CHAPTER FOUR

Are Different Actions Mediated by Distinct Systems of Knowledge in Infancy?

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Abstract

This chapter considers why studies of infant looking and reaching often suggest different patterns of cognitive and perceptual development. In some cases, convergent results have emerged from studies of infant looking and reaching, but differences are
common. The most typical results suggest less adult-like perception and cognition in studies of reaching than in studies of looking. Several reaching studies, however, do not fit this pattern, suggesting that reaching actions may be mediated by distinct systems of knowledge and information processing. Comparisons of research on other behaviors, such as crawling and walking, also suggest that infant knowledge systems vary across actions. Research on how adult size perception differs between verbal and reaching response behaviors is considered and used as a template to interpret the developmental results. Like adults, when infants prepare to engage in particular actions, they seem to shift their sensitivity to particular sources of information and to process that information in action-relevant ways. These tendencies suggest that distinct knowledge systems mediate different actions in infancy.

1. INTRODUCTION

What do infants know, and when do they know it? This fundamental question has motivated decades of research on infant cognitive and perceptual development. One clear conclusion from this body of work is that our understanding of the development of infant perception and cognition is directly tied to how we address these questions. This chapter considers evidence that when infants engage in different types of actions, our answers to these questions must change. If infants reach for and interact with a display, they seem to know—and not know—different things than when they merely view it.

One of the cornerstones of Piaget’s theory of infant development was the apparent lack of object permanence in children younger than 8 months of age (Piaget, 1954). Around 4 months of age, infants begin to make successful reach-to-grasp actions directed at nearby visible objects. But if an object of interest is covered with an uninteresting cloth, children younger than 8 months often stop reaching for it. Piaget inferred that infants in this age group lack the ability to maintain a mental representation of an object unless it is directly visible. Later work, based on looking time measures, contradicted Piaget’s conclusions about the development of object permanence. For instance, Baillargeon’s (1987) “drawbridge” study presented 3.5-month-olds with an event in which a solid, rotating panel appeared to pass through a solid box. Infants looked longer at this “impossible” event, relative to baseline control levels. This pattern of looking emerged even though the rotating panel completely blocked the infants’ view of the solid box. Baillargeon concluded that 3.5-month-olds do possess the ability to mentally represent an object, even when it is not directly visible.
If you ask a 4-month-old whether an occluded object continues to exist using a reaching measure, the answer is no. If you ask the same question using a looking measure, however, the answer is yes. The standard interpretation of these sets of disparate findings is that young infants do possess mental representations of hidden objects; what they lack is the ability to use those mental representations to coordinate actions toward hidden objects (but see Clifton, Rochat, Litovsky, & Perris, 1991). According to this interpretation, the difference in the results of the reaching and looking measures is due to a difference in the relative difficulty of the two tasks. Munakata (2001) has proposed a graded representation strength model of these different looking and reaching results. She assumes that the neural representation of a visible object is quantitatively stronger than that associated with a hidden object. If a smaller amount of representation strength is needed to coordinate looking than reaching actions, then perhaps hidden object representations for young infants fall between the two thresholds. The representations are strong enough to support relatively simple looking actions, but not strong enough to support the more demanding task of reaching.

In this chapter, I will argue for an alternative interpretation of such task-related differences. When study participants prepare to act on a target display, as opposed to simply viewing that display, a variety of evidence suggests that they alter how they process incoming sensory information. This seems to be true for both adult and infant populations. The shift in the perceptual “mode of processing” associated with action preparation increases sensitivity to some sources of information while suppressing other sources. What do infants know and when do they know it? By adding an action dimension to these “what” and “when” questions of development, a more complete understanding may emerge.

When infants’ behaviors are guided by characteristics of the environment on a principled basis, many have described it as indicating infants “knowledge” about the world, and I will adopt this terminology here. There are good arguments for characterizing infant perception and action without invoking the concept of knowledge, which implies conscious, domain-general thought. While I do not intend to evoke these concepts when I use this term, I will nonetheless use it to connect with the literature considered here.

1.1 Chapter Outline
In the first section, I discuss measures of looking and reaching that have been used to characterize infant and adult knowledge about objects. This includes
the reasoning used to infer early infant knowledge based on infant looking times and the concept of “violation of expectation” (VOE). I then discuss studies of adult visually guided reaching behaviors and resulting inferences about the information processing (and knowledge) inherent in these actions. The results of these studies provide a template for considering results from the developmental literature. I end this section with a description of the information processing inherent in the development of visually guided reaching in infants and young children.

In the second section, I consider groups of studies that suggest strong similarities in the course of development for looking and reaching, such as research on infant understanding of containment and occlusion events (Feigenson & Carey, 2003; Hespos & Baillargeon, 2006; 2008; Van de Walle, Carey, & Prevor, 2000). In the third section, I review studies that suggest different courses of development for looking and reaching behaviors, including the A-not-B error and depth perception (Arterberry, Bensen, & Yonas, 1991; Baillargeon & Graber, 1988; Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Cuevas & Bell, 2010). Many of these studies have suggested that infants perform in a more advanced, “adult-like” fashion when looking measures are used as compared to object reaching and search tasks.

In the fourth section, I review evidence that infants rely on different sources of information when performing looking and reaching behaviors. I discuss studies from my own group on infants’ perceptions of object boundaries (Vishton, Ware, & Badger, 2005), and studies that have compared different components of the same overall infant action such as future-oriented reaching for moving objects (Berthier et al., 2001).

In the fifth section, I consider additional evidence that infants and young children process information differently when engaged in different actions, based on comparisons of behaviors other than reaching and looking. For instance, experienced 11-month-old crawlers will reliably avoid steep slopes, but when these same children stand up to walk, they ignore this slope information (Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997).

I will conclude by considering several predictions that emerge from a theory of action-specific knowledge. As action capabilities emerge and humans gain expertise with them, specific perception—cognition—action systems develop. Understanding the information-processing architecture of these subsystems is important for understanding development, and for any theory of the overall function of the human perception—cognition—action system. It is during development that we will be best able to explore the underlying architecture of these systems (e.g., Karmiloff-Smith, 1995).
2. MEASURES OF LOOKING AND REACHING

2.1 Measures of Infant Looking Time and Violation of Expectation

Three characterizations of the development of perception and cognition have been extensively replicated over the past several decades. First, very young infants perceive and make some sense of the world around them. Second, infants and young children perceive and reason about the world differently than adults do. Third, as infants mature and acquire experience they become increasingly adult-like in their perception and cognition. Many findings from developmental science have sought to characterize the ordered list of emerging perceptual and cognitive capacities associated with this development of increasingly adult-like behaviors.

From the day that they are born, indeed for at least several weeks before they are born, infants exhibit a tendency to habituate in their response to repeated stimuli (Fantz, 1964; Leader, Baillie, Martin, & Vermeulen, 1982). For instance, if a typical infant is shown a salient, colorful object, he/she will look at it for some period of time before looking away. If the same object is repeatedly shown on successive trials, then he/she will look at it for progressively shorter amounts of time before looking away. This consistent habituation of the looking-time response demonstrates that infants can see and encode at least some aspects of visual stimuli in a form that influences future behavior. Some rudimentary memory mechanisms must already be functional, enabling the infant to compare what is currently being seen with what has been seen in the past.

Also very reliable is the tendency of infants to exhibit “dishabituation”—a recovery of looking time duration or other response to a stimulus—if the habituation display is replaced with a new stimulus that is different in some way that the child can detect. The well-supported inference in this area is that infants tend to look longer at objects and events that are novel and/or events that are unexpected. This theoretical tool has been applied very fruitfully to explore how young infants perceive and reason about their surrounding environment.

