SOCIAL PERCEPTION

Detection and Interpretation of Animacy, Agency, and Intention

edited by M. D. Rutherford and Valerie A. Kuhlmeier

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16 Online Action Analysis: Infants' Anticipation of Others' Intentional Actions

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Abstract

The ability to understand others' actions as intentional is a critical foundation for human social functioning. Equally critical is the ability to recruit this knowledge rapidly in the course of social interactions to generate online predictions about others' actions. Recent experiments have recruited eye-tracking methods to investigate infants' visual anticipation of others' actions. In this chapter, we consider this newly emerging literature in the context of the larger existing body of work that has principally used visual habituation methods to investigate infants' offline action understanding. This older body of work has shown that infants have relatively rich and generative knowledge about others' intentional actions and that this knowledge is structured, at least in part, by infants' own action experience. We consider whether infants' online anticipation of others' actions recruits this body of knowledge and conclude that although there is initial evidence to indicate that it does, many questions are yet to be answered.

Fundamental to human experience is the perception that we live in a world of intentional agents. We see others' actions not as purely physical movements, but rather as movements that are structured by intentions. This social worldview is pervasive in adults' memory for, reasoning about, and communication of event information, and it has ontogenetic roots early in life. Studies reviewed in this chapter inform us that infants, well before their first birthdays, see others' actions as structured by intentions. In adults, this analysis of others' intentions occurs rapidly and automatically, and it can play a critical role in guiding online social reasoning, allowing interpretations of actions to be informed by what has come before and supporting predictions about others' future actions. The ability to rapidly analyze and anticipate others' intentional actions is essential for engagement in collaborative activities, competition with social partners, communication, and, more generally, the coordination of one's own actions with those of others. Even a simple social response, such as avoiding passersby on a crowded sidewalk, requires that we monitor behavioral indicators of others' intended paths (e.g., gaze direction and shifts in posture) so that we can respond quickly and appropriately to them. More extended social interactions, such as working with someone to prepare a meal, or exchanging information during a conversation, require that this rapid prospective reasoning operate iteratively, updating predictions as the interaction unfolds.

In this chapter we will consider the early ontogeny of this ability. Specifically, we will ask when and whether infants are able to use their understanding of others' intentions to (1) generate predictions about others' next actions and (2) do so in the timescale required to implement this analysis in interactions with others. Recent advances in the use of eye-tracking paradigms in studies with infants have provided initial evidence about infants' visual anticipation of others' actions. Using this approach, several recent studies have investigated infants' ability to use what they know about intentional action to generate predictions, in the moment, about others' subsequent actions. We will review emerging findings that bear on this question, consider the initial conclusions they support, and lay out the questions that will focus future investigations. To frame this review, we begin by briefly summarizing a body of findings that elucidates infants' understanding of others' intentional actions. We then turn to the question of whether and when infants recruit this knowledge in their online responses to others' actions.

Infants' Understanding of Intentional Action

A great deal of research has shown that the propensity to view others' actions as goal directed emerges early in life. In particular, experiments using looking-time paradigms have shown that infants represent others' actions as directed at goals and objects of attention rather than as purely physical movements. To illustrate, when infants are habituated to a goal-directed action (e.g., a person reaching toward and grasping a toy), they subsequently show a stronger novelty response (i.e., longer looking) for test events that alter the goal of the action than they do for test events that preserve the goal while varying the physical properties of the action (e.g., Bíró & Leslie, 2007; Brandone & Wellman, 2009; Luo, 2011, this volume; Woodward, 1998; Woodward et al., 2009). Infants respond selectively to goal changes involving simple, instrumental actions, like reaching, by three to six months (Bíró & Leslie, 2007; Woodward, 1998; Gerson

& Woodward, in press; Luo, 2011; this volume; Sommerville, Woodward, & Needham, 2005). Infants show this sensitivity to others' goals with their hands as well as with their eyes: On viewing an adult who produces a goal-directed action, such as reaching for a toy, seven-month-old infants selectively reproduce the adult's goal, reaching for the same toy (Mahajan & Woodward, 2009).

