ABSTRACT

Title of Dissertation: COMPARING ME TO YOU: COMPARISON BETWEEN NOVEL AND FAMILIAR GOAL-DIRECTED ACTIONS FACILITATES GOAL EXTRACTION AND IMITATION

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Recognizing the goals of others' actions is critical for much of human development and social life. Origins of this knowledge exist in the first year and are a function of both acting as an intentional agent and observing movement cues in actions. In this dissertation, I explore a new mechanism I believe plays an important role in infants' understanding of novel actions---comparison. In four studies, I examine how the opportunity to compare a familiar action with a novel, tool use action (through physical alignment of the two actions) helps 7- and 10-month-old infants extract and imitate the goal of a tool use action. In Studies 1 and 2, 7-month-old infants given the chance to compare their own reach for a toy with an experimenter's reach using a claw later imitated the goals of an experimenter's tool use actions. In contrast, infants who engaged with the claw, were familiarized with the claw's causal properties, learned the associations between claw and toys, or interacted in a socially contingent manner with the experimenter using the claw did not later imitate the experimenter's goals. Study 3 replicated the finding that engagement in physical alignment facilitated goal extraction and imitation and indicated that this was true for older infants (10-month-olds). It also demonstrated that observation of the same physical alignment did not lead to goal imitation at this age. Finally, Study 4 revealed that 10-month-old infants could learn about the goals of novel actions through the observation of physical alignment when a cue to focus on the goal of the two actions was presented during the alignment process (i.e., a verbal label), indicating that infants gained a conceptual representation of the goal and used structure mapping to extract the common goal between actions. Infants who heard a non-label vocalization during the observation of physical alignment did not later imitate the experimenter's goals. The nature, breadth, and implications of these findings are discussed. Together, these findings indicate that infants can extract the goal-relation of a novel action through comparison processes; comparison could thus have a broad impact on the development of action knowledge.

COMPARING ME TO YOU: COMPARISON BETWEEN NOVEL AND FAMILIAR GOAL-DIRECTED ACTIONS FACILITATES GOAL EXTRACTION AND IMITATION

by

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Comparing Me to You: Comparison Between Novel and Familiar Goal-Directed Actions Facilitates Goal Extraction and Imitation

Fundamental to mature social life is the perception of others' actions as more than simply physical bodies in motion. As human adults, we view others' actions in terms of *intentional relations* (Barresi & Moore, 1996), that is, in terms of the relation between the agent and the object at which his or her actions are directed. When we see someone hit a tennis ball over a net, hammer a nail into a wall, or open a drawer to retrieve a utensil, we interpret these actions in terms of their goals (i.e., scoring a point, hanging a picture, or eating a meal) rather than focusing on the precise physical aspects of the actions. Detecting intentional relations is vital to everyday social functioning and foundational for much of human development.

Converging evidence from a variety of experimental paradigms indicates that by six months of age, infants are able to discern the intentional relations that structure some of the actions they see (Bíró & Leslie, 2007; Hamlin, Hallinan, & Woodward, 2008; Woodward, 1998). For example, when 6-month-old infants are habituated to a hand reaching for one of two objects on a stage, they show a novelty response (look longer) during test trials when the goal relation is disrupted (i.e., the hand reaches for a new goal) but not when the physical relation is disrupted (i.e., the hand takes a new path to the same goal). When infants see an inanimate object (e.g., a rod) perform the same actions, they do not differentiate between test trials, indicating that they differentiate between animate and inanimate agents and do not simply respond to a learned association between goal and hand in this paradigm (Woodward, 1998, 1999; see Woodward, Sommerville, Gerson, Henderson, & Buresh, 2009 for a review).

By the second half of the first year, this sensitivity to action goals is evident in infants' overt responses to others' actions. To illustrate, Hamlin and colleagues (Hamlin, Hallinan, & Woodward, 2008) showed 7-month-olds events in which an adult grasped one of two objects. When infants were given the opportunity to choose between the two objects, they systematically chose the adult's prior goal. In control conditions, Hamlin and colleagues demonstrated that infants' tendency to choose the adult's prior goal did not result from the way that the observed actions entrained infants' attention. Infants attended to the experimenter's object choice both when the experimenter grasped the object and when she acted on the object in an unusual or unfamiliar manner (e.g., touching the toy with the back of her hand); they only imitated, however, when the experimenter's action was interpretable as goal-directed (i.e., when she grasped). Thus, 7-month-old infants reproduced the goal-relevant aspects of the actions they had observed (see also Mahajan & Woodward, 2009).

Although infants are sensitive to some aspects of goal-directed action early in the first year, they do not recognize all actions as goal-directed initially. For example, the goal-relations underlying a person's gaze toward a particular object, an individual's use of a tool to retrieve an object, or two people working together toward a common goal are more difficult for infants to recognize initially. By the second year of life children can flexibly interpret others' actions, even when they are novel or when goals are not attained (e.g., Meltzoff, 1995), but several findings indicate limits in younger infants' abilities to fluently identify the intentional structure of abstract or complex actions (see Woodward et al., 2009 for a review). Thus, the range of actions infants interpret as goal-directed increases during early development.

For example, although habituation studies like the one described above have shown that infants are sensitive to the goal structure of reaching actions by 6 months (or 3 months when given training; Sommerville, Woodward, & Needham, 2005; Woodward, 1998, 1999), when studies like these involve tool use (e.g., grasping an object with a claw or cane), infants younger than 12 months do not recognize that the experimenter's actions are organized with respect to the goal object (Cannon & Woodward, 2010; Jovanovic et al., 2007; Sommerville, Hildebrand, & Crane, 2008; Sommerville & Woodward, 2005).

Tool use is one example of a developmentally important accomplishment for both action production and action understanding. Tool use actions are ubiquitous in everyday social environments, yet recognizing the goal of these actions may pose a conceptual challenge to infants. They are complex -- the agent's contact with the tool is not directed at the tool itself but at the object on which it acts and actions with tools are often produced with novel, unfamiliar objects. Because of the importance and relative complexity of tool use actions, I use the recognition of the goal-relations underlying tool use actions in this work as an example of the broader phenomenon of recognizing complex goal-relations.

The goal of this dissertation is to explore how infants become able to discern the intentional relations of others' increasingly complex actions. First, I discuss processes that have previously been shown to support infants' understanding of goal-directed action. I then consider the limitations of these mechanisms, particularly with respect to recognizing the intentional relations that structure the action used as an example throughout this research—tool use. Next, I propose a general cognitive mechanism that could overcome these limitations and provide further support for infants' emerging capacity to recognize increasingly complex actions as goal-directed. Specifically, I consider the possibility that structural analogies help infants gain insight into the goal structure of novel actions. I review evidence that structural analogy facilitates relational extraction in adults, preschoolers, and infants and I consider the extent to which this process could play a role in infant social cognition.