By 3.5 months of age, infants’ looking behaviors suggest that they expect solid objects not to pass through one another (Baillargeon, 1987). If an event is presented that seems to have violated this “solidity and cohesion” principle, infants will look longer at the event relative to baseline control conditions in which a violation does not take place (Spelke & Kinzler, 2007). Prior
to 3.5 months, this tendency is not apparent in infant behaviors, suggesting that some cognitive or perceptual capacity that supports the behavior emerges around this age.

By 4.5 months of age, infants seem to expect that objects will fall downward in the absence of support (Needham & Baillargeon, 1993). Events in which a hand pushes an object beyond the edge of some supporting surface and the object remains in the same vertical location (i.e., it does not fall down) inspire longer looking times. Such looking times are always considered relative to carefully designed control events that are nearly identical but do not contain this violation of a “support” principle. Prior to 4.5 months, this tendency is not apparent, suggesting that this is the age at which this perceptual/cognitive capacity develops.

Hundreds of experiments of this type have explored infant development in this fashion, resulting in a detailed, largely self-consistent literature on the developmental progression of infant perception and cognition (for review see Spelke & Kinzler, 2007). A pervasive but largely implicit inference that has often been made is that looking-time measures provide the most accurate assessment of infants’ perceptual and cognitive abilities at a given age because they are the most sensitive. A looking-time study places a minimum of demands on infant participants in terms of action planning and execution. According to this reasoning, infants possess object permanence by 3.5 months of age, but their ability to demonstrate this ability can be masked in a reaching study by the distraction and difficulty associated with performing the more complex task of planning and executing visually guided reaching actions. If an adult were given a demanding set of distractor tasks, his/her performance on any particular task would be diminished and errors would occur. It stands to reason that the same would be true of infants and young children as well.

Ramachandran and Blakeslee (1998) somewhat fancifully pointed out that if you want to prove pigs can talk, then you only need one talking pig. While many philosophers of science would take issue with this, there is a parallelism to infant research worth noting. As long as some measure, in some experimental context indicates that infants of a particular age possess some perceptual or cognitive ability, that has been taken as sufficient evidence that the ability is present by that age.

The vast majority of this work has relied on looking tendencies of infants, but other indicators of arousal have been used as well. In some studies, heart rate or sucking frequency has been used (e.g., Eimas, Siqueland, Jusczyk, & Vigorito, 1971). Levels of brain activation have also been measured
In almost all cases, however, these studies rely on the same VOE reasoning used to determine what an infant can and cannot perceive and/or what an infant does and does not know.

Looking and reacting to experimenter-controlled events is certainly not the only set of behaviors available to an infant, however. When other behaviors are considered, many results that are not predicted by these VOE studies have emerged. Infant object-directed reaching studies have provided several examples of this. Before considering them, however, it is worth placing them in context with a consideration of some characteristics of adult object-directed reaching behaviors. A wide range of research has suggested that adult visual perception processes make use of different information processing during object-directed reaching behaviors, as compared with verbal response or other consciously mediated perceptual judgment behaviors. These studies of adults provide a template that we can use to consider developmental research. Do infants similarly alter their information processing when they engage in different actions?

### 2.2 Measures of Adult Object-Directed Reaching

When adults reach for objects, they engage in a variety of precise information processing, typically in an unconscious, automatic fashion. Perception of the distance and direction to an object relative to the current position of the hand are critical to coordinating an effective grasping action. Adult reaches typically involve the movement of the hand along a relatively straight path from its starting location to the target (for review see Jeannerod, 1988). In a typical reach, the hand accelerates smoothly through the first half of the movement and decelerates during the second half. This implies that the distance and direction of the hand movement to the target is determined before the movement onset. If an adult view of the target is removed at the onset of a reach—for example, by abruptly turning off the lights at the onset of movement—the hand still exhibits a trajectory with these kinematic characteristics (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1997).

The size of the object is also visually registered and mediates the shape of the grip used during the reach. Marteniuk, Leavitt, MacKenzie, and Athenes (1990) attached precise position sensors to participants’ fingers and wrists and recorded their movements as they made precision grasps using the thumb and index finger. They presented participants with disk-shaped targets of varying sizes and found a canonical grip formation that was precisely mediated by the size of the target. During the first part of the action, the fingers moved apart from one another, until they reached a maximum grip aperture.
(MGA) about half way through the reach. The grip then closed during the second half of the movement until it made contact with the target. The Pearson correlation between the diameter of the disk target and the MGA was quite linear and very high, around 0.99.

The shape of the object is also taken into account during a reaching action. For instance, if the reaching target is an irregular shape, the thumb and index finger are not placed randomly, but instead positioned at opposing positions on the shape, so as to afford a stable grip (Goodale, Meenan, Bülthoff, Nicole, Murphy, & Racicot, 1994). Studies of the force applied to an object when it is grasped and lifted indicate that the approximate weight of an object is also included in the action plan associated with the grasp (Brenner & Smeets, 1996). When lifting an egg shell, far less force is applied than when lifting a heavy metal object, for instance. These many detailed aspects of a “simple” reach-to-grasp movement are computed outside of our awareness in most cases, but they are both complex and essential to the performance of efficient, successful actions.

Vishton et al. (2007) performed several studies on how our conscious perceptions of target size are altered when we prepare to perform a reaching action. The interpretation applied in those experiments provides a template for better understanding how infants’ perception and cognition might be altered when they prepare to perform a reaching action as well.

In these studies, participants were asked to repeatedly choose which of two disks seemed larger. A standard, 28-mm diameter disk was always presented, along with a second disk that varied between 27 and 33 mm in diameter. In some cases, participants were asked to verbally state which disk appeared larger. In others, participants were asked to reach out and grasp the disk that they perceived to be larger. When the pairs of disks were presented on a plain background, participants were very accurate in both the verbal and grasp selection tasks.

The experimenters also presented the disks on a background that induced the Ebbinghaus illusion (Fig. 1). The illusion background made the standard 28-mm disk seem larger and the comparison disks seem smaller. When participants engaged in a verbal response task to indicate which disk was larger, the illusion exerted a 9% effect on perceived size of the disks. That is, the comparison disk needed to be approximately 3 mm larger than the 28-mm standard disk to reliably cause participants to verbally choose it as larger. When participants engaged in a grasp response task, however, the magnitude of the illusion effect was reduced by about 40%. Note here that it is not merely the grip formation that is resistant to the illusion, a
finding that has been obtained in several studies (e.g., Aglioti, DeSouza, & Goodale, 1995). Preparing to reach for a target changed participants’ conscious perception of relative size. When a 30-mm comparison disk was presented to participants in the illusion background condition, they would verbally state that the 28-mm disk appeared larger. When the same display appeared in the grasp response task condition, participants’ hands would typically make the opposite response, indicating that the 30-mm disk seemed larger. Even when making the same perceptual choice, with the same display, when participants were engaged in a reaching behavior, their perceptions of the display were qualitatively altered.

These studies also replicated results obtained by Aglioti et al. (1995), showing that the effect of the illusion on the MGA produced during the grasp was significantly smaller than that obtained for the verbal response task. Aglioti et al. described that result as evidence for the presence of a second, largely independent, somewhat illusion-resistant visual processing stream associated with the parietal cortex. The magnitude of illusion reduction for the Vishton et al. disk choice measure was approximately the same as that seen for the MGA measure, but the changes they identified did not merely affect the grasp formation.