Critically, infants do not show selective attention to goals when the moving entity being observed is not readily identified as an agent (Hofer et al., 2005; Woodward, 1998) or when the action is ambiguous (Woodward, 1999). For example, when infants see an inanimate claw move toward and contact a toy, they do not respond by looking selectively longer at goal changes (Woodward, 1998) or reproducing the claw's goal (Gerson & Woodward, 2012). Similarly, when infants view human movements that seem accidental or ambiguous, such as contacting an object with the back of the hand, they do not respond as if the event were goal directed (Hamlin et al., 2008; Woodward, 1999). The movements of claws and inert hands toward objects lead infants to attend to the contacted object, just as they attend to the objects at which goal-directed actions are directed (see, e.g., Gerson & Woodward, 2012; Hamlin et al., 2008; Woodward, 1998; 1999); nevertheless, infants represent the movements of claws and inert hands differently from the ways they represent goal-directed actions. Thus, infants' responses to goal changes are not readily explained by lower-level factors such as the association between the agent and the object or the way the action draws attention to the object.

Infants' action knowledge also reflects the higher-order plans that organize assemblies of actions. One way that this is evident is in infants' reasoning about means-end actions, in which a person's actions on an intermediary or tool are directed at the attainment of a downstream goal. By nine-to-twelve months of age, infants understand the actions on the tool as directed toward the ultimate goal, rather than at the tool itself (Woodward & Sommerville, 2000; Sommerville & Woodward, 2005). In addition, infants integrate information about a person's different actions over time and across contexts. For example, they can use a person's prior focus of attention to interpret his or her subsequent actions (e.g., Phillips et al., 2002; Vaish & Woodward, 2010; Luo & Baillargeon, 2007), and they use information about a person's preference in one context to interpret his or her actions in a new context (Sommerville & Crane, 2009). Infants also engage in this kind of integrative reasoning when viewing the complementary, collaborative actions of two individuals. They understand that although the specific actions of the two people differ, their goal is the same

(Henderson & Woodward, 2011). These integrative, plan-level aspects of infant action knowledge support inferences about novel actions. For example, although infants do not spontaneously view the movements of a mechanical claw as being goal directed, they do so when they are shown a person using the claw who is coordinating visual attention with the claw's movements in order to act on objects (Hofer, Hauf, & Aschersleben, 2005; cf. Gerson & Woodward, 2012).

Both the action-level and plan-level aspects of infants' intentional action knowledge have been linked to developments in infants' own actions. Infants begin to show sensitivity to the intentional structure of specific actions at the same time that the actions are emerging in their own productive repertoires, and developments in the two kinds of abilities are correlated (Brune & Woodward, 2007; Woodward & Guajardo, 2002). Similarly, infants' understanding of the means-end structure of others' actions correlates with their own ability to produce means-end actions (Sommerville & Woodward, 2005). Moreover, interventions that alter infants' individual and means-end actions affect their understanding of those actions in others (Gerson & Woodward, in press; Sommerville et al., 2008; Sommerville et al., 2005), and active engagement in actions influences infants' subsequent action understanding in ways that simply watching others produce an action does not (Gerson & Woodward, 2012; Sommerville et al., 2008).

These findings indicate that the representations that structure infants' own actions play a role in supporting their understanding of others' actions. That is, these findings suggest that infants' action representations are *embodied* in the sense, described by Wilson (2002), of being "mental structures that originally evolved for perception or action [that are] co-opted and run ... decoupled from the physical inputs and outputs that were their original purpose, to assist in thinking and knowing" (p. 633). This conclusion is consistent with a number of recent theories about the embodied nature of intentional action knowledge, both in its mature state (e.g., Gallese & Goldman, 1998; Rizzolatti & Craighero, 2004) and during early development (e.g., Hauf, this volume; Meltzoff, 2007; Gerson & Woodward, 2010).

Even so, the question of whether embodied action knowledge comprises all of what infants know about intentional action is not fully resolved. For example, in some cases, infants seem able to reason about events that do not involve human actions at all as if they were goal directed (e.g., Luo, 2011; Luo & Choi, this volume; Gergely & Csibra, 2003; Hamlin et al., 2008). Whether these responses reflect the generalization of embodied action representations to novel events or instead reflect a separate, "disembodied" set of conceptual representations is an open question. This issue aside, it is nevertheless clear that significant aspects of the knowledge infants bring to bear in making sense of others' actions are closely linked to their own experiences as agents.

Do Infants Generate Online Action Predictions?

