PART V

Foundations of Social Cognition

CHAPTER 15

Building Intentional Action Knowledge with One's Hands

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Understanding others' actions as intentional is fundamental to everyday social life. Adults view even the simplest and most concrete actions not as sheer movements, but rather as actions organized by intentions. To illustrate, observing a group of children and a ball traversing a soccer field, we perceive the motions of the former, but not the latter, as structured with respect to a goal, in this case the goal of driving the ball across the field to score. This foundational aspect of social perception is a critical ingredient in social, cognitive, and linguistic development. In the first years of life, children acquire a great deal of knowledge from other people. By 12 to 18 months of age, if not earlier, this learning is mediated by an analysis of others' intentions (Baldwin & Moses, 2001; Meltzoff, 1995; Tomasello, 1999). Deficiencies in this ability have devastating developmental effects, as seen in individuals with autism. In this chapter, we will consider the potential origins of the ability to discern others' intentions in acting.

Recent findings have shown that by the middle of the first year, infants represent certain actions in terms of their intentional structure (Gergely & Csibra, 2003; Kuhlmeier, Wynn, & Bloom, 2003; Luo & Baillargeon, 2007; Woodward, 1998; Woodward & Guajardo, 2002). For example, in a series of studies from our laboratory (Guajardo & Woodward, 2004; Woodward, 1998, 1999, 2003), infants 6 months of age and older viewed events in which a person reached toward and grasped one of two toys. The question of interest was whether infants, like adults, would represent this event as goal-directed, that is, in terms of the relation between the agent and her goal. Following habituation, the positions of the two toys were switched. Then the experimenter reached for either a new toy in the same place (new-object trials) or the same toy in a new place (new-side trials). Infants looked longer to the new-object trials than the new-side trials, indicating that they represented the event in terms of the relation between agent and goal, rather than strictly in terms of physical properties such as the movement and position of the actor's arm.

Critically, several subsequent findings confirmed that infants' responses in this paradigm indicate more than an association between the hand and the object it grasps. Rather, infants encoded the reaching events in terms of the relational structure of the action. This conclusion is supported by the outcomes of comparison events in which one object moves toward another, but, unlike the hand, the moving object is not readily construed as an agent. For example, in one control condition, infants saw a mechanical claw move toward and grasp a toy (Woodward, 1998). If infants only encoded the association between two "objects" (the hand and toy or the claw and toy), their responses in these two situations would be equivalent. However, infants in the mechanical claw condition looked equally long at the new-object and new-side test events.

Additional evidence that infants attend to relations between agents and goals comes from recent work by Luo and Baillargeon (2007): 12-month-old infants did not show selective attention to goal change events if the agent could only see one of two objects during habituation (the other object was visible to the infant but hidden from the experimenter's view). In this paradigm, the association between the hand and the goal-object was identical to Woodward's (1998) paradigm but the actor's knowledge of the potential goals differed. Therefore, it can be concluded that infants considered the agent's intentional relations to the objects, rather than simply the association of the hand with the object it grasped. These findings also indicate that infants understand that an agent's goals are limited by perception.

Infants' sensitivity to the goal structure of others' actions is also evident in other paradigms, including those that assess imitative responses (Hamlin, Hallinan, & Woodward, in press; Meltzoff, 1995) and other overt spontaneous social behaviors in experimental contexts (Behne, Carpenter, Call, & Tomasello, 2005). For example, like older infants and children, 7-month-old infants selectively reproduce the goals of observed actions, thereby revealing, with their hands, the same goal analysis that has been shown in looking time studies (Hamlin et al., in press; Mahajan & Woodward, 2007).

Toward the end of the first year of life, infants become increasingly able to discern the goal structure of more complex actions. By 9 to 12 months, for example, infants represent others' gaze as indicating relations between the looker and the object at which her eyes are pointed. Evidence for this ability comes from looking time studies (Johnson, Ok, & Luo, 2007; Phillips, Wellman, & Spelke, 2002; Sodian & Thoermer, 2004; Woodward, 2003) and studies assessing infants' overt social responses (Moll & Tomasello, 2004; Tomasello & Haberl, 2003). Further, by this same age, infants represent goals that span individual actions. For example, they can represent the relation between actions on a tool or intermediary and the attainment of an ultimate goal (Gergely & Csibra, 2003; Sommerville, Hildebrand, & Crane, in press; Sommerville & Woodward, 2005; Woodward & Sommerville, 2000).

ORIGINS OF INTENTIONAL UNDERSTANDING

While this evidence makes clear that the ability to recover intentional structure from observed actions exists early in life, the ontogenetic origins of this ability are still in question. How do the beginnings of these understandings appear? How do changes in understanding come about? As is the case in other domains of infant cognition, current positions on these questions range from the strongly nativist (e.g., Biro & Leslie, 2006; Gergely & Csibra, 2003; Kiraly, Jovanovic, Prinz, Aschersleben, & Gergely, 2003) to strongly emphasizing the role of experience (e.g., Meltzoff, 1995; Tomasello, 1999; Woodward, 2005). At this point, there is little direct evidence available to distinguish among these views because most studies have not investigated developmental change and its possible causes. Instead, studies have typically taken a "snapshots" approach, seeking evidence for focal abilities at a particular point in time but not considering how these abilities may change as a function of other events in development.

In this chapter, we will attempt to begin to fill this void by considering a category of experience that has long been hypothesized to contribute to intentional understanding, namely first-person agentive experience. The idea that action production and action understanding are linked in development has been around for over a century (Baldwin, 1897; Piaget, 1953). A number of current proposals have at their core the idea that one's own actions provide unique insight into the structure of others' actions (Barresi & Moore, 1996; Meltzoff, 1995; Tomasello, 1999).