Figure 1 The Ebbinghaus illusion as presented to participants by Vishton et al. (2007). The two central disks are identical in size and constructed from thin plastic such that they can be grasped and lifted. When assessed by a verbal response choice task, the surrounding arrays of circles printed on paper cause participants to perceive the central disk on the left as approximately 9% larger than the central disk on the right. The magnitude of the illusion is reduced by approximately 40% when participants indicate their choices by grasping or touching the selected disk.
Others have identified related changes in distance perception associated with changes in action intention (e.g., Witt, Proffitt, & Epstein, 2005). Based on these results, Vishton et al. (2007) argued that the preparation to reach engages an alternative “mode” of visual processing. In any particular context, human vision exhibits certain information-processing characteristics. Of the many sources of information available for perceptual processing, some are picked up, whereas others are ignored. By carefully controlling a range of stimuli and observing human performance, experimenters can precisely characterize what information is used and how it relates to perceptual outcomes. The mode of processing approach suggests that these characteristics are malleable, perhaps on a moment-to-moment basis, when participants prepare to engage in different action tasks. For instance, stereopsis cues to size and distance are extremely effective across the relatively small range of distances that are encountered for reaching actions (Cutting & Vishton, 1995). For large distances, however, stereopsis information is not useful, due to physical limitations imposed by the distance between the two eyes and the limits of human retinal acuity. Human vision seems to incorporate this fact by relying more heavily on stereopsis when engaged in reaching actions than when engaged in nonreaching behaviors. An increased weighting of stereopsis information and a corresponding reduction in weighting of nonstereopsis depth information would result in a reduction in the magnitude of illusions caused by that nonstereopsis information.

In the Vishton et al. grasping and touching experiments, the information that causes the Ebbinghaus illusion—presumably the relative size of circles in the display—is somewhat suppressed. In general, preparing to reach for a stimulus can change how the reacher perceives it. An analogous process may take place for infants and children as well. Action planning stimulates a wide range of changes in patterns of neural activity. Reaching-relevant information presumably becomes more salient. Information that is not relevant to action control may be reduced in salience. Infant perception and cognition may change just as has been established in adult participants.

2.3 Measures of Infant Object-Directed Reaching

What information do infants and young children use to guide their reaching for objects? Human infants typically begin to successfully grasp nearby, visible targets by around 4 months of age (von Hofsten, 1991). Even before this age the foundations of visually guided reaching seem to be present. For instance, von Hofsten (1982) has shown that even newborn infants make systematic prereaching movements that bring their hands toward a visible target.
While 4-month-olds typically make successful reach-to-grasp actions, the actions are initially not mediated by target properties as they are in adults. These reaching characteristics emerge in the first 2 years of development (Konczak & Dichgans, 1997). Lockman, Ashmead, and Bushnell (1984) demonstrated that 9-month-olds rotate the hand to account for the orientation of a long, thin target object during a grasping action. By 9 months of age, infants scale their grips to the size of targets (von Hofsten & Rönnqvist, 1988; Siddiqui, 1995), but the scaling is less precise than that of adults and typically incorporates a larger-than-needed grip.

The development of visually guided action clearly develops over an extended period of childhood, but even very young infants’ reaching is controlled on the basis of many sources of information gathered from the environment—many of the same sources that have been shown to influence looking behaviors in VOE studies. As with studies that measure looking time, experimenters have been able to create situations in which the reaching behaviors of infants can be used to infer how the infant perceived and reasoned about displays. The information processing that is implicated by such studies suggests what infants know (and do not know) at particular ages.

2.4 Looking Time Versus Looking Location and Reaching Location Versus Reaching Duration

In this chapter, except where specifically noted, measures of “looking” refer to the amount of time an infant spends looking at a display before looking away. This measure is taken as an assessment of how much a particular display attracts the attention of an infant. Recent work, however, has made increasing use of eye trackers to record not just whether an infant looks at a display, but where the infant directs his/her fixations. In studies in which display objects move, the visual tracking behaviors of infants can be monitored as well.

For most studies, researchers have focused on looking duration and reach location, but this could, in principle, be reversed. The amount of time an infant spends reaching for and interacting with a display can provide a measure of how much it attracts the infant’s attention (e.g., Mandler, Fivush, & Reznick, 1987). Where an infant looks can be taken as a measure of where an infant believes a hidden object to be located (e.g., Cuevas & Bell, 2010; Hoferstader & Reznick, 1996). While there are exceptions that I will note, in general, this chapter adheres to the historical tendency to focus on looking
durations and reach locations. Whether it is the looking versus reaching distinction or the duration versus location distinction that is most important is an issue that remains to be resolved.

3. EVIDENCE FOR SIMILAR DEVELOPMENT OF REACHING AND LOOKING BEHAVIORS

Several lines of research have compared infant reaching and looking measures and obtained very similar results. These parallel patterns of development suggest that reaching and looking may be governed by a single information processing system.

3.1 Occlusion and Containment

In the key conditions of their experiment, Hespos and Baillargeon (2001) showed infants events in which a tall target object was lowered behind an occluder that was shorter than the target object. As such, when the bottom of the target object made contact with the support surface behind the occluder, its motion should have stopped, and much of the object should have remained visible. A hidden hole in that support surface, however, enabled the target object to move downward until only the very top of it remained visible. The 4.5-month-old participants in this experiment looked reliably longer at this event than at relevant control events (e.g., taller occluder or shorter target object). The results suggest that infants at this age are able to reason about the relative heights of objects to develop expectations about what this occlusion event should look like. When those expectations were violated, it attracted the infants’ attention, and thus longer looking times.

Interestingly, if the event involves a target object being placed into a container rather than behind an occluder, 4.5-month-olds do not exhibit this consistent-looking preference. Around 7.5 months of age, however, infants seem to develop the ability to reason about containment events in the same way that they reason about occlusion events at 4.5 months of age.

Hespos and Baillargeon (2006) developed a clever reaching-based study that asked all of these same questions about infant object reasoning. In these studies, infants were shown a tall frog target object. The frog was placed behind an occluding screen. When the screen was removed, infants saw a tall and short occluder; frog legs protruded from each. The short occluder was too short to have hidden the tall frog. If infants were able to reason about the relative heights of the frog target and the occluders, then infants
should have inferred that there was only one frog target and that it was located behind the tall occluder. When the display was moved within reach, 6-month-olds consistently reached more frequently for the tall occluder, relative to baseline preferences (e.g., without prior view of the tall frog target). However, if the target frog appeared to have been placed into a container rather than behind an occluder, 6-month-olds did not exhibit this preferential reaching tendency. The 7.5-month-olds in their study did exhibit the preference, however. This developmental decalage—reasoning about relative size first with occlusion events and only later with containment events—thus seems to occur across both looking and reaching measures.

Note that these looking and reaching studies were not completely parallel. The 4.5-month-olds exhibited adult-like size reasoning for looking measures with the occlusion events. There was no corresponding reaching task for 4.5-month-olds. However, for 6-month-olds, we would expect continued adult-like looking preferences with occlusion. The 6-month-old reaching performance matches this prediction. At 7.5 months of age, the looking data suggest an onset of adult-like size reasoning with containment events. The 7.5-month-old reaching performance matches this prediction as well.

The same research team found strong similarities in the development of infant reasoning about object support (Hespos & Baillargeon, 2008). A series of studies had already explored infant understanding of support relations using looking-time tasks (for review see Baillargeon, Gertner, & Wu, 2010). When 3.5- to 4.5-month-olds watched a hand release a target object, they seemed to expect the object to fall, looking longer than baseline comparison levels if the object remained floating, seemingly unsupported in space. If the target object was placed adjacent to a support platform, this preference was not present. Only 5.5-month-old infants exhibited an increase in looking in this adjacency condition. At this age, however, infants do not seem to differentiate between full support of an object (100% of object base supported) and partial support (only 15% of the object supported). Only at 6.5 months of age do infants seem to reason about support in a way that takes into account both the kind and amount of support provided in events of this type.

Hespos and Baillargeon (2008) explored infants’ understanding of object support using a reaching measure as well. Anyone who has spent time around infants will have seen how they enjoy reaching for objects that can be picked up, handled, and placed in the mouth. If an object is firmly
attached to a wall, it can be touched, but not manipulated. It stands to reason that if infants are given the choice of reaching for an attached versus unattached object, they will tend to choose the unattached target. If an object is suspended in space—not supported from below—then it is likely attached to the background wall. This reasoning enabled the researchers to explore when infants perceive an object as supported (and thus unattached) versus unsupported (and thus attached). They presented infants with displays containing pairs of objects, e.g., one supported by a shelf and another attached to the background. Infants at 5.5 months of age preferred to reach for the supported target. This was true regardless of whether the support was full, or only partial. Only at 6.5 months of age did infants take into account the amount of support provided, reaching more for targets with full support.