The evidence reviewed in the previous section shows that infants have relatively rich and generative knowledge about intentional action. Do infants employ this knowledge to form predictions about others' actions? The evidence summarized so far cannot address this question. Although looking-time methods yield evidence about infants' cognitive representations, they often do not provide clear evidence as to whether infants have generated a prediction. To illustrate, consider the finding that, having been habituated to an action repeatedly directed at one object, infants look longer when the action is directed at a new object than at the same object (e.g., Woodward, 1998). One interpretation of this result is that infants expected the actor to continue to act on the same object, and thus their longer looking during goal-change trials indicates surprise when this expectation is violated. However, it is also possible that infants detect the goal change in test events without having first formed the expectation that the agent would maintain the same goal. That is, infants' responses in looking-time procedures could reflect post hoc detection of goal changes rather than prior expectations. The same concern applies to studies that evaluate infants' ability to relate an agent's actions at one time, such as looking at an object, to that agent's subsequent actions, such as grasping that object versus a different object (e.g., Phillips et al., 2002). Infants might have generated a prediction early in the event, based on the agent's visual attention toward the object. Alternatively, infants might have detected the inconsistency between the two actions by comparing them after the fact. Thus, although the findings of looking-time studies are consistent with the conclusion that infants form action predictions, these findings in themselves do not provide conclusive evidence that infants do so.

A second issue is that, from looking-time data alone, it is not clear whether infants can generate predictions on the time scale required by online social interactions like collaboration, competition, and communication. In looking-time studies, infants have repeated opportunities and relatively long time intervals to encode, analyze, and respond to the actions that they view. In a typical experiment, an infant may view the same action repeated as many as fourteen times and have an open-ended trial length (generally at least several seconds long) to observe and respond to each example. But using intentional analysis to inform real-time social interaction would require that infants generate predictions rapidly in the course of observing an action.

For these reasons, a different kind of evidence is needed, both in terms of requiring clearer evidence for infants' generation of predictions and in terms of the timescale of the response. Measures of infants' anticipatory gaze shifts offer such a method. Even very young infants generate predictive eye movements in response to ongoing events. For example, Haith, Canfield, and their colleagues (Canfield et al., 1997; Haith et al., 1988) documented that infants as young as three-and-a-half months of age can learn a regular sequences of light movements and move their eyes in anticipation of the next light in the sequence. In this case, infants' anticipatory gaze shifts reflected their learning about the novel light pattern over a number of trials (Wentworth & Haith, 1998). Other studies have shown that infants are also able to launch anticipatory gaze shifts based on predictions derived from a priori physical knowledge. To illustrate, when four- to six-month-old infants observe an object passing behind an occluder, they spontaneously anticipate the reemergence of the object on the other side. Further, they do so from the first trials in which they saw this event, thus indicating that this anticipation does not depend on infants' learning within the session that the object will reemerge (Johnson et al., 2003; von Hofsten et al., 2007). Instead, infants' anticipatory responses reflect their knowledge about physical objects and their possible patterns of movement.

The bodies of work outlined in the previous paragraph suggest at least two kinds of mechanisms by which infants could anticipate others' actions. First, drawing on general-purpose learning, infants may come to anticipate regular patterns in others' movements. For example, infants may learn to expect that hands holding phones end up near the ear or that hands holding cups end up near the mouth. In fact, by six months of age, infants show just these kinds of expectations by looking systematically to the body parts associated with familiar objects like phones and cups when these objects are held by people (Gredebäck & Melinder, 2010; Hunnius & Bekkering, 2010; Kochukhova & Gredebäck, 2010). Learning about predictable movement patterns can happen in the laboratory as well. For example, Paulus and colleagues (2011) found that, after viewing an agent who repeatedly took a circuitous path toward a goal, infants visually anticipated that the agent would continue to take the same path even when a more efficient path was available. These findings show that infants are able to extract information about patterns in other's movements and that this information supports their online visual predictions. Even so, these findings do not clarify whether infants recruit their analysis of others' intentions to derive these expectations.

A second means by which infants could generate predictions about others' actions is via their conceptual knowledge about intentional action. That is, infants could use the knowledge described in the first part of this chapter to generate action predictions independent of particular patterns of movement. Southgate and colleagues (2007) reported an elegant demonstration of this kind of anticipation in two-year-old children. Children viewed events in which a protagonist repeatedly retrieved an object that she saw hidden by a puppet in each of two boxes. Following a final hiding event, the protagonist turned away and the puppet removed the toy, taking it offstage. Then, the protagonist turned back toward the boxes as if to approach them and retrieve the toy. Children's visual responses to the event were measured using eye-tracking. Even though the object was no longer hidden in either box, children looked predictively toward the box in which the protagonist had last seen the object hidden. Because the protagonist had previously retrieved the toy from each of the boxes an equal number of times, children's anticipatory responses could not have reflected learning about the prior movements of the protagonist. Instead, children must have generated predictions based on an analysis of the protagonist's prior goals and states of attention (see Senju, Southgate, Snape, Leonard, & Csibra 2011 for similar findings with 18-month-old infants).

