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., Biró & 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 (Biró & Leslie, 2007; Woodward, 1998; Gerson & Woodward, in press; Luo, 2011; this & Needham, 2005). Infants show this sensitivity as well as with their eyes: On a goal-directed action, such as reaching I selectively reproduce the adult's goal, re & Woodward, 2009).

Critically, infants do not show selective monitoring entity being observed is not re et al., 2005; Woodward, 1998) or whereward, 1999. For example, when infants toward and contact a toy, they do not n at goal changes (Woodward, 1998) or & Woodward, 2012). Similarly, when it seem accidental or ambiguous, such as of the hand, they do not respond as if t et al., 2008; Woodward, 1999). The n toward objects lead infants to attend attend to the objects at which goal-di Gerson & Woodward, 2012; Hamlin et c nevertheless, infants represent the n differently from the ways they req infants' responses to goal changes are factors such as the association between way the action draws attention to th Infants' action knowledge also ref nize assemblies of actions. One way soning about means-end actions, intermediary or tool are directed at . By nine-to-twelve months of age, is tool as directed toward the ultima (Woodward & Sommerville, 2000; addtion, infants integrate informat over time and across contexts. For so focus of attention to interpret his c et al., 2002; Vaish & Woodward, 20 use information about a person's pr or her actions in a new context (So engage in this kind of integrative re tary, collaborative actions of tw although the specific actions of the
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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 & Balleine, 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
action representations to novel events: "embodied" set of conceptual represent issue aside, it is nevertheless clear that si infants bring to bear in making sense o to their own experiences as agents.

Do Infants Generate Online Action Pre

The evidence reviewed in the previou relatively rich and generative knowle infants employ this knowledge to form The evidence summarized so far c looking-time methods yield evidencations, they often do not provide clear generated a prediction. To illustrate, cc habituated to an action repeatedly c longer when the action is directed at i (e.g., Woodward, 1998). One interpn expected the actor to continue to act longer looking during goal-change tris tation is violated. However, it is also change in test events without having agent would maintain the same goal. time procedures could reflect post 1 than prior expectations. The same cc infants' ability to relate an agent's at an object, to that agent's subseq versus a different object (e.g., Phil generated a prediction early in the e tion toward the object. Alternativ inconsistency between the two acti Thus, although the findings of looki conclusion that infants form action selves do not provide conclusive ev

A second issue is that, from lo whether infants can generate prec online social interactions like collat ion. In looking-time studies, infan tively long time intervals to encoc that they view. In a typical experim
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 they 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 sequence 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 (Johnsson 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. Extract information about information supports their feelings do not clarify whether actions to derive these expect.

A second means by which others’ actions are via their cognition. That is, infants could use this chapter to generate action of movement. Southgate’s demonstration of this kind of viewed events in which a she saw hidden by a puppet event, the protagonist turn it offstage. Then, the protagonist approach them and retrieve event were measured using a longer hidden in either b in which the protagonist has prior equal number of times, reflected learning about children must have gene
tagonist’s prior goals are Leonard, & Csibra 2011

Infants’ Action Anticipation

What about younger image of Southgate and structured by intention: online predictions above addressed by evaluating actions, such as reaching one location to another is evidence, from both responses in these st expectations.

Consider the event of three balls one at 1
have an open-ended trial length to observe and respond to each in order to inform real-time social interactions rapidly in the course of development. Evidence is needed, both in terms of the generation of predictions and in the measure of infants' anticipatory responses, to understand how young infants generate predictive events. For example, Haith et al. (1997; Haith et al., 1988) found that infants as young as 3 months of age can attend to moving objects and move their eyes in response to events. In this case, infants' anticipatory responses, such as the novel light pattern over time, are important. Other studies have shown that gaze shifts based on predictability. To illustrate, when four- to six-month-olds are watching another infant watching an object, they look at the object on the other side of the screen. When they see this event, they look away from the object on the other side of the screen, which they saw as an event, thus showing that infants can anticipate others' actions, although their responses reflect their possible patterns of observation. The previous paragraph suggests that at least some infants may come to anticipate others' actions. For example, infants may learn to look up near the ear or that hand side, by six months of age, infants watching a moving object systematically to the body parts: phones and cups when these are placed out of reach. Learning about predictable events is also important. For example, after viewing an agent who goal, infants visually anticipate the same path even when a more efficient path was available. These findings show that infants are able to extract information about patterns in others' 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 one of two boxes. Following the 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).