These results with the reaching studies are especially compelling given the opposite preference present in the looking studies. In the looking studies, infants were especially attracted to displays that seemed to violate the physical principles of support. In these reaching studies, the infants reached away from these targets, grasping displays that did not exhibit a violation.

3.2 Object Individuation

Another parallel pattern of looking and reaching studies has been found in the domain of object individuation. If an object moves behind an occluder panel and then another object emerges from the other side, is it the same object? If it looks exactly the same, then adults and infants seem to believe that it is. If the second object looks different from the first, however, adults reason that there must be two objects behind the occluder that are emerging one at a time.

To test infants’ perceptions of this type of event, Xu and Carey (1996) habituated infants to two different objects, alternately emerging from behind a central occluder panel. For instance, a toy truck would emerge from the left of the occluder and then move back out of view. Next, a toy duck would emerge from the right and then move back out of view. Experimenters habituated infants to this repeating sequence of events and then lowered the occluder to reveal either one or two objects. Adults have a clear inference in this situation that there should be two objects—a duck and a truck. If there is only one object, this would constitute a clear VOE event. For infants as old as 10 months of age, however, it does not. If the duck and truck are shown simultaneously during the habituation, then 10-month-olds
seem to expect two objects behind the occluder panel (i.e., they look longer if there is only one). When the objects are shown one at a time, however, infants do not express this looking behavior. For a 10-month-old, apparently it’s reasonable for a toy duck to spontaneously turn into a toy truck (and vice versa) during the period of time when the object is occluded. By 12 months of age, the looking pattern changes, aligning with adults’ intuitions about this occlusion event.

Van de Walle et al. (2000) developed an object search task to address this same question using a more active measure of infant behavior (also see Feigenson & Carey, 2003). Infants watched as an experimenter placed one or two objects into an opaque box. The box was presented such that infants could not look inside, but could only explore it by placing their hand in through a small opening on one end. When infants were allowed to search the box, 10- and 12-month-olds reached into the box an appropriate number of times. That is, if one object had been hidden, then infants retrieved one object and tended not to search the box a second time. If two objects had been placed in the box, then the infants were significantly more likely to continue searching the box, even when the second object had been surreptitiously removed by the experimenters.

To compare their results directly with those of Xu and Carey (1996), these experimenters ran a second experiment in which two objects were removed from the box, one at a time, and then placed back into the box. For instance, the experimenter might reach into the box and remove a cookie monster toy, show it to the infant, and then place it back inside. Next, the experimenter would reach in again and show the infant a toy helicopter before placing it back in the box. After this series of events, the 10-month-olds searched the box as if there were only one toy contained within it. The 12-month-old participants, however, searched the box as if there were two objects (Van de Walle et al., 2000).

If an adult saw a cookie monster toy removed from a box and then placed back inside, and then saw a toy helicopter removed and placed back inside, a clear inference would result. The adult would presume that two objects were in the box. Alternatively, if the same cookie monster toy were shown and then returned twice, no such inference would result. This pattern was produced by the 12-month-olds, but not the 10-month-olds, just as in the earlier looking-time studies. For object individuation, reaching and looking seem to be mediated by the same knowledge system.
4. EVIDENCE FOR LATER DEVELOPMENT OF REACHING THAN LOOKING BEHAVIOR

Several lines of research have found similar results when infant looking and reaching measures have been compared. Many others, however, have found differences. The most common results have suggested more adult-like perception and cognition when based on looking relative to reaching behaviors.

4.1 Object Permanence

Several lines of research have suggested that the perceptual and cognitive processes that support infant looking behaviors are more adult-like than those that support visually guided reaching behaviors. I have already mentioned the earliest example of this with object permanence. Piaget (1954) noted that infants younger than 8 months of age consistently fail to reach for target objects if they are placed out of view. Yet Baillargeon (1987) and many others have found evidence that infants engage in strikingly complex and adult-like reasoning about those hidden objects if looking measures are used.

Several other lines of research have produced a similar pattern of outcomes, all of which suggest that looking measures produce more adult-like perception and cognition than reaching. This might be because looking and reaching inspire the activation of different systems of knowledge, but it could also be that looking simply provides a more sensitive measure of infant knowledge. Perhaps the planning and execution of a reaching action consumes some of a finite pool of mental resources, reducing the ability of the infant to engage in his/her best possible analysis of the presented displays and events. Looking involves looking. Reaching involves looking as well as reaching.

Clifton et al. (1991) found that although 6.5-month-olds infants fail to reach for objects when they are behind some occluding surface, they reach for audible objects in the dark. And those reaching actions were not uncoordinated swipes into the darkness. During reaches under normal illumination conditions, a small object was associated with a particular sound and a large object with a different sound (e.g., a bell and a buzzer). When that sound was played in the dark, the infant reaching was guided by the target size implied by the sound. For the large object sound, the hands were spread laterally during the reach. For the small object sound, the reaches were more likely to involve one hand extending, while the other remained back near
the infant’s trunk. The result suggests that infants’ limitation in the classic Piagetian task was not their inability to see the object, but rather a distraction caused by the sight of the occluder.

A related result was obtained by Jonsson and von Hofsten (2003) in their study of 6-month-olds’ performance in catching a moving target. If the moving object passed behind an occluder, the frequency and accuracy of future-oriented reaching declined precipitously. If the room lights were turned off, however, during the time that the object would have been behind the occluder, the decline in reaching performance was significantly smaller. The loss of the ability to see the object seems to matter for object catching, but the presence of a visible occluder seems to matter more. All of this work suggests that the relative delay in the cognition-supporting reaching relative to looking may result from extra challenges present in reaching studies rather than the presence of a different system of knowledge.

Piaget described the early development of so-called object permanence as relatively fragile, as evidenced by infants’ failures on the classic A-not-B task. In this paradigm, researchers typically study infants between 8 and 12 months of age, who are able to retrieve objects hidden behind an occluder. Two hiding locations are used, referred to as A and B respectively. Children watch an adult hide an object in location A and successfully retrieve it several times. On the key test trials, the experimenter switches to hiding the target object in the B location. All of this is performed in full view of the infants, who watch each step. Even after a delay of only several seconds, however, many infants incorrectly search in the A location.

VOE studies relying on looking time suggest that infants are able to track the location of hidden objects, however. Baillargeon and Graber (1988) showed 8-month-olds a series of events on a stage with two separate occluding panels and a nearby object. The occluding panels were moved laterally such that one of the panels hid the object. In some cases, the object was placed so as to be hidden behind the panel on the left, and in others hidden by the panel on the right. A hand reached in from the side of the display. After lingering there for 15 s, it reached behind the nearest occluder and retrieved an object. The experimenters recorded how long the infant looked at the display before looking away for 2 continuous sec. In the “possible” case, the object was retrieved from the same panel behind which it had been hidden. In the “impossible” case, the experimenters surreptitiously switched the location of the object, without revealing this to the infant. For instance, in some trials, the object would have been hidden behind the occluder on the left, but then retrieved from the occluder on
the right. Eight-month-olds looked significantly longer at these impossible trials, providing strong evidence that they are adept at tracking the location of a hidden object as long as this ability is measured using a looking-time VOE method.