Sources of Infants' Understanding of Action Goals

Two broad sources of evidence have been argued to support infants' analysis of goal-directed actions. The perceptual cues inherent in observed intentional actions and experience acting as an intentional agent have both been proposed to provide important information about others' goals. Indeed, both of these sources of evidence seem to facilitate the detection of novel goal-relations. For the sake of brevity, in reviewing evidence for these sources, I focus on findings concerning recognizing the goals behind one example of the vast array of complex actions: tool use actions. The data summarized below emphasize how behavioral cues and active experience can facilitate the recognition of goals in tool use actions, but evidence concerning tool use actions describes just one piece of the puzzle involved in goal recognition of increasingly complex actions. Both sources have been proposed to drive goal recognition for other kinds of intentional actions as well (e.g., Bíró & Leslie, 2007; Gergely & Csibra, 2003; Gerson & Woodward, in preparation; Király, Jovanovic, Prinz, Aschersleben, & Gergely, 2003; Sommerville et al., 2005).

Perceptual Cues

Findings from several habituation studies indicate that infants tend to recognize familiar goals of human agents prior to recognizing similar action patterns as goal-directed when produced by or with inanimate objects (e.g., Bíró & Leslie, 2007; Jovanovic et al., 2007; Woodward, 1998, 1999). Without training or the addition of perceptual cues, infants interpret grasps as goal-directed by six months but fail to interpret tool use actions as directed toward a goal before twelve months (e.g., Sommerville, Hildebrand, & Crane, 2008; Sommerville & Woodward, 2005).

Recent work has provided infants with additional perceptual cues associated with animacy in order to support their interpretation of unfamiliar actions produced by a person or familiar actions produced by or with inanimate objects (i.e., actions produced by a person with a tool or by an inanimate rod [with no visible hand on the rod]). For example, Király and colleagues (Király et al., 2003) showed infants habituation events in which a person contacted one of two objects with the back of her hand and moved it to a new location. Eight-month-old infants could recognize the goal-relation between the person and the object she moved with the addition of the movement cue (infants at this age otherwise fail to recognize the goal of unfamiliar back of hand actions; Woodward, 1999). Similarly, Bíró and Leslie (2007) showed infants movement effects (a rod or hand picking up a goal toy), equifinality cues (the rod or hand reaching the same goal from several different starting points), and self-propelled movement (the rod or hand demonstrating self-driven movement prior to approaching a toy). The combination of these cues helped infants see the novel rod events as goal-directed earlier than they otherwise would.

Despite the benefits of these cues, younger infants seem less sensitive to behavioral cues than older infants. For example, in Király et al.'s (2003) studies, unlike 8-month-olds, the movement cue did not support 6-month-olds' interpretation of the back of hand action as goal-directed. Likewise, in Bíró and Leslie's (2007) studies, they tested 6-, 9-, and 12-month-olds and infants showed a developmental trend in which they recognized the goals of actions produced by a human hand prior to and with fewer cues than the same actions and cues presented by an inanimate rod. This indicates that the cues were less effective for younger infants than for older infants. Together, these findings suggest that movement cues can help older infants make sense of actions produced by or with a tool, but they are limited in that younger infants seem less sensitive to these cues and seem not to understand tool actions across various studies (see also Cannon & Woodward, 2010; Hofer, Hauf, & Aschersleben, 2005; Jovanovic et al., 2007; Sommerville & Woodward, 2005).

Active Experience

Another process that supports infants' analysis of goal-directed actions is active experience as an intentional agent. The benefits of self-produced experience for infants' understanding of novel goal-relations have been demonstrated in both correlational and training studies. Young infants begin to recognize the goals of particular kinds of actions around the same time they can first produce the actions themselves. For example, Sommerville and Woodward (2005) demonstrated that variability in infants' ability to pull a cloth to retrieve a toy in a well-organized manner was correlated with their understanding of the goal of this action when performed by an experimenter in a looking-time study (see also Brune & Woodward, 2007). This correlation was not due to an age difference (all infants examined in this correlation were around ten months) but rather differences in infants' individual skill level. Additionally, training infants to produce a new action helps them see this action as goal-directed when produced by another (Gerson & Woodward, in preparation; Sommerville, Woodward, & Needham, 2005). For instance, Sommerville and colleagues (Sommerville, Hildebrand, & Crane, 2008) trained one group of 10-month-old infants to pull on a cane to retrieve a toy. A second group of 10-month-old infants observed the experimenter train another experimenter to use the cane to retrieve toys. Infants who received active training, but not those who underwent observational training, subsequently detected the goal-relation in this same action (between experimenter and toy reached with the cane) performed by an experimenter in a habituation paradigm.

As described above, infants' recognition of the goal-relations inherent in tool use actions is limited in the first year of life. Though studies like that described above (Sommerville et al., 2008) indicate that infants can be *trained* to produce means-end actions within the first year of life, these actions do not naturally emerge until about twelve months of age (Sommerville & Woodward, 2005). According to Piaget (1954), infants cannot engage in means-end problem solving until approximately 8 to 12 months of age (substage four of the sensorimotor period: coordination of secondary circular reactions). Earlier in the first year, infants sometimes retrieve toys using tools but often do so incidentally through play with the tool rather than intentionally (Willatts, 1999). Further, infants do not succeed in solving all tool use problems simultaneously. For example, in a study by Bates and colleagues (Bates, Carlson-Luden, & Bretherton, 1980), a group of infants had more difficulty solving tool use problems when the tool and goal matched in color and texture than when they were perceptually differentiated. Even though infants can produce some forms of tool use during their second year, their capacities are still more limited than adults due to the motor demands of using certain tools.

The combination of the relatively late emergence of means-end action production and the ubiquity of tool use actions surrounding infants highlights a limitation of the role active action production can play in supporting goal recognition throughout development. It is not just during infancy that humans are surrounded by individuals producing actions they have never produced themselves (and not just with tool use actions). If we were limited to interpreting intentional actions solely based on our own action experience, the development of action understanding would be a slow, piece-meal, and incomplete process.

We know, however, that humans are not restricted to understanding only the specific actions they can or have produced themselves. Human adults seemingly automatically attribute goals and intentions to novel, unfamiliar agents. In a classic study, adults who viewed animated geometric objects move around a screen in a seemingly non-random fashion created elaborate stories about the actions and intentions of these shapes (Heider & Simmel, 1944). Although there is some debate as to whether young infants see events like these as intentional, evidence indicates that older infants (12 months and older) can infer the goals of similarly abstract actions. When 12-month-old infants were habituated to an animated ball moving over a barrier and stopping near another animated object, they later dishabituated to events in which the ball took the same path over a non-existent barrier (when the barrier had been removed) rather than the more efficient path to reach its “goal,” indicating that they expected the animated object to act rationally and efficiently in achieving its assumed goal (moving straight to the other shape without jumping when no barrier was present; Gergely & Csibra, 2003; see also Kuhlmeier, Wynn, & Bloom, 2003). Therefore, experience as an agent cannot explain all action understanding in and of itself, even within the first few years of life.