Infants' Action Anticipation

What about younger infants? As described above, infants less than half the age of Southgate and colleagues' (2007) subjects see others' actions as structured by intentions. Do infants implement this action analysis in their online predictions about others' actions? To date, this question has been addressed by evaluating infants' visual anticipation of concrete, manual actions, such as reaching for and grasping objects or moving objects from one location to another. Although these are highly familiar actions, there is evidence, from both adults and infants, to suggest that anticipatory responses in these studies reflect more than simply movement-based expectations.

Consider the event depicted in figure 16.1. A person reaches for each of three balls one at time, moving each one across a table and placing it

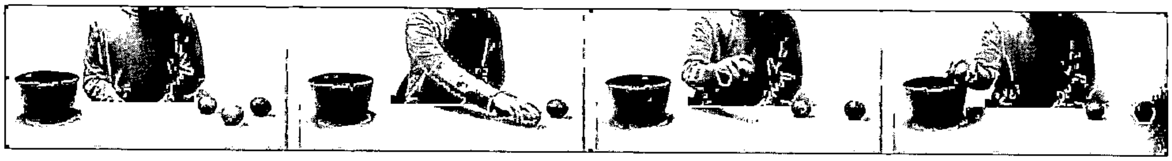

Figure 16.1
Stimulus events used by Cannon and colleagues (2012).

into a bucket. When adults and twelve-month-old infants view events like these, they spontaneously look to the bucket before the ball arrives (Cannon et al., 2012; Eshuis et al., 2009; Falck-Ytter et al., 2006). Although this response is generally assessed in experiments with repeated trials, adults and twelve-month-old infants show anticipation from the earliest trials onward, suggesting that the response does not depend on learning that takes place over trials (Cannon et al., 2012; Falck-Ytter et al., 2006; Flanagan & Johansson, 2003). Moreover, both infants and adults show more robust anticipation of the balls' arrival when a person was seen to move the balls (as in figure 16.1) as opposed to when the balls traversed the same path to the bucket apparently on their own (Falck-Ytter et al., 2006). Thus, infants and adults show heightened anticipation for intentional actions compared to matched movements that did not involve intentional actions.

Infants' anticipation of the endpoints of actions is also influenced by the presence of a goal. Gredebäck and colleagues (2009) found that fourteen-month-old infants showed strong anticipation when actions culminated in a salient goal (e.g., putting an object into a container). However, when infants viewed similar actions for which the goal was less salient (e.g., transporting an object to an unmarked location) or arm movements that followed the same path but did not involve moving an object, they did not show robust anticipation. Eshuis and colleagues (2009) report similar findings for adults.

Several studies report that infants younger than twelve months of age fail to show reliable action anticipation. For example, six-month-old infants tested with "bucket" events like the one depicted in figure 16.1 failed to look to the bucket before the ball's arrival (Falck-Ytter et al., 2006; see also Gredebäck et al., 2009). However, Kanakogi and Itakura (2011) recently reported that infants as young as six months of age are able to anticipate a simpler action—a reach toward an object. When viewing a reaching hand, infants shifted their gaze to the object before the hand arrived, but they did not shift attention to the toy as rapidly when viewing a mechanical claw that moved toward the toy or an ambiguous hand gesture that was directed at the toy. Thus, younger infants seem to show similar patterns of selective anticipation for goal-directed actions. Even so, Kanakogi and Itakura's (2011) findings also indicate that infants' anticipation became more robust between ages six and ten months, and that there were large differences in the timing of anticipatory gaze shifts between ten-month-olds and adults. Given the timing of the events and the magnitude of infants' anticipatory responses, six-month-olds likely shifted gaze to the toy only when the hand was quite close to it, in contrast to older infants and adults who shifted attention to the toy much earlier.