Other versions of the A-not-B task have explored infants’ understanding using a visual tracking methodology (e.g., Cuevas & Bell, 2010). In the looking version of the A-not-B task, the object was hidden in the A location repeatedly but an adult caregiver restrained the arms of the infant so that she could not search for it manually. After the experimenter prompted the infant (e.g., “Where is it?”) the subsequent visual fixation was likely to be in the direction of hiding location A. When the experimenter switched to hiding the target in the B location, infants were still likely to make an initial fixation in the direction of location A. Thus, with looking location (see note above about looking duration vs. location) infants seem to make the A-not-B error. Cuevas and Bell tracked the development of object search behaviors between 5 and 10 months of age and found lower error rates for looking than for reaching. Again, it seems that infants’ performance is more adult-like when the task involves looking rather than reaching.

Keen (2003) presented 2-year-olds with an object search task in which a ball rolled down a ramp, behind an occluder containing four doors. The task of the child was to open the correct door to find the ball. Adults have no difficulty in this task, reasoning that the ball should roll down the ramp until it runs into an obstacle. When Keen placed a barrier on the ramp, however, 2-year-olds did not use it to infer that the ball would stop at the door adjacent to it. This was true even though the top of the barrier remained visible throughout the task. The result is striking given the looking time VOE evidence indicating that infants can reason about solidity and cohesion as early as 3.5 months of age. Fully 20 months later, they seem unable to apply that knowledge in a search task. When a behavioral measure such as this involves several steps—tracking the occluded movement of the ball, considering how the occluder will affect it, and then after several seconds grasping and opening one of several doors—the knowledge inherent in looking behaviors can be strikingly different from that apparent in more complex action tasks.

4.2 Depth Perception

Another example of this tendency of looking behaviors to be more adult-like than reaching behaviors is present in research on infant depth perception. Yonas et al. have extensively studied depth perception using a
preferential reaching task (for review see Kellman & Arterberry, 2006). Infants between 5 and 7 months of age exhibit a consistent tendency to reach for the nearer of two surfaces (see also von Hofsten & Spelke, 1985). If an infant is sensitive to a depth cue suggesting that one surface is closer, then a reaching preference will be observed. This method has been used to suggest that 7-month-old infants are sensitive to static, monocular sources of depth information such as occlusion, height-in-field, familiar size, etc., whereas 5-month-olds are not. Infants at both ages, however, are sensitive to binocular and motion-based sources of depth information. All of these results apply when infants are engaged in reaching actions. Do the same results apply when the infants are merely looking at a display? One study has suggested a similar course of development for looking behaviors, with sensitivity to monocular sources of depth information emerging between 5 and 7 months of age (Arterberry et al., 1991). Several other looking studies, however, have presented evidence for much earlier sensitivity to monocular information when looking behaviors are assessed.

Shuwairi (2009), for example, presented 4-month-olds with 2D images of cubes that were constructed to be “possible” or “impossible” figures. In the impossible case, a normal 2D image of a 3D cube was altered such that more distant surfaces seemed to partially occlude closer surfaces. Four-month-olds’ spontaneous preferences for these impossible images, relative to similar possible images, suggests that they perceived that something was unusual and novel in them. It further suggests that they were able to infer a global 3D structure by integrating static, monocular 2D information across the image.

In another line of work, Bhatt and Bertin (2001; Bertin & Bhatt, 2006) presented 3-month-old infants with pairs of images containing collections of small, geometric figures that adults perceive as 3D rectilinear objects. On one side, all of the depicted objects in the image were identical, whereas on the other side, one target object was different. When alterations were made to the figures that created the illusion of a change in the 3D shape of the object (i.e., shifting the location of line intersections and the shading of the figures), infants exhibited a looking preference. When carefully matched alterations were made to the figures that did not change implied 3D shape, infants did not exhibit a consistent looking preference. These preferential looking studies suggest that infants are sensitive to shading and line-intersection depth cues as early as 3 months of age, well before it influences their preferential reaching at 7 months.
4.3 Interpreting the Meaning of Reaching-Specific Delays in Development

Research on both object permanence and depth perception suggest a delayed pattern of development for infant reaching relative to infant looking. While this pattern of results is consistent with the notion that infants engage different knowledge systems for reaching and looking tasks, there is an alternative explanation based on task difficulty. Reaching may simply be a more difficult task than looking.

A similar challenge has been present in reasoning about loss of cognitive function associated with brain injury (Shallice, 1988). Consider a patient who suffers damage to a region of the inferior temporal cortex (area IT) and thereafter is unable to recognize faces. The patient retains the ability to recognize everyday objects, but not faces. Are face and object recognitions mediated by different information processing systems? Perhaps, but there is an alternative interpretation possible that is analogous to the present comparison of looking and reaching behaviors. Perhaps distinguishing different categories of objects is easier than distinguishing individual faces. Faces are typically very similar to one another, with the same features in approximately the same configuration. Perhaps face and object recognitions are computed by a common network of brain regions rather than two separate systems, and area IT is a part of this common network. If the system still functions, but at a reduced level of ability, then it may retain the ability to perform simple tasks, while losing the ability to perform those that are more difficult. Indeed, the reasoning about the role that the “fusiform face area” plays in recognition of configural, nonface stimuli has been a subject of much research (e.g., Gauthier, Skudlarski, Gore, & Anderson, 2000).

In developing theories of cognitive structure, neurologists typically reason on the basis of more than one patient with more than one pattern of injury and associated deficits (but see Vishton, 2005). In the current example, if a second patient could be identified, who retained the ability to recognize faces while losing the ability to recognize objects after suffering an injury to a different part of the brain, then a “double dissociation” would be found. Such double dissociations cannot be easily explained on the basis of task difficulty: recognizing faces cannot be both harder and easier than recognizing objects.

To argue for the existence of different knowledge systems for reaching and looking behaviors in infants, an analogous dissociation is needed. This
section has identified several cases in which infant looking outperforms infant reaching in terms of adult-like reasoning. In the next section, I will argue that infants are sometimes more adult-like in their reaching than in their looking.

5. EVIDENCE FOR DISTINCT DEVELOPMENT OF REACHING AND LOOKING BEHAVIORS

Some research has suggested that reaching and looking behaviors are governed by distinct information processing systems. The patterns of results suggest that when infants are engaged in a reaching task, they are less influenced by some sources of visual information and more influenced by others. Reaching infants do not seem to know less than infants in a VOE task; they seem to know different things.

5.1 Object Boundary/Gestalt Perception

An extensive series of studies has explored how infants parse their visual input—how they determine where object boundaries are located, and how they decide when two different parts of a display are connected. Often this has been referred to as Gestalt perception, in that it explores how infants group separate stimuli into perceptual units. Kellman and Spelke (1983) presented 4-month-old infants with a display that consisted of a central occluder and two protruding rod parts. If the edges of the two rod pieces are aligned, with the same color and surface features, most adults perceive them as a single object placed behind an occluder. Four-month-olds only seem to perceive the display in this way if the two parts are shown moving together in unison (i.e., exhibiting common motion). Additional work has shown that after habituation to a similar display, 2-month-olds exhibited the opposite preference (Johnson & Aslin, 1995), suggesting that this “perceptual completion” ability emerges between 2 and 4 months of age.

When Kellman and Spelke (1983) presented these same displays without the common motion of the visible rod pieces, the preference for the split rod did not emerge. Common motion seems essential to perceptual completion for 4-month-olds. In a subsequent experiment, in which common motion was present but the two visible parts of the display differed in color and shape, infants still looked longer at a split display than at a connected object. Later studies have found that edge alignment and relative proximity also influence perceptual completion. If the top and bottom figures are substantially misaligned or if the central occluder separates the visible rod pieces
by too much distance, then the preference for the split display does not emerge (Johnson & Aslin, 1995, 1996; Smith, Johnson, & Spelke, 2003). In all cases, however, motion information seems to play a primary role in perceptual completion with these displays.