These abstract and unusual circumstances of animated agents are not the only cases in which we recognize the goals of actions we have not produced. In fact, we recognize the goals of many actions we observe in our everyday lives but have not produced ourselves. Individuals who are not prone to cooking and have little experience in the kitchen still recognize the intentions of an individual they observe moving throughout a kitchen and carrying out a sequence of actions aimed at making a meal. Those who have never worked in a yard or garden still recognize someone's goal when they see that person using pruning sheers in his or her backyard. And even those who have never owned a toolbox and would not be able to tell the difference between a phillips and slotted screw recognize a builder's goal when he uses a screwdriver to put a bookcase together. All of these actions occur regularly in infants' environments but are not actions infants engage in themselves.

Because infants struggle to perform tool use actions themselves and seem to derive little benefit from abstract perceptual cues early in life, in this dissertation, I explore how a different mechanism, structural analogy (described in the following section), could aid infants in recognizing the goal behind tool use actions in the first year. As described above, I examine the problem of tool use as one example of the broader phenomenon of learning about goals behind increasingly complex actions. I expect, however, as I discuss in more detail later, that similar processes to those proposed in this work likely play a role in recognizing the goals behind other actions as well.

A Proposal: Structural Analogies Support Infants' Learning About Novel Actions

In this dissertation, I consider a mechanism that could complement either of the two above-described sources of information (active experience and perceptual cues). Specifically, I consider the possibility that structural analogies between familiar and novel actions contribute to infants' recognition of the goals of novel actions. Learning the goal of a novel action through comparison with a familiar action requires detecting the relational similarity between the two actions. That is, one must understand that, like the familiar action, the relation between the agent and his goal structures the novel action.

Detecting and generalizing relational information is a cognitive challenge across domains and throughout development. Even adults often struggle to detect relational similarities because of the salience of contrasting perceptual similarities. Gentner (e.g., Gentner, 2003) has proposed a domain general cognitive learning mechanism to address this difficulty: structure mapping. According to structure mapping theory, mentally aligning two exemplars supports comparison between the exemplars and the extraction of relational similarities. When the relational structure of one exemplar is known, it can serve as a base for analogical extension, supporting the inference of similar relational structure in a novel instance. The use of this kind of analogical learning has been shown to facilitate relational reasoning in both adults and children, as described below (e.g., Bowdle & Gentner, 2005; Gentner, 1988).

Structural Analogies in Preschoolers and Adults

Research citing the supportive role comparison plays in relational extraction spans several cognitive domains, including spatial reasoning, categorization, and word learning (e.g., Bowdle & Gentner, 2005; Gentner, 2003). Much of this evidence has been found with preschoolers. For example, in a study by Christie and Gentner (2010), comparison supported 3-year-olds' categorization of objects based on relational properties. In this study, children were shown cards depicting a set of animals in a novel spatial arrangement. One group of children saw one card prior to test trials and a second group had the chance to compare two cards (containing different animals but in the same spatial relation). In test trials, children were then asked to find a card that matched a given example. They had the chance to choose between an object match (same animals in a different spatial configuration) and a relational match (same spatial configuration with different animals). Children who compared two structurally matched cards prior to test trials were more likely to choose the relational match than children who only saw one card. This is one of many studies supporting the notion that comparison of structurally similar examples facilitates extraction of relational similarities in preschoolers (see Gentner, 2003 for a review).

Despite the benefits of comparison, perceptual similarities often override relational similarities. In fact, even adults often struggle to create analogies based on relational information when the relational matches compete with matching surface similarities (e.g., Chi, Feltovich, & Glaser, 1981). Several factors, however, facilitate mental alignment and comparison in both adults and preschoolers.

One of the simplest ways comparison can be promoted is through concurrent presentation of exemplars. When two items are presented side-by-side, an individual is likely to mentally align the exemplars, compare both the features and the relations in each, and extract the structural similarities between the exemplars (e.g., Christie & Gentner, 2010; Loewenstein & Gentner, 2001; Namy & Gentner, 2002). Labels also facilitate comparison in preschoolers and adults (e.g., Loewenstein & Gentner, 2005; Ratterman & Gentner, 1998). When an experimenter provides labels that name the spatial relation to be mapped in a task (e.g., using the word "middle" to describe a particular shelf of a bookcase in a hiding room rather than using the word "here"), preschoolers are more likely to extract this relation and map it onto a new exemplar (e.g., the "middle" of a bookcase in a finding room). Labels help children focus their attention on the structure of an exemplar rather than the perceptual features during the process of comparison.

Importantly, comparison can support relational extraction without the construction of an explicit analogy. Comparison can highlight relational similarities even in very young children, and as I review below, even in infants. Further, factors facilitating comparison (e.g., simultaneous presentation and labels) can also function without explicit awareness and were adapted for use with infants in the current research.

Structural Analogies in Infants

Recent evidence suggests that analogical mapping supports learning about relational similarity even in infancy. According to Gentner (1988), the development of relational reasoning is expertise-driven rather than developmentally-driven and occurs separately for different domains. Similarly, Goswami (1996) puts forth a *relational familiarity hypothesis*, citing evidence that knowledge about particular relations (e.g., causal relations) affects children's performance on analogy tasks relying on recognition of relations within the domain (see Ratterman & Gentner, 1998). She theorizes that the capacity to engage in analogical reasoning exists in infancy and application of analogical reasoning to new domains comes about through increased knowledge within that particular domain. Both of these perspectives suggest that infants should be able to use relational knowledge to reason analogically in domains in which they have expertise.

Research by Chen and colleagues (Chen, Sanchez, & Campbell, 1997) implies that comparison supported relational extraction during problem-solving training for 13-month-old infants. In this study, infants were given the opportunity to solve three consecutive problems sharing similar problem structure; comparison of these structurally similar problems aided extraction of an analogous solution across problems. In order to retrieve a goal in this task, infants needed to remove a barrier and then pull on one of two cloths in order to reach one of two strings that they could then pull to retrieve a toy (thus requiring the achievement of three subgoals: barrier, string, and cloth). In the first two of three trials, infants were shown a model of the proper way to complete the task if they did not do so successfully on their own. Infants improved in achieving the goal in a well-organized manner (e.g., contacting the relevant cloth and string first) from the first example to the second and third. Thus, infants benefited from comparing the modeled action to the problem in front of them and were able to extract the relations between the tools and goal objects that were fundamental to solving the problem.

Burgeoning evidence indicates that infants benefit from comparison across a variety of domains, including categorization, physical reasoning, verb learning, and action production (e.g., Baillargeon & Wang, 2002; Chen, Sanchez, & Campbell, 1997; Childers, 2008; Oakes & Ribar, 2005; Wilcox, Smith, & Woods, 2011). Additionally, factors that facilitate comparison in older children also play a role in driving mental alignment for infants. Benefits of simultaneous presentation and labeling on relational extraction in infancy have also been found in the first year of life.