Theoretically, it seems reasonable that one's own experience as an agent could provide useful information for understanding other agents. A true test of this general hypothesis requires (1) measuring infants' analysis of observed action structure and (2) relating this measure to variations in infants' own actions. We turn first to recent studies that have done just this, and in so doing provided initial evidence that this general proposal is on the right track. We will then turn to the much harder question of *why* self-produced experience might have an effect on the development of action understanding. This question will lead us to consider recent work on mirror systems, the limits of mirror systems, and the role of analogy in conceptual development.

EVIDENCE FOR LINKS BETWEEN ACTION PRODUCTION AND ACTION UNDERSTANDING

As researchers began to document infants' emerging sensitivity to the goal structure of action, a coincidence became apparent. Infants and children are generally able to produce particular actions around the same age at which they are also able to understand these actions in others. Around 4 to 5 months of age, infants begin to make intentional grasps themselves (Bertenthal & Clifton, 1998; Rochat, 1989) and also begin to understand grasp as goal-directed (Woodward, 1998). Around 9 to 12 months of age, infants begin to engage in shared attention and triadic interactions (Adamson & McArthur, 1995; Carpenter, Nagell, & Tomasello, 1998) and also begin to understand gaze and pointing as implying a relation between the agent and the target of her attention (Brune & Woodward, 2007; Woodward, 2003; Woodward & Guajardo, 2002). Also, as infants are first able to produce goal-directed action sequences (around 9 to 12 months of age; Bates, Carlson-Luden, & Bretherton, 1980; Piaget, 1953), they begin to understand the ultimate goal of a means–end sequence that another person performs (Sommerville & Woodward, 2005; Woodward & Sommerville, 2000).

Two approaches have been taken to follow up on these coincidences to determine whether, in fact, they reflect developmental relations between acting and understanding actions. The first is to assess, within the same infants, correlations between action production and action perception. The second is to intervene to change infants' self-produced experience and then assess the effects of this intervention on infants' action perception.

Correlational Evidence

During times of developmental change, a great deal of individual variation can be seen in children at a given age, and therefore, links between motor capabilities and understanding of these actions can be examined keeping age constant. For example, between 10 and 12 months of age, a great deal of variability exists in infants' ability to produce planful actions such as pulling a cloth to get a toy. There is also individual variation in the ability to understand goal structure in these kinds of means–end sequences. In a paradigm assessing the understanding of these means–end actions, Sommerville and Woodward (2005) habituated infants to sequences in which an actor pulled a cloth in order to get a toy on its far edge. The question was whether infants represented the actor's action on the cloth as directed at the ultimate goal (the toy) or at the cloth itself. To address this question, after habituation, infants were shown test events in which the toys' positions were reversed and the actor only produced the first action in the sequence, grasping a cloth. Thus, infants viewed new-cloth trials, on which the actor grasped the other cloth, which now supported the previous goal toy, or new-toy trials, on which the actor grasped the same cloth as before, which now held a different toy. Twelve-month-olds looked longer on new-toy trials than new-cloth trials, showing that they represented the action on the cloth as directed at the toy. Ten-month-olds, in contrast, were variable in their responses, showing no reliable group preference. At this age, there was a correlation between infants' own cloth-pulling abilities and their looking time responses (see Figure 15.1). Infants who were well organized in their own ability to pull a cloth to get a toy looked longer on new-toy trials, whereas infants who were unable to produce an organized and planful cloth-pulling action looked longer on new-cloth trials. Importantly, this finding demonstrated that infants who were unable to perform this means–end action were not completely disorganized concerning their understanding of the intention behind this action when observing another. Instead, these infants understood this action on a simpler level, wherein the end-goal of the action was the cloth, as if it were a simple grasp.

Figure 15.1 about here

Other studies have found additional correlations between infants' own abilities to act and their responses to others' actions. For example, between 9 and 12 months of age, a great deal of individual variation exists in infants' production of point and engagement in shared attention; there is also individual variation in the ability to understand point and gaze. Woodward and Guajardo (2002) found a relation between infants' ability to produce object-directed points and their understanding of point in a habituation paradigm. In addition, a study by Brune and Woodward (2007) supported the correlation between production and understanding of pointing and also found a correlation between infants' engagement in shared attention and understanding of gaze as object-directed at 10 months of age.

This correlational evidence is important in that it demonstrates a specific link between production and understanding of particular actions. In addition, these results demonstrate that data from looking time studies is clearly related to developments in infants' overt actions. Most importantly for the current arguments, this evidence provides an initial view of the link between action production and action understanding and how this link may lead to developmental change. It demonstrates that the developmental concordance in time reviewed above is more than mere coincidence. Importantly, however, correlational evidence does not shed light on the causal contributors to this relation. Next, we will discuss evidence that goes beyond correlations in an attempt to examine causality.