Needham and Baillargeon (Needham, 1999; Needham & Baillargeon, 1997) explored infant perception of object boundaries based on how participants looked at “move-apart” and “move-together” events. In general, they presented displays that could have consisted of a single, connected object or two separate, adjacent objects. After presenting a display to infants and allowing them to look at it for several seconds, a hand emerged from the side, grasped one part of the display and pulled it to the side. In some cases, the entire display would move—the move-together event. In others, only part of the display would move, whereas the other part would remain stationary—the move-apart event. If an infant perceived the initial display as a single, connected object, then they should have expected the move-together event. The move-apart event should therefore generate a VOE and longer looking time as compared with the move-together event. Conversely, if the infant perceived the initial display as two separate, adjacent parts, then the move-together event should result in longer looking times relative to the move-apart event. By exploring when infants of different ages exhibited these preferences, these researchers have explored how infants perceive, or fail to perceive, the presence of object boundaries.

Based on this method, 8-month-olds seem to rely on differences in shape and color to decide when two display parts are connected. When two adjacent display parts differed in shape and color, infants looked longer at the move-together event than at the move-apart event. If the two object parts were identical in shape and color, however, then it was the move-apart event that produced longer looking (Needham & Baillargeon, 1997). Eight-month-olds also make use of spatiotemporal information in this paradigm. Needham and Baillargeon (1997) presented infants with displays consisting of two adjacent pieces with identical color and shape. After a thin board was lowered between the two display parts and then removed, infants subsequently looked longer at the move-together event, suggesting that this board event caused infants to perceive the display as two separate objects. Infants also seem to make use of information about object support to parse visual inputs. If one display part is suspended above the presentation stage, and if that part is touching the other display part, adults infer that the two parts must be connected. (Otherwise the floating display part would have fallen down onto the stage.) Eight-month-olds seemed to
make this same inference after familiarization with a display constructed in
this manner, looking longer at a subsequent move-apart event (Needham
& Baillargeon, 1997).

Younger infants only make use of some of this information. With
4-month-olds, when two display parts differed in shape, infants looked
longer at the move-together event, suggesting they perceived the initial
display as consisting of two separate parts. A difference in color, however,
has not seemed sufficient to produce a perception of two separate objects
at this age (Needham, 1999a). In another study, when 4.5-month-old
infants were briefly familiarized with one object before it was placed adja-
cent to another, the memory of having seen the individual object was
sufficient to cause longer looking at the move-together event (Needham

The looking time studies conducted with the center-occluded rod and
with the move-apart and move-together events suggest a largely consistent
pattern of development. Infants develop the ability to use nonmotion infor-
mation (e.g., shape and color) in isolation sometime between 4 and
6 months of age. Nonmotion information can influence the interpretation
of the motion information during this age range, but when spatiotemporal
or motion information suggests one parsing of the display while color and
shape information suggest another, it is the spatiotemporal or motion infor-
mation that determines infants’ perception.

Infant object-directed reaching across this age span suggests a different
use of these information sources. Vishton et al. (2005) presented 8- and
9-month-olds with long narrow displays consisting of two wooden blocks.
In the connected condition, the blocks were attached together to form one
object (16 cm wide, 2 cm in height and depth). In the split condition, the
two blocks sat next to one another, but were not connected. (Two 8-cm
blocks, placed adjacent to one another resulted in display that was identical
in appearance.) In the gap condition, a space of approximately 1 cm was left
between two slightly smaller display parts (approximately 7.5 cm wide),
resulting in a display of the same 16-cm width, but with a visible separation
between the two parts.

In these object-directed reaching studies, the experimenter held the
display block(s) with two hands, tapped the display part(s) against the table
surface, and allowed the infant to view it for several seconds. If the display
consisted of a single object, this presentation provided common motion
information. When the display consisted of two separate pieces (either the
adjacent or gap conditions), the two pieces were moved separately from
one another, providing separate motion information as well as a clear spatial separation between the two parts. Once the infant had viewed the display for several seconds, the experimenter would place the display (either one piece or the two parts) onto a marked position on a display board, which was immediately slid across the table to where the infant could reach out and grasp the display.

When the two display parts were of the same color, shape, and texture, and when experimenters showed the two display parts undergoing common motion, 8- and 9-month-olds tended to aim their one-handed reaches for the middle of the display. When experimenters showed a two-part display undergoing separate motion and/or when there was a visible gap left between the two display parts, these infants aimed their reaches away from the center of the display, closer to the display ends. These one-handed reaches directed away from the display center were perhaps aimed for the centers of one of the two display parts. Regardless, the infants’ pattern of reaching provides a clear indication of how they perceived the display. For a one-object display, one-handed reaches are directed near the middle of the object. For a two-object display, those reaches are significantly shifted away from the middle. Based on this, we can explore what information is necessary to generate a perception of object connectedness and separation.1

Whereas the 8- and 9-month-olds in the Vishton et al. (2005) study seemed to make use of visible separation or separate motion information to perceive an object boundary, when the same study was conducted with 6- and 7-month-olds, a different pattern emerged. With the connected display, reaches were again directed near the middle. If a visible gap was left between the two parts of the display, reaches away from the center were frequent. These two results were similar to what was found with 8- and 9-month-olds. In the split condition, however, when the two display parts were moved separately and then placed adjacent to one another, the 6- and 7-month-olds reached for the center of the display in approximately the same way they did with the connected display. It was as if, in the 5 s

1 It is worth noting that this result applies with these particular display dimensions and participant ages. In a separate study, which made use of larger displays and older children, a different pattern of reaching emerged (Needham, 1999b). In that study, after handling a 24 × 3 × 3 cm single-object display, 9.5- and 12.5-month-old participants tended to use one hand as in the Vishton et al. (2005) study. However, if the participants instead handled two separate 12 × 3 × 3 cm display parts, then when the experimenters later placed them adjacent to one another, 12.5-month-olds commonly made two-handed reaches, making contact near the ends of the display, away from the center. No such shift between one- and two-handed reaching was found in the Vishton et al. study.
between the separate motion presentation and the onset of the reach, the 6- and 7-month-olds forgot that there were two separate parts and treated the display as a single, connected object.

Vishton et al. (2005) also conducted a looking time, VOE study with these displays using the move-apart versus move-together method. When infants were shown separate motion, they looked longer at the move-together event than at the move-apart event. How many objects did infants perceive to be present in the split motion condition? When the experimenters asked the infants using reaching, the answer was one object; when they asked the infants using looking-time behaviors, the answer was two.

Thus far, the Vishton et al. (2005) results are similar to other findings suggesting more advanced performance in looking than in reaching studies. For looking purposes, it seems that 6- and 7-month-olds remember the composition of a display longer than they can for reaching purposes. An additional experiment with 6- and 7-month-olds suggests something different, however. Vishton et al. conducted a version of their reaching experiment using a display constructed from two blocks that differed in color and shape—a blue rectilinear block and a red cylinder. The 6- and 7-month-olds consistently reached away from the center of the displays, regardless of what spatiotemporal information was presented. Even if common motion information presented by the experimenter indicated that the display consisted of a single, connected object, the infants still reached away from the center.

No looking time study was conducted with these stimuli with the shape and color differences, but the predictions from the looking time, VOE literature seem clear. When common motion, spatiotemporal information indicates that two display parts are connected, even if there is a difference in color and shape, we would expect that infants would perceive a single, connected object. Infants would be expected to look longer at a split display, as in the center-occluded object studies. Infants would also be expected to look longer at the move-apart event. Nonetheless, their reaching indicates a perception of two separate display parts.

In VOE studies, many factors influence infants’ perception of object boundaries. Across several studies, motion and spatiotemporal information seemed to be the most powerful influences. If two display parts move together, infants tend to perceive them as connected. Infants seem to perceive the two display parts as not connected if the following conditions hold: (1) the two display parts move separately, (2) one part is presented in isolation, (3) a visible gap is present between two parts, or (4) a thin board is inserted between them.
In the Vishton et al. (2005) reaching study, infants were sensitive to motion information, but shape and color exerted a stronger influence. This pattern of results is difficult to interpret without suggesting a different process of object boundary perception for infants engaged in looking versus reaching tasks. The result is consistent with the adult studies of Vishton et al. (2007) that suggest engaging in a reaching behavior changes the nature of human perception, rendering certain sources of information (i.e., shape and/or color) more salient, whereas rendering other sources (i.e., motion) less salient.