For example, Pruden and colleagues (Pruden, Hirsh-Pasek, Maguire, & Meyer, 2004; Pruden, Shallcross, Hirsh-Pasek, & Golinkoff, 2008) found that simultaneous comparison of exemplars facilitated infants' detection of the relational similarity between structurally similar actions. In this line of research, Pruden et al. examined 7- to 9-month-old infants' capacity to abstract an object's consistent path across varying manners. For example, infants were shown an animated starfish that moved *over* a dot on a screen (in contrast to moving under or past the dot) in several different manners (e.g., spinning, jumping, side bending). When infants were able to simultaneously view and compare the starfish engaging in two different but structurally matched actions during familiarization trials (i.e., the starfish moved along the same path but in two different manners on screens next to one another), they then looked longer to test events in which the starfish moved along a new path than to test events in which it moved in a new manner along the same path (Pruden et al., 2008). In contrast, when they saw the same familiarization events consecutively rather than simultaneously, they did not show a novelty response to new path movements during test trials (Pruden et al., 2004). This suggests that infants extracted relational information through the comparison of simultaneously presented exemplars.

Further research conducted by Pruden and colleagues (Pruden & Hirsh-Pasek, 2006) provides evidence for the benefits of labels on relational extraction in infancy. As in the study by Pruden and colleagues discussed above (Pruden et al., 2008), 7- to 9-month-old infants saw a cartoon starfish move across a screen several times during familiarization. In this study, infants always saw these familiarization trials presented consecutively rather than simultaneously. The starfish once again moved in a different manner during each familiarization trial (e.g., spinning or bending) but traveled a consistent path. Throughout the familiarization trials, one set of infants heard a novel verb: *javing.* The infants who heard the label during familiarization (but not those who did not hear a label) then showed a novelty preference for the starfish moving in a different path during test. This finding demonstrates that labels supported infants' comparison of exemplars and helped them detect similarities in path across exemplars that were presented consecutively.

Together, these studies show that comparison between multiple exemplars facilitates extraction of relational similarities in infancy. The benefit of simultaneous presentation of exemplars implies that infants' comparison of the two exemplars was critical to relational extraction. This comparison then enables infants to detect relational similarities across exemplars and to detect relational properties of novel events. Further, labels were shown to facilitate relational extraction in the first year of life. Collectively, this work indicates that structure mapping is a domain-general mechanism that is active in the first year of life and can support infants' extraction and generalization of relational information.

Comparison in the Domain of Social Cognition

It has been proposed that comparison processes play an important role in infants' social cognitive development as well. In a seminal theoretical paper, Barresi and Moore (1996) formulated an account of how comparison could support analogical insights in the context of joint attention. During joint attention, the infant's intentional actions are physically copresent with and directed at the same object as an adult. Barresi and Moore hypothesized that this physical alignment of the intentional relation between the infant and the object of his gaze can be compared to the intentional relation between the adult and the same object, allowing infants to map this intentional relation from self to other. Although it may be possible to gain insights from comparing the actions of observed social partners to one another, Barresi and Moore (1996) hypothesize that comparison to oneself is particularly informative because it enables infants to draw on their own experience in attending to objects in understanding others' states of attention.

In support of this perspective, research by Moll and colleagues (Moll, Carpenter, & Tomasello, 2007; Moll & Tomasello, 2007) indicates that infants learned about others' knowledge states from participation in joint engagement before they were able to extract this same information from observing social partners jointly engaged in play with an object. In a series of studies, 14-month-old infants either engaged in joint play on a toy with an experimenter or observed this experimenter jointly play with the toy and a second experimenter. Infants were later able to identify which toy the experimenter had previously seen only in the case in which the child actively participated in joint engagement with the experimenter and not when he or she observed the experimenter engaged in play with another social partner. This suggests that active participation in joint actions uniquely informed infants' understanding of others' knowledge states. Comparable to Barresi and Moore's (1996) perspective, Tomasello and Moll (2007) claim that participating in collaborative interactions with "shared intentionality" allows an infant to create "perspectival" cognitive representations and "conceptualize the interaction simultaneously both from the first and third person's perspective" (p. 344).

As in the above-described theories, Meltzoff (2005, 2007) proposes that observation and execution of actions are innately coupled in humans. He argues that infants' understanding of others' intentions is a product of the recognition of other humans as agents that are "like me," the propensity of infants to imitate other humans, and the matching of one's own actions and mental states with those of others.

The hypothesis I put forth is in accordance with the perspectives put forth by Barresi and Moore (1996), Tomasello and Moll (2007) and Meltzoff (2005) in that I also suggest that infants learn about others' intentions through comparisons between self and other during social interactions. According to my proposal, however, the knowledge gained from joint actions with a social partner is a function of the supportive environment created by joint actions for comparing the intentional relations driving one's own actions and those of the social partner. When infants reach for a toy at the same time as a parent, for example, they have the chance to view the physical alignment of their reach for an object with the parent's reach and can extract the relational goal (between agent and object) shared by themselves and their parent. Like the simultaneous presentation of similar spatial relations described above (e.g., Pruden et al., 2006), simultaneous engagement in joint actions allows individuals to align and compare concrete elements of exemplars (e.g., the starfish and its movement or the people and objects with which they engage) and extract abstract relations (spatial and intentional relations). I test this hypothesis in the studies presented below.

Current Research

In the following series of experiments, I examined whether comparison supported infants' detection of relational structure in others' goal-directed actions. As an example of the broadening of action understanding, I considered two ages at which infants recognize the goal of grasping actions but do not yet recognize tool use actions as goal-directed (7 and 10 months) and examined whether comparison helped these infants detect the goals of tool use actions earlier than they otherwise would.

In all of the studies, I used a goal-imitation paradigm based on Hamlin and colleagues' paradigm (Hamlin et al., 2008) to assess infants' understanding of the goal of a tool use action. In Hamlin and colleagues' study, 7-month-old infants saw an experimenter select one of two toys and were then given the chance to choose a toy themselves. The experimenter either selected the toy using a familiar intentional action (e.g., a grasp) or an ambiguous action (e.g., touching the toy with the back of her hand). If infants understood the action as goal-directed, they should have imitated the experimenter's goal by choosing the same toy she chose. Infants in this study imitated the experimenter's toy-choice when she chose the toy using a familiar, goal-directed action but not when she chose the toy using an ambiguous action. These findings are in accord with results of looking time studies indicating infants at six months detect goals in grasps but not back of hand gestures. They demonstrate that imitation of intentional actions closely follows understanding of these actions. This paradigm allows the examination of whether infants can detect and imitate an experimenter's goal when the experimenter uses a tool to reach her goal.

In the current studies, all infants viewed test trials in which an experimenter reached for one of two toys using a claw as a tool and were then given the chance to choose a toy themselves. As a point of clarification, in this paradigm, imitation refers to recognizing and choosing the same *goal* as the experimenter. It does not require the imitation of the exact action produced by the experimenter in order to achieve her goal. Infants did not have the opportunity to act on the toys with the tool in any of the following studies. Instead, I examined goal imitation (choosing the toy by intentionally touching it) as a measure of recognition of the goal of the experimenter's action.