Taken together, these findings indicate that infants have a special propensity to anticipate goal-directed actions. Like adults, infants (1) look ahead to the endpoints of others' actions, (2) do so from the first experimental trials onward, and (3) show this response most robustly for actions of agents that are directed toward goals. To go back to the distinction we raised earlier, we can ask whether these findings show that infants' anticipatory responses reflect something more than learned movement regularities. On the one hand, infants' anticipatory responses seem to be tuned to goal-directed actions and seem not to reflect learning about the experimental events during the testing session. On the other hand, it seems possible that these anticipatory responses could reflect learned regularities from everyday experience—for example, when a container is present, hands tend to move objects to it—in much the same way that infants have learned that phones are held to the ear and cups to the mouth. Therefore, although they are suggestive, these findings do not resolve with certainty the question of whether infants generate anticipatory responses based on an analysis of an agent's goals.

Goal-Based Action Prediction in Infants

The principal paradigm that has been used to investigate action anticipation in both adults and infants demonstrates rapid online anticipation of others' actions, but ultimately leaves open the question of the nature of the cognitive representations that underlie these anticipatory responses. In the studies described in the previous section, the goal and pattern of movement were confounded: Infants always saw the same pattern of movement directed to the same goal. Thus, the results do not clarify whether infants anticipated the goal per se. Infants may anticipate regularities in movement but fail to predict that an agent will maintain the same goal despite changes in movements.

To distinguish goal-based action prediction from movement anticipation, we adapted the logic used in our prior visual-habituation studies. Eleven-month-old infants viewed events in which a hand reached for and

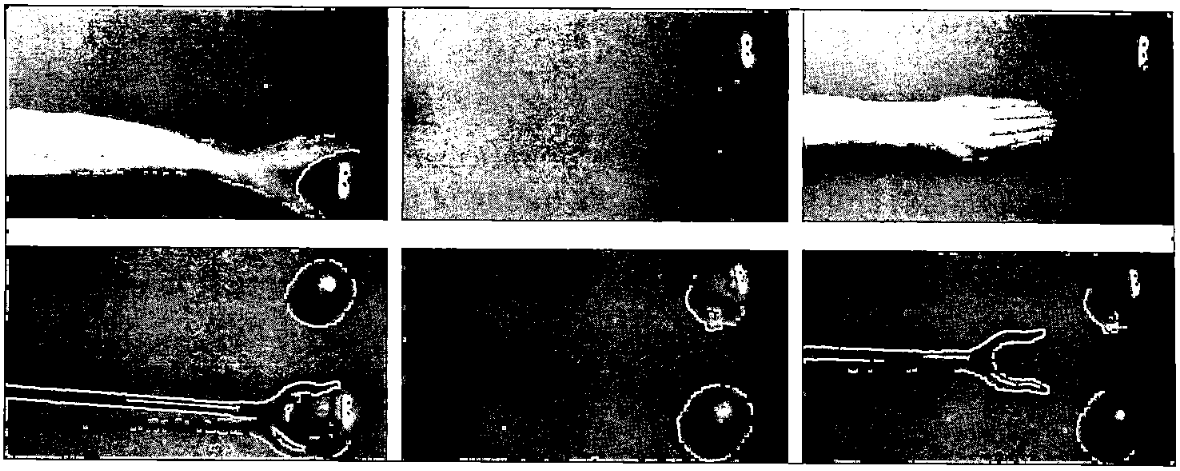

Figure 16.2
Events used in the hand (top row) and claw (bottom row) conditions in Cannon and Woodward (2012).

grasped one of two objects (see figure 16.2; Cannon & Woodward, 2012). Infants viewed three familiarization trials showing this event, each one two-and-a-half seconds in duration. Next, the positions of the objects were reversed and infants were given one trial to view the objects in their new locations. Then, in the test trial, infants saw the hand reach halfway across the stage and stop one-and-a-half second later, equidistant between the two objects. We evaluated whether infants launched an anticipatory saccade from the hand to one of the objects, and if so, whether they predicted that the hand would move to the same goal object or, instead, to the same location as it had previously. Infants generated predictive eye movements in most test trials, looking first to the hand region and then to one of the two toys. Critically, these saccades were systematically directed to the prior goal object rather than to the location that had been previously reached toward.

To evaluate whether this pattern of response was selective for goal-directed actions, we tested a second group of infants using events in which a mechanical claw moved toward and grasped the object (see figure 16.2). Prior studies have shown that infants do not spontaneously view events like these as being goal directed, although when additional cues to the goal-directedness of the action are present, infants can sometimes make use of them (Gerson & Woodward, 2012; Hofer et al., 2005; Woodward, 1998). Thus, the claw events provided a test of whether infants' attention would be drawn to the previously contacted object even when the events did not involve a goal-directed action. The findings indicated that infants' responses to the claw differed from responses to the hand. Infants in this condition showed an equal propensity to launch predictive eye movements during test trials as in the hand condition, but they systematically looked to the prior location rather than the prior goal-object.