Kaufman, Mareschal, and Johnson (2003) presented a similar argument, based on a review of looking time, VOE studies. The center-occluded object studies suggested that motion information was the primary and perhaps only source of information that influenced infant object boundary perception. No effects of shape or color similarity have been identified in that line of research. For instance, when the top and bottom portions of the center-occluded object greatly differed in shape and color, common motion information still inspired longer looking in the split object test trials.

In the studies of the move-apart versus move-together events, however, several results have suggested that shape and color differences do influence infant object boundary perception. Kaufman et al. (2003) argued that this may be due to different sizes of stimuli typically used in these two lines of research. The objects used in the move-apart versus move-together studies reviewed here were quite large (approximately 30 × 10 × 10 cm), whereas the rod parts of the center-occluded rod displays were only about 1.3 cm in diameter. The large objects were ungraspable by young infants, whereas the small rod would have been graspable. Perhaps for stimuli that afford a grasping action, a different set of brain systems became more active. This difference could then have resulted in selective encoding or weighting of different sources of display information as different segments of the visual cortex were used (e.g., Milner & Goodale, 2006).

The Vishton et al. (2005) stimuli were all graspable. In some procedures, grasping was encouraged. In the looking time studies, the objects were presented slightly beyond the infants’ reach. Perhaps these differences resulted in a shift in the pattern of neural activation such as that proposed by Kaufman et al. (2003). Vishton et al. did not vary color and shape separately, but it would be reasonable to expect that information sources that are more important for grasping (i.e., shape) would exert a greater effect than those that do not (i.e., color).
5.2 Comparing Different Aspects of the Same Action

Studies of infant reaching have produced results that are not easy to predict based on existing studies of infant looking. Up to this point, I have contrasted experiments that involve only looking or reaching. Some of the most compelling evidence that different actions inspire different information processing comes, however, from examining different aspects of the same action. When an infant engages in a particular action, one aspect of the action suggests one pattern of perception and cognition, whereas another aspect of the same action suggests a different pattern of perception and cognition. This is true in some cases with the same display and the same infant at nearly the same moment in time.

Berthier et al. (2001) presented a set of experiments exploring how 9-month-olds visually track and catch a ball as it rolls past them. To succeed at this task, infants cannot reach for the current location of the target object, but must be “prospective” or “future-oriented” in their action control. They must reach ahead of the object, along its path of future motion, so that the hand and the object arrive at some place at the same moment in time. If the path of a rolling ball is unobstructed and fully visible, even 4-month-olds are capable of succeeding at this task (von Hofsten, 1983).

Berthier et al. (2001) placed an occluder panel between the infants and the path of the ball. This occluder blocked the infant’s view of approximately 13 cm of the ball’s horizontal motion as it approached. Infants were still effective at catching the ball in this situation. For some conditions of the experiment, the infant watched as an experimenter placed a barrier along the path that the ball would travel. The barrier was placed behind the occluder and was tall enough that it could still be seen protruding above it. When the barrier was in place, it would always stop the ball; the ball would disappear behind the occluder and not reemerge on the other side. Although the frequency of infant reaches during these barrier trials declined substantially, infants still made frequent reaches in the barrier condition (44% of trials). Moreover, the timing and general kinematics of these reaches were virtually identical to those observed when the barrier was not present.

Taken together, these two distinct measures suggest the presence of different systems of knowledge guiding two different aspects of the same object-directed reaching behavior. The infants’ choice of whether to reach was influenced by the presence of the barrier, but when the infant did choose to reach, another system was engaged. This action implementation system considered the location and velocity of the ball, but not the presence
of obstacles along the path of the motion. This implementation system does not seem to know about principles of solidity and cohesion.

A similar distinction in action choice and action implementation has been identified in 2-year-old children by DeLoache, Rosengren, and Uttal (2004), who were the first to characterize “scale errors.” After encouraging children to play with full-size versions of several toys for 15 min (e.g., a sliding board, chair, and child-sized car), these experimenters took participants for a short walk outside of the play area. While they were out of the room, other experimenters removed the full-sized toys and replaced them with miniature replicas. In the subsequent play session with the miniature toys, about half of the children produced at least one behavior in which they attempted to use the miniatures in the same way that they had used the full-sized toys. For instance, a child might try to climb into the tiny car or slide down the tiny sliding board. These actions were always unsuccessful, as the objects were far too small to support the chosen behaviors.

When watching the children perform these scale error behaviors, however, it is clear that they mentally register the actual size of the targets. When they pick up the tiny car, they do not reach for it with two hands, spread far apart as they would have with the full-size car. Instead, they make a well-coordinated, one-handed reach with the fingers scaled to the approximate size of the toy. In terms of the choice of what actions to perform, children seem to sometimes ignore the sizes of objects. The implementation of these chosen actions, however, seems to engage a different system of knowledge that clearly does consider object size.

An analogous pattern has occasionally been suggested in the A-not-B domain as well. Some infants have been reported to reach to an incorrect location while simultaneously looking at the correct location. This has not been carefully documented, but such a result would parallel the pattern observed in the Berthier et al. (2001) and DeLoache, Uttal, and Rosengren (2004) studies. Different systems of knowledge may operate at different times (e.g., Vishton et al., 2007), but in at least some instances, they seem to be activated simultaneously and operate in parallel within the same infant brain.

6. DIFFERENCES BETWEEN ACTIONS OTHER THAN LOOKING AND REACHING

Comparisons of infant looking and reaching behaviors suggest the presence of different systems of knowledge, but these are not the only pairs
of behaviors that have shown this pattern. Between 4 and 7 months of age, infants typically learn to sit independently and thereafter learn about their environment from this posture. Between 6 and 10 months of age, infants typically learn to shift onto their bellies and crawl. When they do so, it seems that they forget some of the things they had clearly learned while in that sitting position. When they return to a sitting posture, however, the knowledge returns. When they stand up and walk several months later, they again seem to need to relearn for this new behavior (Adolph & Joh, 2009). There is a surprising lack of generalization of knowledge across these different postures and actions.

This line of thought is closely associated with Karen Adolph and her collaborators, who have studied how infant motor development affects their action choices. In one study, 9-month-olds were seated on the edge of a support surface, with an attractive target suspended some distance in front of them. If the target was close, the infants would lean forward, reach out, and grasp it. When the target was located too far away, engaging in a sufficient forward lean and reach would cause the infant to fall forward, off of the support surface (Adolph, 2000). (Experimenters would gently catch the infant to prevent injury in this case.) After presenting a series of trials to identify the maximum distance at which the infant could successfully retrieve an object, the experimenter would present a randomized series of test trials with the object located at a safe distance, near the maximum distance limit, and beyond the limit. These 9-month-olds had an average of 104 days of sitting experience prior to the study. They responded to these test trials very appropriately. When the object was close enough, a reaching action was very likely. When the object was too far, infants only rarely attempted a reach (Adolph, 2000).

These same infants also participated in the same set of tasks while in a crawling posture at the edge of the same table. The experimenters again determined the distance limit for the child to reach away from the support surface and obtain the object without falling. Test trials were then administered around this limit. These same infants who had been so accurate in the seated version of the task were surprisingly bad at the task when performing it from the crawling posture. They often fell off of the table and showed very little improvement over the course of the study. The infants were all relatively inexperienced with crawling (average of 45 days). Even though the apparatus and task were essentially the same, when a different task posture was adopted, the infants seemed to have lost the ability to recognize a situation that would produce a fall (Adolph, 2000).
This pattern has emerged from studies of other pairs of motor behaviors. Kretch and Adolph (2013) constructed an apparatus with an adjustable height “cliff.” When the cliff was low, it was easy for crawling or walking infants to move from the upper to lower platforms. When the cliff was adjusted to be higher, the infants could not descend without falling. (Again, the infants were gently caught to prevent injury whenever they tried to descend.) Novice crawlers were very error prone, producing many falls. Experienced crawlers learned to perceive when the step could be safely descended and when it should be avoided. When the infants started to walk, however, this learning process had to be repeated, seemingly from scratch. As with the reaching study, simply changing the posture of the infant seems to change their knowledge about affordances in their surroundings.