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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 a time, moving each one across a table and placing it
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.

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Kanakogi and Itakura’s (2011) findings suggest that action anticipation became more robust between ages 6 and 12 months for both infants and adults. Given the magnitude of infants’ anticipatory responses to the toy only when the hand was present, it is possible that infants and adults who shifted attention.

Taken together, these findings indicate that infants’ anticipatory responses reflect something more than passivity. On the one hand, infants’ anticipatory responses are not the result of goal-directed actions during the testing session. The anticipatory responses reflect everyday experience—for example, that hands tend to move objects to it—informed by the question of whether infants generated an analysis of an agent’s goals.

Goal-Based Action Prediction in Infants

The principal paradigm that has been used in both adults and infants is to determine whether infants’ actions are based on cognitive representations that are targeted to movement. In the studies described in the present paper, movement was not confounded: Infants moved to the same goal, whether infants anticipated the goal. Infants in movement but fail to predict goals despite changes in movement.

To distinguish goal-based action prediction, we adapted the logic used in the present paper. Eleven-month-old infants viewed
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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
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 those of infants in the hand condition showed an equal propensity during test trials as in the hand looked to the prior location rather than the object. Importantly, infants in the hand attentive to the experimental events objects and showed similar patterns of claw and hand toward the object. Thus to hands and claws on test probes with attention to the events. These findings generate at least two different kinds of for the action of an agent and movements of an inanimate object.

These findings indicate that by adolescence drives infants’ predictions about the is evident in looking-time studies on online responses to others’ actions. C younger infants generate such details demonstrate an understanding of actions that are months of age in looking that infants’ action knowledge is acquired from the start. Infants at these ages the movements of inanimate object would be similarly able to use social hand, the recruiting of action know of later aspects of executive function, memory or attentional control, or development. In this case, the findings reflect a more limited sensitivity, structure but not prospective social.

If there was a lag in the emergence to earlier aspects of action knowledge developmental paradox: Looking toward twelve months of age) infants directed, and yet younger infants do behaviors that are generally taken intentional. For example, infants engage in collaborative and refer social partners, but these social benefits. If younger infants possess
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 action representations support action anticipation: to others’ actions closely mirrors thany one’s own actions, suggesting th be driven by the same underlying m might be driven by the same underlying m movement activity associated before the observed action (Kilner et al., 2003; Hauf, this volume). Further, the electrophysiological activity associated with the anticipated action (Kilner et al., laboratory have confirmed that motor adults’ action anticipation. Specifically, current action task disrupts anticipat (Woodward, 2008, in preparation). These events depicted in figure 16.1 while, in one hand in a scripted cascade pattern significantly reduced adults’ anticipation to baseline trials with no concurrence in which the concurrent task (a verb motor in nature. Further, the finger-anticipation of inanimate events (e.g. an occluder), indicating a specific coi and action anticipation.

If embodied action representations are involved in these developments that occur in infancy, we would be expected to have action anticipation. Falck-Ytter and this may be the case: Six-month-old (anticipating actions in which balls fall to the action. The researchers specifically do not engage in containment action to reflect their lack of motor represent Kochukhova (2010) conducted a n assessing both action production at children. They found that children’ puzzle was correlated with their ten actions with the puzzle.

