; Smith & Samuelson, 1997). If this is so, the construct of "an object concept" is without causal content. Thus, it hardly matters whether the more variable moments of knowing of infants or the more stable ones of adults are accorded the status of "an object concept."

References

- Acredolo, L. P. (1985). Coordinating perspectives on infant spatial orientation. In R. Cohen (Ed.), *The development of spatial cognition* (pp. 115–140). Hillsdale, NJ: Erlbaum.
- Acredolo, L. P., Adams, A., & Goodwyn, S. W. (1984). The role of self-produced movement and visual tracking in infant spatial orientation. *Journal of Experimental Child Psychology*, *38*, 312–327.
- Ahmed, A., & Ruffman, T. (1996). *Do infants know when they are searching incorrectly? Looking times in a non-search A not B task*. Manuscript submitted for publication.
- Allport, A. (1987). Visual attention. In M. I. Posner (Ed.), *Foundations of cognitive science* (pp. 631–682). Cambridge, MA: MIT Press.
- Appel, K. J., & Gratch, G. (1984). Will infants search when "no toy" is hidden? A study of implicit assumptions about the development of object permanence. *British Journal of Developmental Psychology*, *2*, 179–188.
- Ashmead, D. H., McCarty, M. E., Lucas, L. S., & Belvedere, M. C. (1993). Visual guidance in infants' reaching toward suddenly displaced targets. *Child Development*, *64*, 1111–1127.
- Baillargeon, R., & DeVos, J. (1991). Object permanence in young infants: Further evidence. *Child Development*, *62*, 1227–1246.
- Baillargeon, R., & Graber, M. (1988). Evidence of a location memory in 8 month-old-infants in a non-search AB task. *Developmental Psychology*, *24*, 502–511.
- Baillargeon, R., Graber, M., DeVos, J., & Black, J. (1990). Why do young infants fail to search for hidden objects? *Cognition*, *36*, 255–284.
- Bell, M., & Fox, N. (1992). The relations between frontal brain electrical activity and cognitive development during infancy. *Child Development*, *63*, 1142–1164.
- Benson, J., & Uzgiris, I. (1985). Effect of self-initiated locomotion on infant search activity. *Developmental Psychology*, *21*, 923–931.
- Bertenthal, B. I. (1996). Origins and early development of perception, action, and representation. *Annual Review of Psychology*, *47*, 431–459.
- Bertenthal, B. I., & Campos, J. J. (1990). A systems approach to the