Adolph (1995) found the same pattern of results with an adjustable sloped walkway. If you ask an infant whether a slope is too steep to safely traverse, his/her answer depends on his/her current postural state. An experienced crawler who is a novice at walking will safely avoid falling down a steep slope when crawling. When that same infant stands up, however, he/she will fall down a slope that is too steep to even have been traversed while crawling. All of this work builds on extensive studies of infants crawling on a fixed-height visual cliff that was covered with a sturdy piece of transparent glass to prevent falls (e.g., Bertenthal, Campos, & Kermoian, 1994; Gibson & Walk, 1960).

Adolph and Joh (2009) describe these findings in terms of “learning sets” (after Harlow, 1949). According to this theory, infants fail to generalize from crawling to walking tasks because the physical constraints that govern the two tasks are very different. Both crawling and walking are means of locomotion achieved by exertion of the body, but there are few other similarities. The balance demands are different when on four versus two limbs. The resting and starting positions of the limbs are different. The muscle groups and the ways in which those muscle groups are activated to create movement are very different. And, of course, the structure of affordances is different. How big does a gap need to be to afford passing through it? What is the maximum height of a vertical step before it cannot be traversed? How many toys can be carried without hindering successful forward movement? Given all of these differences, it seems quite sensible that different, largely independent learning processes would take place for the two different types of actions. Those independent learning processes may result in two distinct sets of knowledge that are accessed whenever the child prepares to perform a particular action.
A great deal of research has been directed at characterizing what infants know and do not know at different points in their development. If our exploration of this topic focuses on only one behavior, such as looking, then the results of that research might be summarized as an ordered list, specifying the ages at which infants first develop an understanding of various principles that govern the world around them. When studies of other behaviors, such as reaching, are considered, however, the results become more complex. In many cases, such as those summarized here, the study of particular action behaviors seems to suggest that different systems of knowledge mediate various behaviors. Looking is only one of many behaviors.

To be sure, some studies have found close agreement between reaching and looking measures. Many other studies have simply found that reaching behaviors lag behind looking in their apparent development, perhaps because reaching is more difficult to perform, and thus more likely to distract study participants. A growing number of studies, however, do not fit well into either of these categories. Reaching performance is not worse than looking performance, but it instead seems to function according to different knowledge and inherent information processing.

When considered in the context of studies of adult perception, cognition, and action, the presence of action-specific perceptual and cognitive processes is not surprising. Different human behaviors are mediated by an enormously complex set of neural subsystems. Many of these subsystems are specifically associated with the performance of particular action behaviors. If knowledge is a property that emerges from brain activity, and if different parts of the brain are associated with different tasks, it would be surprising if there were no different knowledge systems associated with different behaviors.

If different action systems are mediated by distinct systems of knowledge in infancy, how should developmental science account for it? First, it seems clear that our theories should consider not just what infants seem to know or what principles form the foundations of infant cognition and perception. Rather the theories should account for infant knowledge and foundations on an action-by-action basis. Some principles might be found to govern all behaviors, but that is an inherently empirical question.

It is typically not difficult to develop a reaching-based study to assess any question that might be addressed using looking, VOE measures. The only
clear exception is for the study of development prior to 4 months of age, when infants are typically not able to control successful object-directed reaching behaviors. If the results of the reaching experiment match those of a looking-time study, then a powerful piece of convergent evidence is obtained. If the results of the reaching experiment differ from those of the looking study, there is no cause for alarm. Indeed, it is the comparisons of reaching and looking performance in cases where the results diverge that are potentially the most interesting.

Some of the most exciting action-based research has suggested ways in which action development may influence the knowledge that guides looking performance. For instance, Sommerville, Woodward, and Needham (2005) habituated 3-month-olds to a display consisting of two objects, placed on two different platforms (e.g., a toy bear and a ball). Infants watched a hand reach in from the side of the display and grasp one of the objects (e.g., the ball). Once infants were familiar with this repeated event, test trials were conducted in which the positions of the objects were switched from one platform to the other. On alternate test trials, infants saw the hand either reach for the same location (i.e., a different object) or the same object (i.e., in a different location).

Woodward (1998) had previously found that 6-month-olds, but not 5-month-olds, look longer at the test trials in which the hand grasps a different object. She interpreted this result as suggesting that infants in this age range are developing intuitions about other humans having preferences and intentions. Even if the hand changes its path of motion, moving to a different end location in the display, this does not generate as much of a VOE as a human changing his/her intention. At no point in that earlier research was there a hint that 3-month-olds should produce this pattern of results.

Sommerville et al. (2005) tested whether accelerating infants’ reaching experience would lead to enhanced performance in the hand intention task. This work was based on earlier work in which prereaching 3-month-olds were given experience with Velcro “sticky mittens” (Needham, Barrett, & Peterman, 2002). One part of the Velcro was sewn onto the mittens, whereas the corresponding side was attached to toys. When infants played with these, they were able to make contact with the toys and cause them to adhere to the mittens. As such, they were able to lift and manipulate the object several weeks before they would typically have been able to. Half of the 3-month-olds in the Sommerville et al. (2005) study were given experience with the sticky mittens, whereas the others were not. Even after
only 200 s of sticky mitten experience, 3-month-olds performed like 6-month-olds on the hand intention task. The 3-month-olds who did not have the sticky mitten experience exhibited a significantly less adult-like interpretation of the displays.

Action may not only be driven by different systems of knowledge but also may create them. Indeed, the development of knowledge itself may be driven by the development of action abilities (e.g., Gibson, 1969). Most researchers think of the brains of young infants as being less capable than those of older infants. Studies of infant perception and cognition certainly support this assertion. While this may be true to some extent, it may alternatively be the smaller action repertoire of young infants that drives these findings. I have argued that an understanding of infant knowledge development can only be achieved by considering how the knowledge changes in the context of different actions. Based on results such as these, it seems increasingly likely that an understanding of infant action development may provide the most direct path to understanding infant knowledge itself.

This chapter has argued for the presence of distinct, action-specific systems of knowledge in infancy. As research in this area progresses, however, it may be that the term infant “knowledge” should be abandoned, or at least defined more carefully. The term knowledge implies a set of facts, skills, and/or principles that are possessed by someone. Knowledge, as we usually conceive of it, is inherently task- and context-general. The idea that someone could “know” something at one moment in time, then not know it a few seconds later, and then know it again a few seconds after that violates the typical definition of the term.

For early research in this area, based largely on a single behavioral measure, the term was sensible. Indeed, as long as a single, coherent set of principles could be used to predict infant behaviors at different ages, those principles could be appropriately described as infant knowledge. As an increasing body of findings suggests the presence of context- and action-specific principles of perception and cognition, however, the use of the term has become increasingly problematic.

Rather than asking what infants know and when they know it, a more precise theoretical language seems appropriate. Developmental experiments can characterize the information processing of infants in a particular context, detailing what information is picked up and how that information influences infants’ behaviors. The computations and inferences that take place between the perception and action control can be characterized. Additional studies
can test and refine those characterizations. As infants develop, the changes in these perception and action processes can be described. Certainly infants know things, but that knowledge seems to be an outcome rather than a starting point for infant behavior. Knowledge seems not to be a static representation in the head, but rather the outcome of an emergent process that brings together many aspects of perceptual, cognitive, and motor functioning.

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REFERENCES


**FURTHER READING**