Intervention Evidence

In intervention studies, infants at the cusp of performing a particular skill are trained or supported in a new self-produced action and then the effect of the training on their understanding of that action is assessed. This approach provides clearer evidence about the effects of acting on action understanding. For example, 3-month-olds are generally not yet skilled in producing goal-directed grasps and they do not typically understand the relation between another's grasp and his or her goal. In a study by Sommerville, Woodward, and Needham (2005), infants received training in which they were able to manipulate the movement of toys using Velcro mittens. Infants' object-directed touching (as indicated by simultaneous looking and touching of the toys) increased with the use of the mittens. After training, infants responded to observed mittened reaching actions as goal-directed in the habituation paradigm described earlier (see Figure 15.2). That is, infants who had undergone training showed a strong novelty response on new-object trials but not on new-side trials. In contrast, infants who had not undergone training looked equally on the two kinds of test trials. Moreover, in the training group, there was a strong correlation between the extent to which infants had engaged in object-directed actions with the mittens and the degree of their novelty response on new-object trials. Thus, engaging in object-directed action seemed to drive infants' subsequent responses to observed reaching events. These results support the conclusion that infants' own actions provide structure for the perception of others' actions.

Figure 15.2 about here

Similar intervention effects have also been found with means–ends actions such as cane-pulling (Sommerville et al., in press). In this study, 10-month-old infants trained to use a cane to reach for a toy were able to understand the ultimate goal of a cane-pulling sequence in a habituation paradigm (they looked longer to a reach for the old cane to get a new toy than a reach for a new cane to get the old toy; see Figure 15.3). Moreover, as in Sommerville et al.'s (2005) study, infants' success in cane-pulling during training was correlated with their response to the habituation events. Infants who were more successful at cane-pulling during training showed stronger attention to the goal structure of the habituation events. Critically, first-person experience had unique effects on infants' analysis of the observed actions. Infants who received observational, rather than active, training recovered attention to both test events, indicating that they detected the changes in the test events, but did not respond differentially to the new-toy versus the new-cane events.

Figure 15.3 about here

Work by Meltzoff and Brooks provides further evidence that self-produced experience can inform infants' analysis of others' actions. In a previous study, Brooks and Meltzoff (2002) used infants' propensity to follow gaze as a measure of their understanding of attentional relations. They found that, 14 and 18, but not 12-month-old, infants understood that an adult wearing a blindfold was not attending to an object in the direction of her head turn. Specifically, 14- and 18-month-old infants were less likely to follow the direction of the adults' gaze when the adult was wearing a blindfold, but 12-month-olds continued to follow the adults' "gaze" under these conditions. However, in an intervention study (Meltzoff & Brooks, in press), after 12-month-old infants were given experience wearing a blindfold, they inhibited the tendency to follow gaze when the adult was wearing the blindfold. Thus, self-produced experience with the blindfold seemed to give them insight into the perceptual experience of others in the same situation.

These three examples demonstrating the effects of intervention suggest that being an agent provides infants with information about others' actions. There are a number of issues that require further investigation. For one, the relative impacts of self-produced and matched observational experience require further study. Sommerville et al. (in press) findings indicate that self-produced experience has unique effects on infants' action perception, but whether this is always the case is not yet known. Even so, evidence from these studies is strongly suggestive of a causal link between action production and understanding. Ongoing work in our laboratory seeks to replicate and extend these findings.

THEORETICAL LINKS BETWEEN ACTION PRODUCTION AND ACTION UNDERSTANDING

Natural concordance in time, correlational data, and intervention data all support the conclusion that a link exists between action production and understanding. But why? One possibility is that by acting, infants produce for themselves examples for observational analysis. There is evidence that infants analyze the structure of observed actions in several ways that could support the extraction of goal information. First, infants attend to the outcomes of actions, and, in some cases, use these to infer the function, and perhaps goal, behind the action. For example, in a study by Hauf, Elsner, and Aschersleben (2004), 12- and 18-month-old infants were more likely to imitate an action that produced a sound than an action that did not produce any effect. Further, in some cases, action effects (such as moving an object to a new location) may help infants to interpret the goals of ambiguous actions (Biro & Leslie, 2006; Kiraly et al., 2003; but see Heineman-Pieper & Woodward, 2003).

In addition, infants are sensitive to statistical regularities in temporally extended events (Kirkham, Slemmer, & Johnson, 2003; Saffran, Aslin & Newport, 1996; see also Gomez, Kirkham, and Saffran chapters in this volume), and may therefore be able to extract recurring patterns in actions. Baldwin, Baird, Saylor, & Clark (2001) found that 10- and 11-month-old infants were sensitive to units in naturalistic action that corresponded to those defined by goal completions to adult observers. This finding may, in part, reflect infants' statistical analysis of action elements that typically co-occur as units (Baird & Baldwin, 2001).

Clearly, self-produced actions would provide data for these kinds of statistical learning mechanisms to exploit. However, here we explore the further possibility that self-produced actions also provide unique information for the perception of goal-directed action. In support of this possibility, consider what infants seem not to learn by watching alone. Infants are constant witnesses to goal-directed actions like grasping, looking, and tool use, but knowledge about the goal structure of these actions is not evident from the start. Rather, as described earlier, infants' sensitivity to the goal structure of these actions emerges, at different points, during the first year of life.

SELF-PRODUCED ACTIONS AS UNIQUE SOURCES OF INFORMATION

Unlike observed actions, which can only provide information "at the surface" (e.g., the sequelae of actions), the regular patterns in self-produced actions could also provide unique information about the underlying goal structure of action. Agency requires representing the goals of one's actions at some level. To coordinate complex actions in service of a goal, or to acquire a new goal-directed skill, like reaching by gradually gaining control over the relevant effectors, individuals must continue to represent the goals that structure their actions and adjust their actions as needed to attain the goal. This information could potentially be recruited to then interpret the perceived actions of others.