I present a dissertation of four experiments using the above-described method to assess whether analogical learning plays a role in action understanding. In an initial study (Study 1), I allowed one group of 7-month-old infants to simultaneously compare a familiar action (their own grasp) with a novel action (an experimenter's grasp with a tool) through physical alignment and examined whether this facilitated analogical extension of the goal-relation. I assessed infants' imitation of the experimenter's goal (when using a claw) relative to that of infants who were familiarized with the claw and its properties but were not given the chance to align their goals with the experimenter using the claw. In Study 2, I aimed to replicate the effect of physical alignment in 7-month-old infants with a slight variation in the paradigm and also control for the effects of social contingency, a cue that aids infants in inferring intentionality (e.g., Johnson, Shimizu, & Ok, 2007). In a third study, I investigated whether active engagement in physical alignment was equally or more beneficial than the observation of physical alignment in 10-month-old infants. In Study 4, I provided a further test of the comparison process by giving infants observing physical alignment an additional cue that has been shown to facilitate comparison and relational extraction: a label. In this study, infants once again observed the physical alignment of a familiar and novel action, and they also saw the goal labeled by both experimenters during each demonstration.

Broadly, these experiments examined whether structure mapping facilitates the generalization of action understanding. Specifically, in this series of experiments, I examined:

- Whether simultaneous presentation of familiar and unfamiliar goal-relations through physical alignment aided infants in detecting the novel, tool use goal-relations (Study 1)
- Whether other perceptual cues about the tool's properties provided the same benefits (Study 1)
- Whether social contingency could have driven imitation in the physical alignment condition in the first study (Study 2)
- Whether observing physical alignment leads to similar goal-imitation as active engagement in physical alignment (Study 3)

- Whether factors shown to facilitate alignment in older children and in different domains also facilitated alignment for infants in the domain of action understanding (Study 4)

Study 1

In Study 1, I conducted the first examination of comparison as a mechanism for the generalization of action understanding in 7-month-old infants. I considered an action that infants this age do not readily see as goal-directed (a tool use action) and investigated whether providing the opportunity to simultaneously align this action with an extremely familiar, well-understood action (their own grasping action) provided support for extracting and imitating the goal of the novel action.

As described above, all infants in the current study (and all studies following) viewed test trials in which an experimenter chose between two toys using a claw as a tool and infants were then given the chance to act on the toys themselves. Because infants of this age do not yet detect the goals behind tool use actions even with perceptual cues, I hypothesized that infants who viewed an experimenter using a tool to choose a toy would not imitate the experimenter's toy-choice on their own. I further hypothesized that allowing infants to simultaneously compare a familiar action with the novel, tool use action would facilitate extraction of the goal of the novel action and thus lead to imitation.

In Study 1, infants participated in one of three conditions: *physical alignment, control touch,* or *control move*. In the *physical alignment condition*, before test trials, infants were given the chance to physically align their reaches for toys with the experimenter's reaches for toys with a tool (a claw). Infants were passed each toy by the experimenter with the tool, allowing them to simultaneously compare a highly familiar action (their own grasp) with the novel action (the experimenter using the tool to grasp the toy). I hypothesized that this physical alignment would allow the infant to compare the familiar and novel action and thus extract the goal-relation inherent in the experimenter's action with the tool. This goal-detection should then lead the infant to imitate the experimenter's toy-choice in test trials (see Hamlin et al., 2008, described above).

Two control conditions were conducted to evaluate whether positive findings in the *physical alignment condition* depended on alignment per se rather than the behavioral cues present in the event or the mechanical information it provided. Infants in the *physical alignment condition* and both control conditions saw the experimenter manipulate the claw and look at the toy she grasped during test trials. To adults, these cues are sufficient for recognition of the experimenter's action as goal-directed. Although this may also be true for older infants, evidence suggests that 7-month-old infants do not interpret tool use as goal-directed even with these cues. Infants are not sensitive to the goal-directed nature of gaze (e.g., Woodward, 2003) and seem not to use coordinated gaze as a cue for other means-end actions (e.g., Sommerville & Woodward, 2005) before 12 months of age. Despite lack of evidence suggesting that infants can use these cues at this age, the current control conditions counter the possibility that any findings in the *physical alignment condition* are due to these cues. If these cues were sufficient to lead to goal imitation in the *physical alignment condition*, infants should also imitate the experimenter's goals in both control conditions.

The two control conditions further accounted for additional cues present in the *physical alignment condition.* In the *control touch condition,* infants were given the opportunity to engage with the claw without a toy present on which to physically align their goal. This allowed infants to gain familiarity with the mechanics of the claw and gave them the opportunity to touch and interact with the claw. In the *control move condition*, infants watched the experimenter move each of the toys with the claw without allowing infants the opportunity to reach for the claw while it acted on the toy. This controlled for learning the causal properties of the tool. As discussed in the introduction, behavioral cues such as movement of a goal support infants' goal analysis in some cases, though research indicates this cue is not sufficient for learning the goals of novel actions for younger infants (e.g., Bíró & Leslie, 2007; Jovanovic et al., 2005). Assuming that physical alignment is the vital component driving infants' actions, infants in the *control touch* and *control move* conditions should not imitate the experimenters' actions with the tool despite these added perceptual cues.

Methods

Participants*.* Sixty full-term 7-month-old infants (6.5-7.5 months) participated in this study. Infants were recruited from the Washington, DC metropolitan area through mailings and advertisements. Twenty infants participated in each of the three conditions: *physical alignment* (10 boys; *M* age = 6;28), *control touch* (10 boys; *M* age = 6;27), and *control move* (9 boys; *M* age = 6;24). Twenty additional infants began the study but were not included in final analyses due to side preference (*n* = 11; i.e., only reaching to one side of the tray across test trials), or inactivity (i.e., not acting on either toy for more than half of the test trials) or inability to complete the procedure due to crying (n = 9). The sample of infants was 20% African-American, 53% Caucasian,10% Hispanic, 12% multiracial, and 5% unreported.

Procedure. Infants in all conditions sat on a parent's lap at a table (at torso level) across from an experimenter (approximately 76 cm away). Parents were told not to influence their infant's actions in any way by talking, pointing, or generally interfering. A camera behind the experimenter focused on the infant and a camera behind the infant focused on the event. These recordings were then used for offline coding.

The procedure began with a familiarization phase. All infants were familiarized to each of the 12 experimental toys (in a randomized order), which were presented to them on alternating sides of a rectangular 76 cm X 23 cm marble gray laminated foam core tray. The infants' experience with the claw during the familiarization phase differed among the three experimental conditions (see Figure 2.1). In the *physical alignment* condition, the experimenter passed infants each toy using the claw. She passed the toys one at a time and then retrieved the previous toy from the infants with her hand before passing the next toy with the claw. This familiarization phase allowed infants to physically align their reach for the toy with the experimenter's reach with the claw up to 12 times (infants initiated their reaches during the claw's reach on approximately 87% of trials on average). In both the *control touch* and the *control move* conditions, the experimenter passed the infants each toy with her hand (without the claw).