- organizing effects of self-produced locomotion during infancy. In C. Rovee-Collier & L. P. Lipsitt (Eds.), *Advances in infancy research*, Vol. 6 (pp. 1–60). Norwood, NJ: Ablex.
- Berthier, N. E. (1996). Learning to reach: A mathematical model. *Developmental Psychology*, 32, 811–823.
- Berthier, N. E., & Robin, D. J. (1997). *Mid-reach correction of infant reaching*. Manuscript submitted for publication.
- Biguer, B., Jeannerod, M., & Prablanc, P. (1982). The coordination of eye, head, and arm movements during reaching at a single visual target. *Experimental Brain Research*, 46, 301–304.
- Bjork, E. L., & Cummings, E. M. (1984). Infant search errors: Stage of concept development or stage of memory development. *Memory & Cognition*, 12, 1–19.
- Bogartz, R. S., Shinsky, J. L., & Speaker, C. J. (in press). Interpreting infant looking: The Event Set \times Event Set design. *Developmental Psychology*.
- Bremner, J. G. (1978). Spatial errors made by infants: Inadequate spatial cues or evidence of egocentrism? *British Journal of Psychology*, 69, 77–84.
- Bremner, J. G. (1985). Object tracking and search in infancy: A review of the data and a theoretical evaluation. *Developmental Review*, 5, 371–396.
- Bremner, J. G., & Bryant, P. E. (1977). Place versus response as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology*, 23, 162–177.
- Butterworth, G. (1976). Object identity in infancy: The interaction of spatial location codes in determining search errors. *Child Development*, 46, 866–870.
- Butterworth, G. (1977). Object disappearance and error in Piaget's Stage IV task. *Journal of Experimental Child Psychology*, 23, 391–401.
- Butterworth, G., Jarrett, N., & Hicks, L. (1982). Spatiotemporal identity in infancy: Perceptual competence or conceptual deficit? *Developmental Psychology*, 18, 435–449.
- Carranza, J., Brito, A., & Escudero, A. (1990). The absence of the second container in the A not B error. *Archives de Psychologie*, 58, 275–282.
- Castiello, U. (1996). Grasping a fruit: Selection for action. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 582–603.
- Cohen, J., Dunbar, K., & McClelland, J. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, 97, 332–361.
- Cummings, E. M., & Bjork, E. L. (1983a). Perseveration and search on a five-choice visible displacement hiding task. *The Journal of Genetic Psychology*, 142, 283–291.
- Cummings, E. M., & Bjork, E. L. (1983b). Search behavior on multi-choice hiding tasks: Evidence for an objective conception of space in infancy. *International Journal of Behavioral Development*, 6, 71–87.
- Dehaene, S., & Changeux, J. P. (1989). A simple model of prefrontal cortex function in delayed-response tasks. *Journal of Cognitive Neuroscience*, 1, 244–261.
- Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by infants' performance on A-not-B. *Child Development*, 56, 868–883.
- Diamond, A. (1988). Differences between adult and infant cognition: Is the crucial variable presence or absence of language? In L. Weiskrantz (Ed.), *Thought without language* (pp. 337–370). Oxford, England: Clarendon Press.
- Diamond, A. (1990a). Development and neural bases of AB and DR. In A. Diamond (Ed.), *The development and neural bases of higher cognitive functions* (pp. 267–317). New York: National Academy of Sciences.
- Diamond, A. (1990b). Developmental time course in human infants and infant monkeys, and the neural bases of inhibitory control in reaching. In A. Diamond (Ed.), *The development and neural bases of higher cognitive functions* (pp. 637–676). New York: National Academy of Sciences.