This general idea has been broadly proposed in the developmental literature (Barresi & Moore, 1996; Meltzoff, 2005; Sommerville & Woodward, in press; Tomasello, 1999). Accounts differ, however, on two important dimensions: the nature of the information carried from self to other and the means by which information about the self is related to the actions of another person. On the first dimension, some have proposed that infants or young children derive mental state information from first-person experience, which they then use to infer similar states in others (e.g. Meltzoff, 2005). In contrast, it is possible that the information available to infants from first-person experience is in terms of action level descriptions, rather than mental states. On the second dimension, some have hypothesized that children extend information from self to others via a process of analogical mapping (e.g., Barresi & Moore, 1996). In contrast, others have suggested a direct link between self and other, in the form of shared representations for one's own and others' actions (Hauf, Aschersleben, & Prinz, 2007; Meltzoff, 2005; Sommerville et al., 2005). Although current evidence suggests that there is some truth to the general proposal that self-produced actions provide unique information for perceiving others' actions, it does not indicate which of these more specific accounts is correct. Indeed, more than one of them could provide an accurate depiction of different aspects of action knowledge development.

In one current proposal, Meltzoff (2005) proposes a developmental framework, nicknamed the "like me" account, in which information about self and other is directly connected because both are instantiated in a common supramodal representation and grounded in a common body schema. This direct connection provides infants with a means for apprehending the inner states that correlate with others' observed actions, and it also supports imitation. By imitating an observed action, Meltzoff proposes, infants gain information, via their own experience, about the inner states of the other person. Meltzoff further proposes that infants do not begin with full-fledged conceptions of mental states like intention or perception, but rather they construct these concepts in the course of back and forth information sharing about their own and others' actions. In this way, action understanding is direct and linked with internal states from the onset and infants' understanding of their own and others' mental lives becomes more abstract with development.

A somewhat different view has been elaborated by Barresi and Moore (1996). In this account, as in Meltzoff's, information derived from first-person experience is critical for understanding the mental lives of others. Their perspective, however, views the connection between self and other as indirect and emerging through analogical mapping. According to their perspective, triadic interactions, in which individuals jointly attend to an object or event, are a key element in understanding the relation between self and others. Through joint engagement with an adult, the infant can directly align the actions of himself or herself with the actions of another individual. This physical alignment of actions provides the basis for the building of an intentional schema through analogy.

Below, we propose an alternative account, similar in some respects to each of these perspectives, but also differing in several respects. Our proposal is informed by recent findings concerning the mirror system and recent debates concerning the nature of information this system provides the perceiver. To foreshadow, we propose that direct and indirect, mental and action-level information sharing occur at different points during development. Initially, the information provided by self-produced actions provides a direct, action-level description of goal-directedness. This beginning point sets up the conditions for subsequent analogical mappings, which lead to more abstract levels of analysis. Before elaborating our proposal, we first review relevant research on the mirror system.

ROLE OF MIRROR REPRESENTATIONS IN ACTION PERCEPTION

Findings from the past decade provide evidence for a direct link between neurocognitive systems that subserve action production and action perception. The first evidence for this link came from primate research that identified neurons in motor regions that discharge both during the performance and the observation of goal-directed actions (Rizzolatti & Arbib, 1998; Rizzolatti &

Fadiga, 1998). Subsequent research in humans has similarly indicated shared neural (Buccino et al, 2001; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Grezes & Decety, 2001; Iacoboni et al., 1999) and cognitive (Hommel, Musseler, Aschersleben, & Prinz, 2001) representations for perceiving and producing actions. Evidence in humans does not isolate individual neurons. Instead, researchers ask whether common brain regions support the production and perception of action. Our focus is not on the exact nature of the neural representations, but rather the functions that mirror representations may support in development. Specifically, three important functional characteristics of mirror representations have been revealed across a number of studies: (1) they provide a direct link between action and perception, (2) they are selectively sensitive to goal-directed action, and (3) they are shaped by motor experience. Below, we will review evidence for each of these features. We will then discuss the status of infancy research in this area.

Rizzolatti and colleagues (Rizzolatti & Arbib, 1998; Rizzolatti & Fadiga, 1998) found that neurons fire during both performance and observation of actions in monkeys, thus providing neural evidence for the link between action production and perception. In research with humans, transcranial magnetic stimulation (TMS) studies have found a selective increase in motor-evoked potentials during observation of actions that are specific to those muscles used in the action (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Gangitano, Mottaghy, & Pascual-Leone, 2001). In addition, evidence of corresponding areas of activation in the premotor cortex during action observation and execution has been found in functional magnetic resonance imaging (MRI) and positron emission tomography (PET) studies (Buccino et al, 2001; Grafton et al., 1996; Grezes & Decety, 2001; Iacoboni et al., 1999). More recently, electroencephalography (EEG) studies have found a suppression of mu rhythm in both the production and the observation of actions (Altschuler, Vankov, Wang, Ramachandran, & Pineda, 1997; Cochin, Barthelemy, Roux, &

Martineau, 1999). The mu rhythm is evident over motor areas, and is suppressed by movement, intended movement, or observation of movement (Muthukumaraswamy, Johnson, & McNair, 2004; Pineda, Allison, & Vankov, 2000). Together, these diverse findings point to the existence of shared neural representations for the production and perception of action.

Rizzolatti, Fogassi, & Gallese (2001) also found that mirror neurons in monkeys only discharged to an agent grasping an object, not to either the agent or object alone, suggesting that these neurons are selectively responsive to goal-directed actions (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). Similar findings have been obtained in humans. For example, Muthukumaraswamy and colleagues (2004) found mu rhythm suppression occurred when adults viewed a grasping action of an object but not when this same action was produced without an object present. In humans, mirror representations seem to be sensitive to goals at more abstract levels as well, responding to events beyond the simple attainment of objects to include such actions as a dance movement or the use of chopsticks (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Calvo-Merino, Grezes, Glaser, Passingham, & Haggard, 2006; Järveläinen, Schürmann, & Hari, 2004).