A. B. C.

Figure 2.1. Infants in the *physical alignment condition* physically aligned their reach for the toy with the claw's reach (A). Infants in the two control conditions were first passed each toy by the experimenter and were then familiarized with the claw by either being able to touch it without a toy present (*control touch;* B) or by viewing the experimenter move each toy across the tray with the claw (*control move;* C).

After interacting with each toy, infants in the control conditions were familiarized to the claw in one of two ways before test trials. In the *control touch condition*, infants were given approximately 20 seconds to reach for, grasp, and/or view the claw (held by the experimenter) in order to control for experience interacting with the experimenter holding the claw and learning the mechanics of the claw. The experimenter showed the infant that the claw opened and closed, but there was no toy with which the infant could align his or her reach. Infants in the *control move condition* watched the experimenter move each of the toys across the table using the claw in order to account for the benefit of viewing the claw's causal properties (i.e., that it could move toys). The experimenter ensured that the infant watched each movement and drew the infant's attention to the action if looking away. In this way, infants saw the experimenter acting on the toys with the claw but were not able to reach for the toys themselves simultaneously and thus not able to align their goals with the experimenter's during tool use.

After familiarization, infants in all three conditions underwent the same exact test trials. During test trials, infants were presented with a pair of toys, 28 cm apart, on the same tray as in familiarization. First, the experimenter ensured that the infants saw both of the toys and made noise on each side to direct the infant's attention if necessary. She then made eye contact with the infant and said, "Hi! Look!" As the experimenter said look, she shifted her gaze toward the target toy. She then reached contralaterally and grasped the toy using the claw but did not pick up or move the toy (see Figure 2.2). The experimenter gazed at the toy throughout the grasping episode and said "Oooh!" twice in order to engage the infant's attention. The experimenter then withdrew the claw, placed it on her lap, and again established eye contact with the infant. Once eye contact was established, the experimenter said "Hi!" pushed the tray to the infant's side of the table, and said, "Now it's your turn!" She then looked down so as not to influence the infant's choice in any way.

This procedure was repeated for six trials with a new pair of toys presented for each trial. Infants saw the same 12 toys, each of which they had had the opportunity to interact with during familiarization. The experimenter alternated reaching for the toy to her left or right. Between infants (within each condition), the experimenter reached for each toy 50% of the time, and side of placement of each toy and side of first reach was counterbalanced. The order of the pairs was randomized.

A. B.

Figure 2.2. Infants in all conditions across all experiments underwent the same exact test trials after familiarization. They viewed the experimenter choose between two toys using a claw (A) and were then given the opportunity to choose a toy themselves (B).

Coding. Infants' goal imitation in test trials was coded through video by trained observers who were unaware of the condition and the target toy in each trial. Infants' first intentional touch was coded as the first toy the infant looked at and then reached for and touched. If the infant touched a toy without looking and the touch subsequently drew the infant's attention to the toy, this was coded as a mistrial. A second independent coder scored all of the infants, and the two coders agreed on 95% of the trials.

In addition, I assessed the amount of visual familiarity infants received with both the claw and the experimenter during familiarization in each condition. A trained coder measured infants' attention during the familiarization phase using a digital coding program (Mangold, 1998). In the *physical alignment condition,* infants' attention to the claw, toy, and experimenter were coded for each instance of toy passing. In the *control touch condition,* infants' attention to the claw and experimenter was coded for the period during which infants had the chance to engage with the claw. In the *control move condition,* infants' attention to the toy, claw, and experimenter was measured during each movement of the toys by the claw. A second independent coder coded 25% of the infants' familiarization trials and the two coders' judgments were strongly correlated (*r's* > .90).

Although infants viewed identical test trials, it is possible that experience in familiarization could have led to differential attention during test trials across the conditions. In order to assess whether each condition was equally successful in drawing infants' attention to the action and the experimenter's goal during test trials, infants' attention to each toy and the experimenter during the target action (the experimenter's toy reach demonstration) was assessed. Coders could not see the event during coding and were thus blind to condition. They coded infants' attention to the different pieces of the event at the start of each trial, beginning with "Look!" and ended coding when the claw withdrew from the toy. A second independent coder coded 25% of the infants' test trials and the two coders' judgments were strongly correlated (*r's* > .90).

Results

The focal analyses examined the proportion of trials on which infants chose the experimenter's goal toy. Preliminary effects indicated no effects of gender, so it was not included in further analyses. A one-way ANOVA with condition as the between subjects factor indicated that infants' toy choices differed by condition, $F(2, 57) = 3.92$, $p = .025$ (partial $\eta^2 = .12$; see Figure 2.3). Due to our hypothesis that infants in the *physical alignment condition* would imitate more than infants in either control condition, a priori tests were conducted using LSD to evaluate pairwise differences among the means. As expected, these comparisons revealed that infants in the *physical alignment condition* chose the goal toy significantly more often than infants in both the *control touch* (*p* = .035) and *control move* (*p* = .011) conditions. Furthermore, infants in the *physical alignment condition* selected the goal toy more often than would be expected by chance (50%), *t*(19) = 2.59, *p* = .018. Infants in the control conditions did not differ from chance in their choices (*t*'s < 1). Thus, infants who aligned their actions with the experimenter's tool use actions subsequently imitated the goal of the experimenter's tool use actions, but infants familiarized with the claw and its functional movements did not.

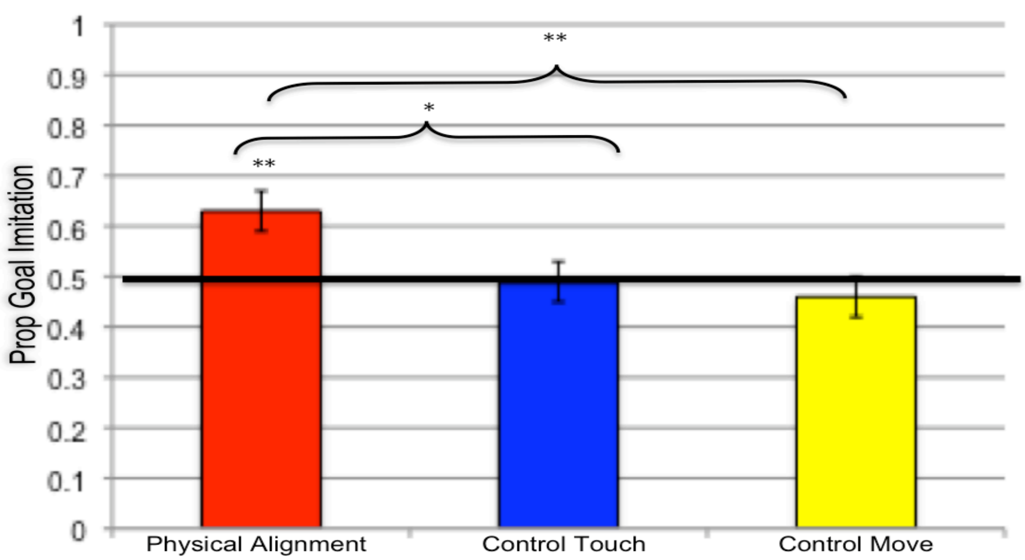


Figure 2.3. Infants in the *physical alignment condition* chose the experimenter's goal toy significantly more than infants in both the *control touch* and the *control move* conditions and significantly more than would be expected by chance. ** *p* < .02; * *p* < .05