In a recent study (Cannon et al.), could be traced to earlier: in infra- engagement in containment action actions with containers. Although t place objects into containers, th
that would be expected. That is, what they know to generate late these social interactions. Whether and how infants' action competence in real-world social action anticipation goes beyond seeing goal directed and reflects that has been revealed in infant digms, infants integrate informing prior actions to interpret infants to interpret novel actions. For example, this ability allows tool as goal directed based on an agent's other actions. Do duate their online predictions (Rithgate and colleagues, 2007), of age, children generate pre-agent's reaching actions based re have been no studies of this infants.

This article presents a close relation between ons and their understanding of me studies. Development in pments in their action under-change infants' actions also actions as goal directed. These entations are embodied, in the resentations that guide action lsignificance for the question of 'goal-directed actions because ive process, requiring the gent one's actions as they occur 01). Actions are prospectively ten, 2004), and this fact raises itations could support infants'

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; Hau, 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. Falk-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 action goals. Because these anticipatory movement-based regularities, it is not embodied representations contribute anticipations of others’ actions. Either representations that guide action pr analysis—from the generation of specific plans that organize sequences of action (e.g., Claxton et al., 2003; von Hofsten’s no reason why embodied action reg higher-order and lower-order aspects.

The findings from our finger-tap example, the interference effects decreased became automatized, suggesting it motor performance, and not the motor sense, that mattered. In addition, concerns the anticipation not only of specific abstract goal-directed events. Special the anticipation of tool-use events placing it into a bucket) in which to infered; this interference effect was participants to view the claw event by a person.

These findings with adults suggest reflect action structure that is moments, instead reflecting an analysis. However, further research is needed embodied action representations, and example, are the embodied representation of others’ actions base of attention?

The level at which embodied action anticipation is an open question, aside from the findings of month-olds (Cannon & Woodwar
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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 rep-
resentations 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 move-
ments, 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, the level of description of the representations, and how these may change. How can they represent others’ actions not merely actions structured by goals, both at the level of higher-order plans that strings in studies with eleven-month-olds informs action predictions. However, connection is established in early development in infants under the age of two years. Analysis. It remains possible, therefore, not fully expressed in their online representations in development.

Further, there are reasons to suspect knowledge may explain the engage action anticipation, but, as yet, see. There is evidence that connects both to developments in infants’ own action knowledge reflects both less in studies with adults indicates that em the anticipation of goal-directed actions production to action anticipates open the question of whether embodied role in infants’ action anticipation.

In pursuing these questions, an ability that the answers will change is a period of dramatic changes in motor competence. Prior research findings between these domains of actions in the context of infants’ action opens new questions and new possible areas.

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ign gaps remain in the empirical record. Most critically, these gaps concern
the level of description of the representations that guide infants’ action
expectation, and how this may change over early development. Infants
represent others’ actions not merely as movements through space, but as
ctions structured by goals, both at the level of individual actions and at
the level of higher-order plans that structure groups of actions. Our find-
ings in studies with eleven-month-olds indicate that this knowledge
forms 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
alysis. It remains possible, therefore, that infants’ action knowledge is
ot fully expressed in their online responses to others’ actions until later
oints 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’ em-
bodied 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
ction 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 pos-
sibility 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 rela-
tions between these domains of development, but considering these rela-
tions in the context of infants’ active online responses to others’ actions
opens new questions and new possibilities.

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References


Hamlin, J. K., Hallinan, E. V., & Woodw infants selectively reproduce others’ goals.


Kilner, J. M., Vargas, C., Duval, S., Blakemore, S., & Els, 1301.
Online Action Analysis


Southgate, V., Johnson, M. H., El Karoui, I. vation reveals infants’ on-line prediction

355–359.


Cognitive Sciences, 8, 266–272.

von Hofsten, C., Kuchukhova, O., & Ro: occlusions by 4-month-old infants. *Devei


Woodward, A. L., & Guajardo, J. J. (2) gesture as an object-directed action. *Co

Woodward, A. L., & Sommerville, J. A. action in context. *Psychological Science,


The psychology of learning and motiva
Online Action Analysis