Importantly, infants in the hand and claw conditions were equally attentive to the experimental events. They looked equally to the two objects and showed similar patterns of monitoring the movements of the claw and hand toward the object. Thus, the difference in their responses to hands and claws on test probes was not due to differences in overall attention to the events. These findings suggest that infants at this age generate at least two different kinds of predictions—goal-based predictions for the action of an agent and movement-based predictions for the motion of an inanimate object.

These findings indicate that by eleven months of age, conceptual analysis drives infants' predictions about others' actions. That is, the knowledge that is evident in looking-time studies seems to contribute to infants' rapid, online responses to others' actions. One obvious next question is whether younger infants generate such predictions. As reviewed earlier, infants demonstrate an understanding of actions as being goal directed as early as three-to-six months of age in looking-time procedures. One possibility is that infants' action knowledge is accessible to online prospective reasoning from the start. Infants at these ages recruit physical knowledge to predict the movements of inanimate objects, and so it seems possible that they would be similarly able to use social knowledge in this way. On the other hand, the recruiting of action knowledge to generate predictions may rely on later aspects of executive function, such as developments in working memory or attentional control, or on later aspects of social cognitive development. In this case, the findings of habituation experiments may reflect a more limited sensitivity, supporting the perception of action structure but not prospective social reasoning.

If there were a lag in the emergence of goal-based action prediction relative to earlier aspects of action knowledge, this could help to explain a developmental paradox: Looking-time studies tell us that younger (i.e., under twelve months of age) infants understand others' actions as goal-directed, and yet younger infants do not engage in many of the overt social behaviors that are generally taken to reflect an understanding others as intentional. For example, infants twelve months of age and older actively engage in collaborative and referential, communicative interactions with social partners, but these social behaviors are minimal or absent in younger infants. If younger infants possess limited abilities to generate goal-based action predictions, then this is exactly what would be expected. That is, younger infants may not be able to use what they know to generate the online anticipations needed to regulate these social interactions. Further studies are required to evaluate whether and how infants' action anticipation relates to their emerging competence in real-world social interactions.

A second question is whether infants' action anticipation goes beyond the understanding of isolated actions as being goal directed and reflects the knowledge of higher-order action plans that has been revealed in infant looking-time studies. In looking-time paradigms, infants integrate information about an agent's actions over time, using prior actions to interpret subsequent actions. This ability enables infants to interpret novel actions in the context of higher-order action plans. For example, this ability allows infants to understand the use of a novel tool as goal directed based on their seeing the tool use coordinated with an agent's other actions. Do infants engage in similar reasoning to modulate their online predictions about others actions? The findings of Southgate and colleagues (2007), described earlier, indicate that by two years of age, children generate predictions of this sort, such as predicting an agent's reaching actions based on her prior focus of attention. As yet, there have been no studies of this kind of predictive reasoning in younger infants.

Embodiment and Anticipation

As described earlier, prior research has documented a close relation between infants' emerging control of their own actions and their understanding of others' actions as measured in looking-time studies. Developments in infants' own actions correlate with developments in their action understanding, and training interventions that change infants' actions also influence their understanding of others' actions as goal directed. These findings suggest that infants' action representations are embodied, in the sense that they borrow structure from representations that guide action production. This possibility has particular significance for the question of whether and how infants anticipate others' goal-directed actions because action production is an inherently prospective process, requiring the generation and updating of predictions about one's actions as they occur (Rosenbaum et al., 2009; Wolpert et al., 2001). Actions are prospectively organized from early in infancy (von Hofsten, 2004), and this fact raises the possibility that embodied action representations could support infants' prospective attention to others' actions.