Work by Calvo-Merino and colleagues (2005, 2006) highlights the expertise-driven nature of mirror representations. In one study, male dancers showed motor activation during the observation of dance movements they regularly produced but not during observation of movements regularly performed by female dancers, with which the males were extremely familiar but had no firsthand experience producing. Additionally, simple effects of gender were accounted for in that males watching females perform an action common to both genders did show activation of the mirror system. These findings demonstrate that action experience can lead to activation of the system and that mirror system activity is dependent on possessing a motor representation for an action rather than simply having visual knowledge of the action. Additional evidence that action experience influences the mirror system is provided by Catmur, Walsh, & Heyes (2007). In this study, training in producing an action opposite to the one being observed reversed mirror effects, demonstrating that the mirror system is reliant on sensorimotor learning.

Mirror Systems in Infancy

Due to limitations in techniques for brain imaging with infants, the majority of work concerning the mirror system in humans has been done with adults. Currently, brain-based evidence of mirror systems in infants is extremely limited, but behavioral studies have provided indirect support for the idea that the mirror system may be functioning in human infants (see Lepage & Theoret, 2007). For example, neonatal imitation, in which newborn infants are able to imitate tongue protrusions without the ability to see the action they make themselves suggests a correspondence between representations of self and other in infancy (Meltzoff & Moore, 1989). In addition, the evidence from looking time studies with older infants that is discussed above, in which infants' understanding of goal-directed actions is correlated with their actions, is consistent with the notion that mirror system activity exists in infancy.

A study by Falck-Ytter, Gredeback, and von Hofsten (2006) provides additional indirect support for the existence of mirror representations in infancy. Previous research has shown that adults produce systematic, proactive eye movements during the production of goal-directed actions. That is, adults make predictive eye movements in order to control and coordinate their actions. The same kind of predictive eye movements are made when an adult is watching others produce similar goal-directed actions (Flanagan & Johansson, 2003). This finding is consistent with the possibility that a common system drives both attention to one's own actions and attention to others' actions. Following on this finding, Falck-Ytter and colleagues asked whether infants anticipate the goals of observed actions. They showed infants sequences in which a person placed each of a set of balls into a container. Like adults, 12-month-old infants anticipated the goal of this sequence, looking to the bucket reliably before the ball's arrival. In contrast, infants who viewed the same ball movements, this time without a human mover, followed the balls, but did not anticipate their arrival at the bucket. Based on these results, these researchers speculate that the mirror system is active in infancy and drives infants' predictive attention to observed actions.

A recent study provides the only brain-based evidence for the presence of a mirror system in human infants. Shimada and Hiraki (2006) conducted a study that examined brain activity during action observation in 7- and 8-month-old infants. In this study, the sensorimotor area was identified during a motor task in which adult participants were prompted to engage in repetitive hand movements and infant participants engaged in structured free-play. Then, the activity of motor areas was measured using near-infrared spectroscopy during action observation (in one condition, infants watched an experimenter manipulate a toy) in both adults and infants. The sensorimotor area was selectively activated during live action observation in both adults and infants. This area was not activated when observing a live object-motion condition in which the object moved on its own. Additionally, coding of the infants' arm movements during free-play indicated that the observed motion was part of the motor repertoire of most infants, supporting the claim that the mirror system is sensitive to motions within an individual's motor repertoire, even in infancy.

MIRROR REPRESENTATIONS: MENTAL STATE OR ACTION LEVEL DESCRIPTIONS?

Mirror representations provide a direct path between actions of self and others that may be in place from infancy. They respond selectively to goal-directed actions and are shaped by agentive experience. A critical open question, however, is the extent to which mirror representations make contact with mental state concepts. Debates in the literature on the functions of mature mirror systems have highlighted this issue.

Some theorists have taken up the mirror system findings as evidence in favor of simulation theory. The simulationist account posits that individuals can gain an understanding of others' mental states by mentally simulating those actions themselves (Goldman, 1989; Gordon, 1986; Harris, 1989; Heal, 1998). This theory proposes a direct link between first-person mental states and the comprehension of others' mental states. In this way, individuals can "mirror" the actions of another and come to understand another's actions based on their own past experience (without analyzing or building a theory). To illustrate, Gallese and Goldman (1998) proposed that mirror systems allow an individual to detect mental states in others because mirroring creates a match between mental activity of the observer and the actor, and, thus, the observer is able to use his or her own mental processes to understand and predict the mental goals of others. Blakemore and Decety (2001) also proposed that mental states can be inferred directly from biological motion through a process of simulation.

Other researchers have countered this view with the argument that the mirror system may be useful in determining motor intentions but that it is not sufficient for understanding prior intentions and mental states more generally. Representing prior intentions entails an understanding of intentions as mental states that exist independent of the particular actions used to achieve the intended goal. Motor intentions, in contrast, are specified at the level of the goal at which a particular action is directed. Jacob and Jeannerod (2005) argue that perceiving an action will lead to an understanding of motor intention but cannot lead to the understanding of an agent's prior intention. They state, for example, that infants' understanding of a basic grasp in a habituation paradigm may be due to motor simulation, but that this simulation is only possible for basic actions and intentions. Prior intentions, however, wherein the goal is not inherent in the action itself (i.e., opening a drawer in order to retrieve a pen from inside), cannot be represented by mirror systems alone.