- Diamond, A., Cruttenden, L., & Neiderman, D. (1994). AB with multiple wells: 1. Why are multiple wells sometimes easier than two wells? 2. Memory or memory + inhibition? *Developmental Psychology*, 30, 192–205.
- Diamond, A., & Goldman-Rakic, P. S. (1989). Comparison of human infants and rhesus monkeys on Piaget's AB task: Evidence for dependence on dorsolateral prefrontal cortex. *Experimental Brain Research*, 74, 24–40.
- Diamond, A., Zola-Morgan, S., & Squire, L. R. (1989). Successful performance by monkeys with lesions of the hippocampal formation on AB and object retrieval, two tasks that mark developmental changes in human infants. *Behavioral Neuroscience*, 103, 526–537.
- Diedrich, F. J., Thelen, E., Corbetta, D., & Smith, L. B. (1998). *Perseverative errors in infancy as a window on dynamic perception action memories*. Manuscript submitted for publication.
- Enright, J. T. (1995). The non-visual impact of eye orientation on eye-hand coordination. *Vision Research*, 11, 1611–1618.
- Fisk, J. D., & Goodale, M. A. (1985). The organization of eye and limb movements during unrestricted reaching in targets in contralateral and ipsilateral visual space. *Experimental Brain Research*, 60, 159–178.
- Fox, N., Kagan, J., & Weiskopf, S. (1979). The growth of memory during infancy. *Genetic Psychology Monographs*, 99, 91–130.
- Frye, D. (1980). Stages of development: The stage IV error. *Infant Behavior and Development*, 3, 115–126.
- Georgopoulos, A. P. (1986). On reaching. *Annual Review of Neurosciences*, 9, 147–170.
- Georgopoulos, A. P. (1990). Neurophysiology of reaching. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 227–263). Hillsdale, NJ: Erlbaum.
- Georgopoulos, A. P. (1991). Higher order motor control. *Annual Review of Neurosciences*, 14, 361–377.
- Georgopoulos, A. P. (1995). Motor cortex and cognitive processing. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 507–517). Cambridge, MA: MIT Press.
- Georgopoulos, A. P., Crutcher, M. D., & Schwartz, A. B. (1989). Cognitive spatial motor processes: 3. Motor cortical prediction of movement direction during an instructed delay period. *Experimental Brain Research*, 75, 183–194.
- Georgopoulos, A. P., Schwartz, A., & Kettner, R. (1986). Neuronal population coding of movement direction. *Science*, 233, 1416–1419.
- Ghez, C., Hening, W., & Favilla, M. (1990). Parallel interacting channels in the initiation and specification of motor response features. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 265–293). Hillsdale, NJ: Erlbaum.
- Ghilardi, M. F., Gordon, J., & Ghez, C. (1995). Learning a visuomotor transformation in a local area of work space produces directional biases in other areas. *Journal of Neurophysiology*, 73, 2535–2539.
- Goldfield, E. C., & Dickerson, D. J. (1981). Keeping track of locations during movement in 8- to 10-month-old infants. *Journal of Experimental Child Psychology*, 32, 48–64.
- Goodale, M. A., Pélisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature*, 320, 748–750.
- Gratch, G., Appel, K. J., Evans, W. F., LeCompte, G. K., & Wright, N. A. (1974). Piaget's stage IV object concept error: Evidence of forgetting or object conception. *Child Development*, 45, 71–77.
- Halverson, H. M. (1931). An experimental study of prehension in infants by means of systematic cinema records. *Genetic Psychology Monographs*, 10, 107–286.
- Harris, P. L. (1973). Perseverative errors in search by young infants. *Child Development*, 44, 28–33.
- Harris, P. L. (1974). Perseverative search at a visibly empty place by young infants. *Journal of Experimental Child Psychology*, 18, 535–542.
- Harris, P. L. (1987). The development of search. In P. Salapatek & L. B.