Indeed, several converging lines of evidence indicate that embodied action representations support action anticipation in adults. Visual attention to others' actions closely mirrors the anticipatory patterns that accompany one's own actions, suggesting that both kinds of anticipation may be driven by the same underlying mechanism (Flanagan & Johansson, 2003; Hauf, this volume). Further, when adults view a predictable action, electrophysiological activity associated with motor preparation occurs just before the observed action (Kilner et al., 2004). Recent studies from our laboratory have confirmed that motor processes play a functional role in adults' action anticipation. Specifically, we found that engaging in a concurrent action task disrupts anticipation of others' actions (Cannon & Woodward, 2008, in preparation). In these studies, adults viewed the events depicted in figure 16.1 while, in one condition, tapping four fingers on one hand in a scripted cascade pattern. This concurrent motor task significantly reduced adults' anticipation of the actions they viewed relative to baseline trials with no concurrent task and relative to a condition in which the concurrent task (a verbal working-memory task) was not motor in nature. Further, the finger-tapping task did not disrupt adults' anticipation of inanimate events (e.g., tracking a ball as it rolled behind an occluder), indicating a specific connection between action production and action anticipation.

If embodied action representations support infants' action anticipation, then developments that occur in infants' action control during the first years of life would be expected to have an effect on developments in their action anticipation. Falck-Ytter and colleagues' (2006) findings suggested this may be the case: Six-month-old infants tested in their procedure (anticipating actions in which balls are placed into a bucket) did not anticipate the action. The researchers speculated that, because infants at this age do not engage in containment actions, their lack of anticipation might reflect their lack of motor representation for that action. Gredebäck and Kochukhova (2010) conducted a more direct test of this possibility by assessing both action production and action anticipation in two-year-old children. They found that children's level of skill at placing pieces into a puzzle was correlated with their tendency to visually anticipate an adult's actions with the puzzle.

In a recent study (Cannon et al., 2012), we asked whether this relation could be traced to earlier in infancy by testing whether infants' own engagement in containment actions predicted their anticipation of others' actions with containers. Although most twelve-month-old infants are able to place objects into containers, there is variation in the extent to which they spontaneously do so. We assessed this individual variation by giving infants the opportunity to act on containers and small toys either before or after we assessed their action anticipation for the events depicted in figure 16.1. We found that when infants were given the opportunity to engage in containment actions prior to the observation task, their spontaneous level of activity when placing objects into containers predicted their subsequent tendency to anticipate the observed containment actions. The same relation did not hold when the action and perception tasks were given in the reverse order, suggesting that engaging in the actions had primed infants' subsequent anticipatory responses.

Kanakogi and Itakura (2011) report a similar correlation in six- to ten-month-old infants. As described earlier, they assessed infants' anticipation of events in which a hand moved toward and grasped one of two objects; they found that infants six months of age and older reliably anticipated the arrival of the hand at the object. They also assessed the quality of infants' own reaches by analyzing the extent to which infants reached toward a toy using just one hand. Infants tend to act bimanually earlier in development and later transition to more efficient, unimanual reaches. They found that this measure of reaching ability correlated with infants' visual anticipation of the reaching events independent of the effects of increasing age on visual anticipation. Further, on analogy with Kilner and colleagues (2004) findings in adults, Southgate and colleagues (2007) report that infants show electroencephalographic (EEG) activity associated with motor system activation when they view the initial stages of an event that includes a predictable, repeated reaching action (see also Nystrom, 2008; Marshall & Meltzoff, 2011).

Thus, findings from several laboratories suggest that for infants, as for adults, visual anticipation of others' actions draws on embodied action representations. However, further research is needed to fully evaluate this possibility: Unlike the studies with adults, all of the current evidence for infants' action anticipation derives from correlational studies, so it is not yet clear whether embodied representations play a functional role in infants' action anticipation. Our studies with adults have begun to move beyond documenting correlated activation to interventions that can test the causal effects of motor processes on action perception. It will be important to pursue this same strategy, using motor training or motor-interference manipulations, with infants.

A further open issue concerns the level at which embodied action representations support action anticipation. In these studies, as in much of the research reviewed earlier, the research design does not provide a clear test of whether the anticipatory responses were based on an analysis of action goals. Because these anticipation tasks confounded goal-based and movement-based regularities, it is not clear from these findings whether embodied representations contribute to movement-based or goal-based anticipations of others' actions. Either (or both) is possible. The prospective representations that guide action production reflect multiple levels of analysis—from the generation of specific movements to the higher-order plans that organize sequences of actions (Rosenbaum et al., 2009; Wolpert et al., 2001). This is true in infants as well as adults, as evidenced by the fact that infants, like adults, shape the first actions in a sequence with respect to the downstream goals toward which the sequence is directed (e.g., Claxton et al., 2003; von Hofsten, 2004). Thus there is, in principle, no reason why embodied action representations could not reflect both higher-order and lower-order aspects of action structure.