In its strongest form, the claim that the mirror system can only be used on the most basic level has been disputed by subsequent evidence that mirror neurons in primates and mirror systems in humans can represent not only the goals of simple actions, but also overarching goals that structure action sequences (Fogassi et al., 2005; Iacoboni et al., 2005). For example, Fogassi and colleagues (2005) found mirror neurons in macaque monkeys that fired differentially to grasping actions that preceded eating versus placing of the grasped object when there were contextual cues to support one of these two analyses of the grasp. Thus, these neurons reflected processing, not of the basic action itself (grasping), but rather the ultimate goal at which the grasp was apparently directed (eating versus placing). Further, Ferrari, Rozzi, and Fogassi (2005) report the existence of "grasping" mirror neurons that fired for grasping done by varied effectors (e.g., the hand, the mouth or even a tool), thus indicating that mirror systems can reflect goal representations that are relatively abstract, at the level of action plans.

Even so, mirror representations alone seem unlikely to account for the full range of mental state knowledge humans eventually acquire. To illustrate, Saxe (2005) argues that if belief attribution derived from direct simulation, then the pervasive belief attribution errors seen in children (and even in adults) would be difficult to explain. Rather, these errors indicate that people's judgments about others' epistemic states are the product of an interpretive system (theory of mind) that can, in some cases, generate incorrect analyses.

This debate concerning more mature mirror systems sheds light on the probable limitations of developing mirror systems in infants. Mirror systems, on their own, seem unlikely to directly yield higher order mental state descriptions. At the very least, however, they would provide action level or even plan level descriptions of actions as structured in relation to a goal. Descriptions at this level, whether or not they make contact with mental state concepts, could account for many of the infant findings reviewed in this chapter. For example, when an infant responds selectively to the change in the goal of a grasp in a habituation paradigm, this response, at a minimum, reflects an understanding of the relational goal structure of grasping actions (see also Gergely & Csibra, 2003). It may also reflect the attribution of a mental state, such as wanting the object or liking the object, but as of yet there is not strong evidence for this in infants under 12 months of age (see Biro & Leslie, 2006; Gergely & Csibra, 2003; Onishi & Baillargeon, 2005; and Woodward, 2005 for different perspectives on this issue).

Thus, we assume at this point that, at a minimum, infants in the first year have action level and plan level representations of goal-directed action, leaving open the possibility that they may also represent information about the inner states that drive action. In addition to accounting for the data from younger infants, the structural level of description could provide an initial representational kernel for the subsequent development of intentional action knowledge. We turn next to this possibility.

RELATIONAL ACTION REPRESENTATIONS AND STRUCTURE MAPPING: A PROPOSAL

We propose that early in the first year, as infants begin to organize their own actions with respect to external goal objects, they acquire relational action representations that enable the perception of others' actions as structured by goals. Thus, as infants acquire new ways of acting (i.e., reaching, using a tool to acquire an object, pointing), they also attain new action level representations of each of these actions. These representations may reflect the activity of a mirror system that, as reviewed above, reflects representations accessible to both action production and action perception, is tuned to actions that are goal-directed, and is shaped by motor experience. This proposal is motivated by the findings, reviewed above, that (1) young infants encode others' actions as goal-directed and they express this action analysis in their overt actions as well as their looking time responses; (2) infants' goal encoding is correlated with developments in their own actions; (3) interventions that shape infants' own actions also affect their responses to others' actions; and (4) initial evidence suggesting that self-produced actions exert unique, or especially potent, effects on infants' action perception.

On our proposal, the action representations infants initially glean from agentive experience may be limited in two ways: They may be specific to particular actions and they may describe action in structural rather than rich mentalistic terms. Despite these limitations, they reflect a critical aspect of action structure, namely, that actions are structured by the relation between the agent and his or her goal. We propose that this relational core provides a basis for generalizing initial knowledge so as to create broader classes of goal-directed actions and to move toward more abstract representations of goals.

The literature on conceptual generalization in older children and adults provides a model of how this process could occur in infancy. In particular, Gentner and her colleagues have described a general cognitive mechanism that can extract increasingly abstract levels of relational similarity across instances (Gentner, 1988; Gentner & Medina, 1998). Because it yields abstract relational representations, this structure mapping engine (SME) seems especially well suited to the case of goal-directed action. The structure mapping engine is essentially an analogy maker. Instances are aligned based on similar features and this alignment promotes attention to other shared dimensions. Alignment and comparison supports the detection of abstract, relational similarities that may not be initially obvious to the observer.

To illustrate, in one set of studies, Loewenstein and Gentner (2001) showed 3-year-old children a toy bone hidden in relation to an object in a model room (e.g., under the bed). Then, children were shown another model room that had different-looking exemplars of each piece of furniture, similarly arranged to the first room. They were told there was a bone in the same place in this room. Children were generally unsuccessful in finding the second bone, suggesting they found it difficult to apply the relational information (the bone is under the bed) to the new, dissimilar room. To facilitate children's ability to see the common relational structure between the two rooms, Loewenstein and Gentner showed a second group of children two nearly identical model rooms with bones hidden in the same location. Then, children saw the dissimilar test room and were asked to find the bone hidden in the "same place." In this condition, children generally succeeded in finding the bone. Thus, alignment of perceptually similar instances supported children's ability to extract the common relational structure among even dissimilar instances. These effects were strongest when children could directly compare the first two models at the same time. However, even comparison across sequentially presented models helped.