- Cohen (Eds.), *Handbook of infant perception*. Vol. 2 (pp. 48–62). New York: Academic Press.
- Hening, W., Favilla, M., & Ghez, C. (1988). Trajectory control in targeted force impulses. V. Gradual specification of response amplitude. *Experimental Brain Research*, *71*, 116–128.
- Hening, W., Vaccaria, D., & Ghez, C. (1988). Trajectory control in targeted force impulses. IV. Influence of choice, prior experience, and urgency. *Experimental Brain Research*, *71*, 103–115.
- Hofstadter, M. C., & Reznick, J. S. (1996). Response modality affects human infant delayed-response performance. *Child Development*, *67*, 646–658.
- Hofsten, C. von. (1991). Structuring of early reaching movements: A longitudinal study. *Journal of Motor Behavior*, *23*, 280–292.
- Horobin, K., & Acredolo, L. (1986). The role of attentiveness, mobility history, and separation of hiding sites on Stage IV search behavior. *Journal of Experimental Child Psychology*, *41*, 114–127.
- Huttenlocher, J., Newcombe, N., & Sandberg, E. (1994). The coding of spatial location in young children. *Cognitive Psychology*, *27*, 115–148.
- Jackson, S. R., Jackson, G. M., & Rosicky, J. (1995). Are non-relevant objects represented in working memory? The effect of non-target objects on reach and grasp kinematics. *Experimental Brain Research*, *102*, 519–530.
- Jones, S., & Smith, L. B. (1993). The place of perception in children's concepts. *Cognitive Development*, *8*, 113–140.
- Jeannerod, M. (1988). *The neural and behavioural organization of goal-directed movements*. Oxford, England: Clarendon.
- Keele, S. W. (1981). Behavioural analysis of movement. In V. B. Brooks (Ed.), *Handbook of physiology*. Sect. 1. *The nervous system*. Vol. II. *Motor control, Part 2* (pp. 1391–1414). Bethesda, MD: American Physiological Society.
- Kermoian, R., & Campos, J. J. (1988). Locomotor experience: A facilitator of spatial cognitive development. *Child Development*, *59*, 908–917.
- Lackner, J. R., & DiZio, P. (1994). Rapid adaptations to Coriolis force perturbations of arm trajectory. *Journal of Neurophysiology*, *72*, 299–313.
- Landers, W. F. (1971). Effects of differential experience on infants' performance in a Piagetian Stage IV object-concept task. *Developmental Psychology*, *5*, 48–54.
- Matthews, A., Ellis, A. E., & Nelson, C. E. (1996). Development of preterm and full-term infant ability on AB, recall memory, transparent barrier, and means-end tasks. *Child Development*, *67*, 2658–2676.
- Munakata, Y. (1997). Perseverative reaching in infancy: The role of hidden toys and motor history in the AB task. *Infant Behavior and Development*, *20*, 405–416.
- Munakata, Y. (1998). Infant perseveration and implications for object permanence theories: A POP model of the AB task. *Developmental Science*, *1*, 161–184.
- Munakata, Y., McClelland, J. L., Johnson, M. H., & Siegler, R. S. (1997). Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review*, *104*, 686–719.
- Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.
- Poulton, E. C. (1981). Human manual control. In V. B. Brooks (Ed.), *Handbook of physiology*. Sect. 1. *The nervous system*. Vol. II. *Motor control, Part 2* (pp. 1337–1389). Bethesda, MD: American Physiological Society.
- Recanzone, G., Merzenich, M., & Schreiner, C. (1992). Changes in the distributed temporal response properties of SI cortical neurons reflect improvements in performance on a temporally based tactile discrimination task. *Journal of Neurophysiology*, *67*, 1071–1091.
- Roby-Brami, A., & Burnod, Y. (1995). Learning a new visuomotor transformation: Error correction and generalization. *Cognitive Brain Research*, *2*, 229–242.
- Schilling, T., & Clifton, R. (1998). Nine-month-old infants learn about a physical event in a single session. *Cognitive Development*, *13*, 165–184.
- Schöner, G. (1995). Recent developments and problems in human movement science and their conceptual implications. *Ecological Psychology*, *7*, 291–314.
- Schuberth, R. E., Werner, J. S., & Lipsitt, L. P. (1978). The stage IV error in Piaget's theory of object concept development: A reconsideration of the spatial location hypothesis. *Child Development*, *49*, 744–748.
- Shadmehr, R., & Mussa-Ivaldi, F. A. (1994). Adaptive representation of dynamics during learning of a motor task. *Journal of Neuroscience*, *14*, 3208–3224.
- Smith, L. B., & Samuelson, L. K. (1997). Perceiving and remembering: Category stability, variability and development. In K. Lamberts & D. Shanks (Eds.), *Knowledge, concepts, and categories* (pp. 161–195). Cambridge, England: Cambridge University Press.
- Smith, L. B., & Thelen, E. (1993). *A dynamic systems approach to development: Applications*. Cambridge, MA: MIT Press.
- Sophian, C. (1985). Perseveration and infants' search: A comparison of two- and three-location tasks. *Developmental Psychology*, *21*, 187–194.
- Spencer, J., Smith, L. B., & Thelen, E. (1997). *Tests of a dynamic systems account of the A-not-B error: Perseverative reaching by 2- to 3-year olds*. Unpublished manuscript.
- Thelen, E., Corbetta, D., & Spencer, J. P. (1996). The development of reaching during the first year. The role of movement speed. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 1059–1076.
- Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (1999). *A dynamic field theory of infant perseverative errors*. Manuscript submitted for publication.
- Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of perception and action*. Cambridge, MA: MIT Press.
- Tipper, S. P., Lortie, C., & Baylis, G. C. (1992). Selective reaching: Evidence for action-centered attention. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 891–905.
- Titze, R., Thelen, E., & Smith, L. B. (1998). *The developmental dynamics of understanding transparency: A new interpretation of the object retrieval task*. Manuscript submitted for publication.
- Webb, R. A., Massar, B., & Nadolny, T. (1972). Information and strategy in the young child's search for hidden objects. *Child Development*, *43*, 91–104.
- Wellman, H. M., Cross, D., & Bartsch, K. (1987). Infant search and object permanence: A meta-analysis of the A-not-B error. *Monographs of the Society for Research in Child Development*, *51*, 1–51.
- Willats, P. (1985). Adjustment of means-ends coordination and the representation of spatial relations in the production of search errors by infants. *British Journal of Developmental Psychology*, *3*, 259–272.
- Xu, F., & Carey, S. (1996). Infants' metaphysics: The case of numerical identity. *Cognition Psychology*, *30*(2), 111–153.
- Yates, D. J., & Bremner, J. G. (1988). Conditions for Piagetian stage IV search errors in a task using transparent occluders. *Infant Behavior and Development*, *11*, 411–417.

Received June 20, 1997

Revision received August 6, 1998

Accepted August 6, 1998 ■