In follow-up analyses, I evaluated whether differences in infants' responses could be attributed to lower level effects of familiarization on infants' attention to the toys, experimenter, or claw. In particular, I wondered whether the *physical alignment condition* supported infants' goal imitation simply because it led to more attention on the claw or experimenter. There were differences across conditions in infants' attention to the claw ($F(2,52) = 28.33$, $p < .001$), but these differences did not coincide with systematic performance on goal imitation. Infants in the *control move condition* attended most to the claw ($M = 29.16$s, $SD = 3.80$), infants in the *control touch condition* attended least ($M = 16.84$s, $SD = 3.14$), and infants in the *physical alignment condition* fell between these two groups ($M = 23.55$, $SD = 7.16$). Furthermore, attention to the claw was not related to infants' rates of imitation in any condition (*p's* > .6). Infants' attention to the experimenter during familiarization did not vary as a function of condition ($F(2,52) = .94$, $p = .34$) and was not related to imitation in either control condition (*p's* > .6). In the *physical alignment condition,* attention to the experimenter during familiarization was marginally related to imitation during test trials ($r = .46$, $p = .056$; see Figure 2.4).

Next, I verified that infants' attention to the experimenter and the goal toy during test trial demonstrations did not differ across conditions. One-way ANOVAs indicated that attention to the goal and experimenter did not differ between conditions (*p*'s > .6). In each condition, infants spent significantly more time attending to the experimenter's goal than the non-goal (the other toy present; *p*'s < .03; see Figure 2.5). Moreover, attention to the experimenter's goal or to the experimenter during test trial demonstrations was not related to imitation in any condition (*p*'s > .17).

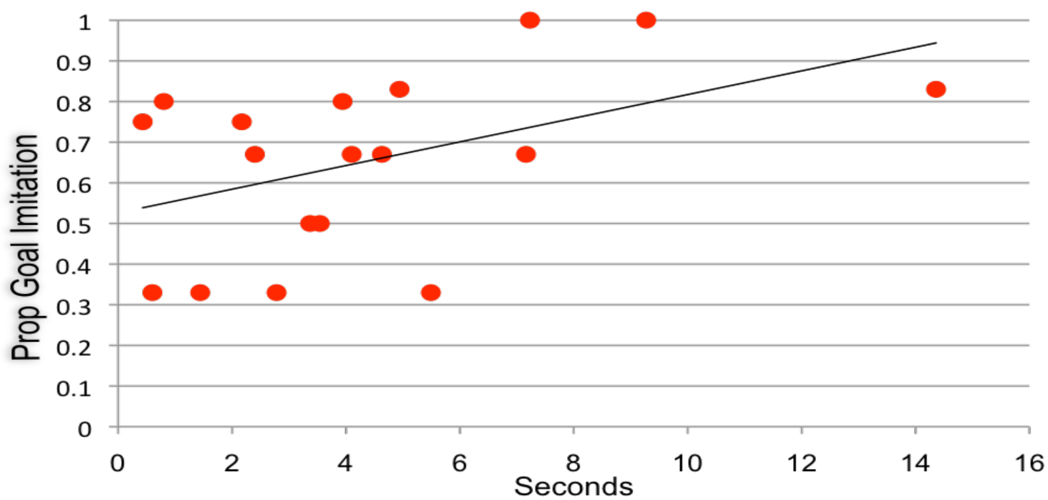


Figure 2.4. Attention to the experimenter during familiarization trials was marginally related to infants' goal imitation in the *physical alignment condition.*

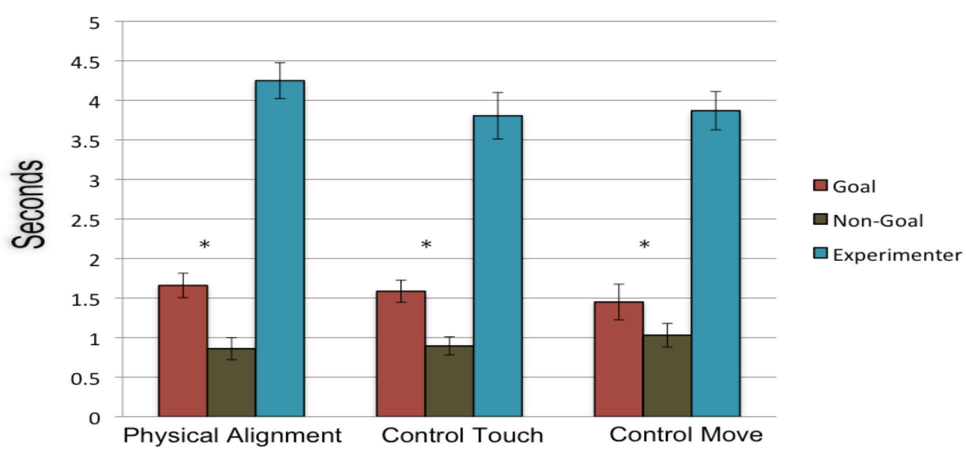


Figure 2.5. Infants' attention to test trial demonstrations was similar across all three conditions in Study 1. One-way ANOVAs indicated that attention to the goal, non-goal, and experimenter did not differ between conditions (*p*'s > .6). In each condition, infants spent significantly more time attending to the experimenter's goal than the non-goal (**p*'s < .03).

Thus, I found no evidence that differences between infants' responses in the different conditions resulted from differences in how their attention was directed during either test trial demonstrations or familiarization.

Discussion

In this initial study, I asked whether infants used knowledge about a familiar action to make sense of a novel one. Results suggest they did. As in prior studies, current findings indicate that 7-month-old infants had difficulty discerning goals of tool use actions. When infants first aligned their actions with the tool use actions, however, they subsequently responded selectively to the goal structure of the tool use event. Specifically, infants who had acted simultaneously on a toy with an experimenter using a claw later imitated the goal of the experimenter's tool use actions. Because the infant and claw acted on each toy during physical alignment training (i.e., not only the toys later chosen by the experimenter in test trials), infants' goal imitation during test trials could not be due to reinforcement of actions on particular objects. Rather, physical alignment training provided infants with information about the claw actions they then used during test trials.

The fact that goal imitation in the *physical alignment condition* was marginally related to infants' attention to the experimenter during the familiarization phase suggests that infants who referenced the experimenter during engagement in alignment were more likely to extract and imitate the goal of her tool use action. Importantly, infants' attention to the experimenter during non-alignment events (reaching for the claw without a toy or watching the experimenter move the claw/toy in control conditions) was not related to their later imitation. Although this marginal finding is not conclusive, it is worth pursuing in future research.