Further, alignment of perceptually similar instances also supports children's extraction of higher-order relations. For example, Loewenstein and Gentner (2001) found that the opportunity to compare similar rooms also facilitated the extraction of embedded relational similarities. Specifically, on some trials, the bone was hidden under one of two identical chairs. To find the hidden bone, children had to represent not only the relation between the bone and the hiding place (i.e., *under the chair*) but also the relation between the chair and other objects in the room (i.e., *under the chair that is next to the bed*). The older children in the study were able to use comparisons of this embedded relational structure to find the hidden bone. Furthermore, Kotovsky and Gentner (1996) found that aligning items based on relatively concrete relations facilitated 4-year-old children's subsequent ability to discern higher-order relational structure. For example, if children were trained with perceptually similar examples of the relation small-big-small, they were then better able to detect the higher-order relational similarity between small-big-small patterns and A-B-A patterns in other dimensions (e.g., dark-light-dark). These examples show that beginning with relatively concrete comparisons can support the extraction of higher-order relational structure.

If infants, like older children, engage in structure mapping, then this mechanism could explain how initial, self-generated action representations become more general and abstract. For one, it would provide a mechanism for moving beyond particular actions, e.g., grasping with the hand, to categories of actions that subsume a broader range of instances, e.g. obtaining objects with varied hand postures or other affectors. As in Loewenstein and Gentner's (2001) studies, infants may begin by detecting relational similarities among similar-looking actions (e.g., grasping with the hands), and by so doing become more sensitive to the relational similarity among more disparate actions.

Recent findings show that infants sometimes detect goal relations for events in which objects are moved or obtained by unusual hand postures or inanimate agents (Biro & Leslie, 2006; Hauf et al., 2004; Kiraly et al., 2003). These results are generally taken as evidence that infants possess abstract concepts of intention that arise independent of experience (see Biro & Leslie, 2006; Kiraly et al., 2003). However, many of these findings would also be expected if infants generalized familiar action representations via structure mapping. Specifically, these extensions seem to occur most readily when (1) infants have a well-established relational action representation and (2) the situation promotes alignment between the infants' action representation and the novel event. First, the propensity to view unusual events as goal-directed is more often seen in older than younger infants, and those experiments that include infants at multiple ages find age differences (Biro & Leslie, 2006; Gergely, Nadasdy, Csibra, & Biro, 1995; Hauf et al., 2004). It could be assumed that age is a reasonable proxy for the robustness of infants' self-produced action representations. Second, infants more readily construe unusual events as goal-directed when they involve unusual hand postures than when they involve inanimate agents (Biro & Leslie, 2006; Hauf et al., 2004; Woodward, 1998). This effect may be due to the presence of hands supporting alignment with familiar hand actions.

Structure mapping may also facilitate extracting and generalizing the relational structure of embedded actions, such as using a tool to draw an object near before grasping it. Tool use presents a challenge for the perceiver because the action on the tool does not make direct contact with the goal object. Sommerville and colleagues' (in press) work suggests that self-produced means–end action provides insight into the embedded relational structure of others' actions. Once this is in place, structure mapping would allow infants to generalize this structure across diverse tool use events. For example, an infant who had experienced and observed multiple cloth-pulling events might then be able to discern means–end structure in a novel tool use event, just as children in Kotovsky and Gentner's (1996) study were able to detect higher-order relational similarities among patterns after aligning multiple instances of the relation.

Structure mapping can extract relational similarities starting at the level of pure object similarity, with no initial relational content. However, as detailed above, we hypothesize that infants begin one step ahead in this process in that they bring with them relational representations of some actions. This differs from Barresi and Moore's (1996) view of the role of analogy in extracting intentional relations. In their view, infants do not begin with relational representations, but rather derive them from the physical alignment of their own actions with the actions of others. For this reason, they hypothesize that triadic interactions are especially important for the process. On our proposal, infants may represent intentional relations before they reliably engage in triadic interactions.

Beginning with a relational kernel would have several advantages. Real world actions are not as neatly packaged as are habituation events or stimuli in analogical mapping experiments. Hand trajectories and shapes differ as different objects are grasped. People seldom grasp the same object again and again. Furthermore, except in some specific contexts, like triadic interactions, it is relatively rare for infants' actions to be directed at the same objects as others' actions at the same time. Thus, infants must be able to extract common goal structure across exemplars that are varied and distributed in time. Therefore, the conditions that have been shown to support the extraction of relational structure from initial object similarity may rarely occur in the domain of action, especially early in infancy. Beginning with a few self-generated relational action representations would support infants' ability to identify others' goal-directed actions in the face of the challenges posed by variability and temporal dispersion. As work with older children has shown, once children have established relational representations, they are less dependent on surface similarity and physical alignment of instances in extending this relational information to new instances.

Furthermore, hands move in many ways, not all of them object-directed. If infants began only with the ability to map events in terms of similarities in the objects involved, they might note that events with hands that grasp, gesture, snap, tap, scratch, etc. are all similar in that they involve hands. However, they would miss the critical underlying similarity that unites disparate goal-directed actions (e.g., lifting a box with two hands and picking up a cheerio with a pincer grip) and makes them different from other “hand events.” Relational action representations would highlight for infants the common relational structure of goal-directed actions, thus distinguishing them from other hand movements or motion events.

In summary, we propose that infants begin with self-generated, relational action representations that guide their perception of others’ actions. Structure mapping provides one means for going beyond these initial representations, allowing infants to discern common relational structure across diverse actions. In this way, infants may take the first step in separating goals from the particular actions that pursue them.