The findings from our finger-tapping studies (Cannon & Woodward, 2008, in preparation) suggest that, for adults, the relevant embodied representations reflect structure above the level of movement generation. For example, the interference effects declined as the finger-tapping sequence became automatized, suggesting it was the planning of components of motor performance, and not the generation of the finger movements per se, that mattered. In addition, concurrent motor activity interfered with the anticipation not only of specific body movements, but also with more abstract goal-directed events. Specifically, finger tapping interfered with the anticipation of tool-use events (e.g., a claw picking up a ball and placing it into a bucket) in which the presence of the agent could only be inferred; this interference effect was reduced by a manipulation that led participants to view the claw events as mechanical rather than generated by a person.

These findings with adults suggest that embodied action representations reflect action structure that is more abstract than specific motor movements, instead reflecting an analysis of movements as goal directed. However, further research is needed to evaluate the other levels at which embodied action representations may support action anticipation. For example, are the embodied representations that are involved in adults' anticipation of others' actions based on higher-order plans or prior states of attention?

The level at which embodied representations are involved in infants' action anticipation is an open question at this point. As we concluded earlier, aside from the findings of the goal-prediction study with eleven-month-olds (Cannon & Woodward, 2012), little is known about infants' ability to recruit goal information for the generation of action anticipations. More research is needed to evaluate when in development this ability emerges, as well as the extent to which infants can integrate action information to generate flexible online predictions. As this research moves forward, a second question will be whether and how embodied action representations are involved. One possibility is that we will find developmental change in the level at which embodied representations support infants' action anticipation. Over the course of their first two years, infants become able to form and implement progressively more abstract action plans that organize longer and more complex chains of actions. These developments in action control may have implications for infants' ability to anticipate actions structured by higher-order plans in others.

Conclusions

The development of infant eye-tracking paradigms has allowed researchers access to aspects of social cognitive development that were not easily studied in the past. In particular, these methods have given researchers a window into infants' rapid, online responses to others' intentional actions—an aspect of social information processing that is critical for engaging in well-structured social interactions. In recent years, a number of studies have employed these methods to investigate infants' prospective attention to others' actions. These studies have revealed that (1) infants, like adults, generate rapid anticipatory responses when viewing others' actions, and (2) this response is particularly robust for events that involve well-structured, goal-directed actions as compared to events that involve only the movements of objects or ambiguous human movements.

These findings raise a number of new questions. Our goal in this chapter has been to (1) articulate some of these questions, (2) consider the progress that has been made in addressing them, and (3) highlight the important issues that are still unresolved. The open questions center on two general issues. First, research over the past fifteen years has documented that infants possess rich and generative knowledge about intentional action. Is this knowledge recruited in infants' online action anticipation? Second, research with adults indicates that the visual anticipation of others' actions recruits representations involved in action production. That is, action anticipation is supported by embodied action representations. Is this also true of infants?

As we hope our review makes clear, the current literature offers preliminary affirmative answers to both of these questions. But a number of striking gaps remain in the empirical record. Most critically, these gaps concern the level of description of the representations that guide infants' action anticipation, and how this may change over early development. Infants represent others' actions not merely as movements through space, but as actions structured by goals, both at the level of individual actions and at the level of higher-order plans that structure groups of actions. Our findings in studies with eleven-month-olds indicate that this knowledge informs action predictions. However, as yet, we do not know when this connection is established in early development, and there is no evidence, in infants under the age of two years, for anticipation based on a plan-level analysis. It remains possible, therefore, that infants' action knowledge is not fully expressed in their online responses to others' actions until later points in development.

Further, there are reasons to suspect that the embodied nature of action knowledge may explain the engagement of this knowledge in infants' action anticipation, but, as yet, several links in the account are untested. There is evidence that connects both action-level and plan-level knowledge to developments in infants' own actions, suggesting that infants' embodied action knowledge reflects both levels of analysis. Further, evidence from studies with adults indicates that embodied action representations support the anticipation of goal-directed actions. But the only evidence that relates action production to action anticipation in infants is correlational, leaving open the question of whether embodied representations play a functional role in infants' action anticipation.

In pursuing these questions, an additional challenge is the likely possibility that the answers will change as early development unfolds. Infancy is a period of dramatic changes not only in social cognition, but also in motor competence. Prior research has made headway in uncovering relations between these domains of development, but considering these relations in the context of infants' active online responses to others' actions opens new questions and new possibilities.

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