This independence from particular actions is one critical piece of what it means to understand a goal or plan as a mental state. Thus, it is possible that structure mapping plays a role in the development of folk concepts of mental states. We assume that this is only part of the story. Mature mental state concepts are embedded in and defined by theory-like systems of knowledge (Wellman, 1990). The acquisition of such knowledge systems involves the interplay of cognitive learning mechanisms in the child and information from the environment, including linguistic information. Indeed, Gentner (2003) has highlighted the role of language in supporting the acquisition of abstract relational concepts. Gentner and Medina (1998) have proposed a similar account for the role of structure mapping in the acquisition of folk theoretical knowledge in other domains, for example the concept of essences in folk biology.

Mental state knowledge becomes increasingly rich during the preschool years (Wellman, 1990). Even as early as 18 to 24 months of age, children verbally express knowledge about mental states, such as states of attention, emotions, and intentions (Bartch & Wellman, 1995). Further, recent experiments suggest that by these same ages children may understand belief states (Csibra & Southgate, 2006; Onishi & Baillargeon, 2005; Southgate, Senju, & Csibra, 2007; Surian, Caldi, & Sperber, 2007). This interpretation of the findings is debated, but at the very least, these studies demonstrate relatively rich understanding of others' states of attention. It is beyond the scope of this chapter to resolve this debate. Nevertheless, by these ages, we think it is possible that joint contributions of action analysis and linguistic input could contribute to initial mental state concepts.

CONCLUSION

In this chapter, we have presented a constructivist hypothesis regarding the development of action and intention understanding. We propose that emerging abilities to act, mirror representations, and analogy each play an important role in this constructive process. The development of intention understanding occurs through the progression from an initial structural understanding of goal-directed actions provided by mirror systems to a more abstract understanding through application of general purpose analogical mapping processes. Mirror systems may get the process started, but further ontogenetic processes are needed to produce the abstract action knowledge children eventually attain.

Our account is similar to Meltzoff's (2005) "like me" hypothesis in many important ways. We concur that action understanding is grounded in shared representation of self and other, and that action knowledge develops from relatively concrete to abstract forms during infancy and early childhood. Our account differs in two respects. For one, we propose that the extension of self-generated action representations to others can take place without the infant or child needing to engage in motor imitation. On Meltzoff's account, engagement in imitation is critical for infants' interpretation of others' intentions in acting. On our view, action representations acquired from first-person experience can then function "off-line" to provide structure for perceiving other's actions.

Further, we suggest that these action representations can undergo change as a function of observational extension. An infant with well-structured means-end action representations may extend them to observed actions with a novel tool, and by so doing, enrich the action knowledge they can bring to bear in future events. That is, once it is engaged, structure mapping can operate on observational as well as self-produced examples. This proposal is consistent with the finding that by the second year of life, infants engage in observational learning, imitating new actions with artifacts or tools. Even so, because they bring with them relational content, self-produced actions may continue to render especially powerful effects on children's emerging action knowledge.

A second difference between our proposal and Meltzoff's is that we are more conservative in our estimation of whether and when infants conceive of others' actions as being caused by mental states. In Meltzoff's account (2005), inner or mental states are part of what is extended from self to other from the start. As we have described, we think it is also possible to account for young infants' action knowledge in structural terms, and we further hypothesize that structural representations of goal-directed action may provide a foundation for later emerging mental state concepts. On the other hand, our account does not make a clear prediction of when in this chain of events the first “mental” concepts will arise. In fact, we think the question of when an action representation counts as “mental” is complex and difficult to address given evidence from infancy research (see Woodward, 2005).

Our proposal, though consistent with much of what is currently known, raises a number of questions to motivate future research. To start, we propose that infants’ own actions yield relational action representations that observation alone cannot provide. If we are right, then laboratory manipulations of infants’ own actions should change their perceptual responses in ways that observational training does not. Recent findings from Sommerville’s group (Sommerville et al., in press) are consistent with this hypothesis, but more work is needed to test the limits of this hypothesis. Further, we hypothesize that structure mapping processes play a role in the generalization of infants’ action knowledge. If we are right, then the same kinds of laboratory manipulations that have been shown to influence older children’s generalization of relational information should influence infants’ responses to action structure. Work currently underway in our laboratory is investigating each of these hypotheses.

Finally, our account predicts that the action representations derived in infancy contribute to the eventual emergence of folk concepts of mental states. Evidence in favor of this final prediction comes from several recent longitudinal studies documenting that infants’ action analysis predicts their responses, some years later, on verbal theory of mind measures (Aschersleben & Hohenberger, 2007; Kuhlmeier & Yamaguchi, 2007; Poulin-Dubois & Olineck, 2007; Wellman, Phillips, Dunphy-Lelii, & Lalonde, 2004). Infants who respond more systematically to the intentional structure of others’ actions go on to become preschoolers who respond more systematically on classic theory of mind assessments, like the false-belief task.

Thus, the initial steps we have begun to uncover during infancy seem to begin a long journey in the construction of folk psychology.

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Figure 15.1 Infants who were able to produce planful cloth-pulling actions themselves were sensitive to the means–end structure of an observed sequence of actions. From Sommerville and Woodward (2005).

Figure 15.2 Infants given experience producing object-directed actions with Velcro mittens were sensitive to the goal structure of an observed mittened reach. From Sommerville et al. (2005).

Figure 15.3 Infants given training producing cane-pulling actions were sensitive to the means–end structure of an observed sequence of actions. From Sommerville et al. (in press).