There were several cues in the *physical alignment condition* that could have supported infants' goal analysis, but the findings of the control conditions suggest that physical alignment per se was critical for this effect. In each condition, infants saw the claw wielded by an experimenter who coordinated her attention and actions on the objects during test trials. To adults, these aspects of the event provide clear evidence that the claw movements were goal-directed, but, given the negative findings in the two control conditions, they seemed not to drive infants' goal analysis. The *physical alignment condition* also involved a social interaction with the claw and experimenter and demonstrations of the claw's functional capabilities (that it moved objects). The *control touch condition* allowed infants to interact with the claw in the course of a contingent social interaction. The *control move condition* showed infants that the claw could move objects. Lack of systematic responses in either of the control conditions suggests that none of these cues supported 7-month-olds' goal analysis in this study. This finding is consistent with previously summarized results showing that infants younger than 9-12 months are relatively insensitive to movement cues involving tool use (Cannon & Woodward, 2010; Hofer et al., 2005; Jovanovic et al., 2007). The current findings suggest that physical alignment between their own, familiar action, and a novel action played a critical role in supporting infants' analysis of the novel action as goal-directed.

Despite all of these controls, an alternative explanation concerning infants' imitation in the *physical alignment condition* remains. In this condition, infants saw iterative presentations of the claw holding the toy, after which they were able to grasp the toy held by the claw. This association between the claw and a toy with which they then had the opportunity to engage might have led infants to choose the toy with which the claw was associated in each test trial. To clarify, infants could not have learned that the claw was associated with particular toys later chosen in test trials (as they saw the claw with all 12 toys in familiarization). Instead, it has not yet been ruled out that infants in the *physical alignment condition* learned that they got to play with the toy that was presented within the claw's grasp and used this information to choose the toy the experimenter reached for with the claw in test trials. In order to evaluate this alternative explanation for the findings, I conducted a followup study (Study 1B) in which infants were given the opportunity to grasp toys that were held by the claw during familiarization, but the claw was not used as a tool by the experimenter. Thus, the contingency between seeing the claw and receiving the toy was the same as in the *physical alignment condition* of Study 1, but this experience did not occur in the context of infants' actions (and goals) being aligned with those of the experimenter.

Study 1B

Methods

Participants*.* Twenty full-term 7-month-old infants (6.5-7.5 months) participated in this study (10 males; *M* age = 7;1). Eight additional infants began the study but were not included in final analyses due to side preference (*n* = 7), or inactivity or inability to complete the procedure due to crying (*n* = 1). Infants were recruited from the Washington, DC metropolitan area through mailings and advertisements. The sample of infants was 15% African-American, 5% Asian, 45% Caucasian, 25% Hispanic, and 10% multiracial.

Procedure*.* Infants sat on a parent's lap at a table across from an experimenter. Parents were not informed of the experimental hypotheses and were asked not to influence their infant's actions. Infants' responses and the experimenter's actions were video-recorded on two cameras for subsequent offline coding.

Infants were familiarized to both the claw and each toy by being passed the mat 12 times (once for each toy), on which both a toy and the claw rested (see Figure 3.1). The claw was secured to the mat so the infant could not pick it up. The toy, however, was free for the infant to grasp and/or pick up. If infants did not immediately attend to the toy, the experimenter drew the infant's attention to the toy by tapping near it. The mat was passed to the infants with the claw resting on it with each toy consecutively. This gave infants the opportunity to associate the claw with each toy without the chance to compare the experimenter's goal when using the claw with their own goal (because the experimenter did not hold the claw during familiarization trials in this condition). Immediately after familiarization, infants underwent the same exact test trials as infants in Study 1. Coders once again assessed infants' toy-choice (a second, reliability coder agreed on 96% of trials) and measured infants' attention to the claw, toys, and experimenter during both test trials (two coders' judgments were strongly correlated; r >.98) and familiarization (two coders' judgments were strongly correlated; r >.97).

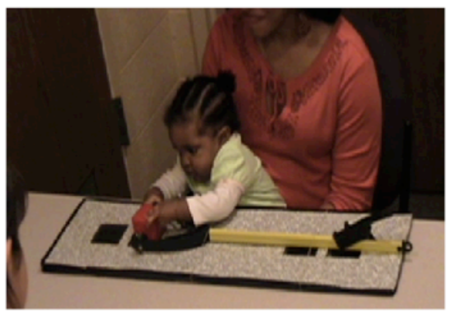


Figure 3.1. Infants in the *control association condition* in Study 1B had the chance to reach for each toy presented to them on the mat with the claw.

Results

As in Study 1, the focal analysis concerned whether infants imitated the experimenter's goal significantly more often than would be expected by chance. A one-sample t-test indicated that infants in Study 1B did not differ from chance in their imitation of the experimenter's goal, $t(19) = .53$, $p = .60$. Additionally, infants in Study 1B differed significantly from infants in the *physical alignment condition* (from Study 1) in their goal imitation, $t(38) = 2.31$, $p = .027$ (see Figure 3.2).

Next, I examined infants' attention during both the test trials and the familiarization period. As in Study 1, infants spent significantly more time attending to the experimenter's goal than the non-goal ($p < .001$; see Figure 3.3).

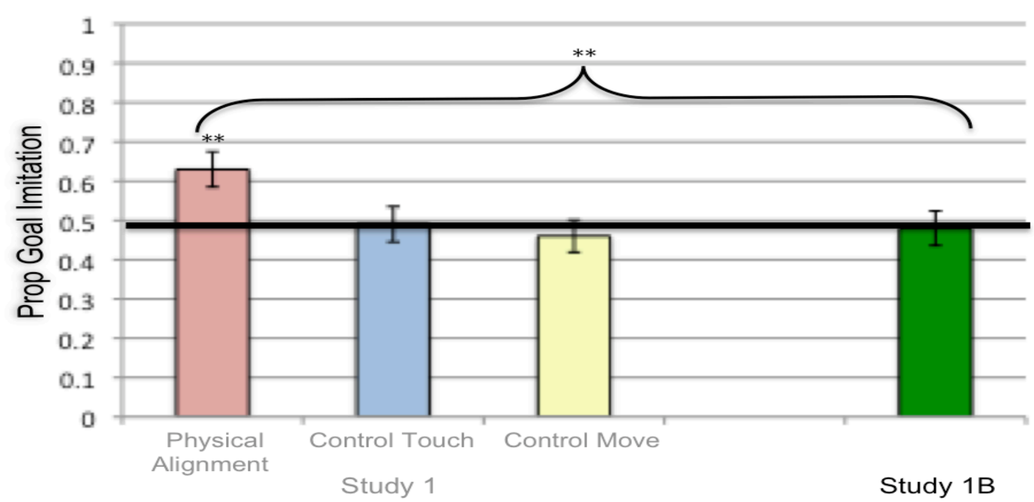


Figure 3.2. Infants in the *control association condition* did not differ from chance in their rate of goal imitation. They did differ significantly from infants in the *physical alignment condition* from Study 1. ** $p < .02$

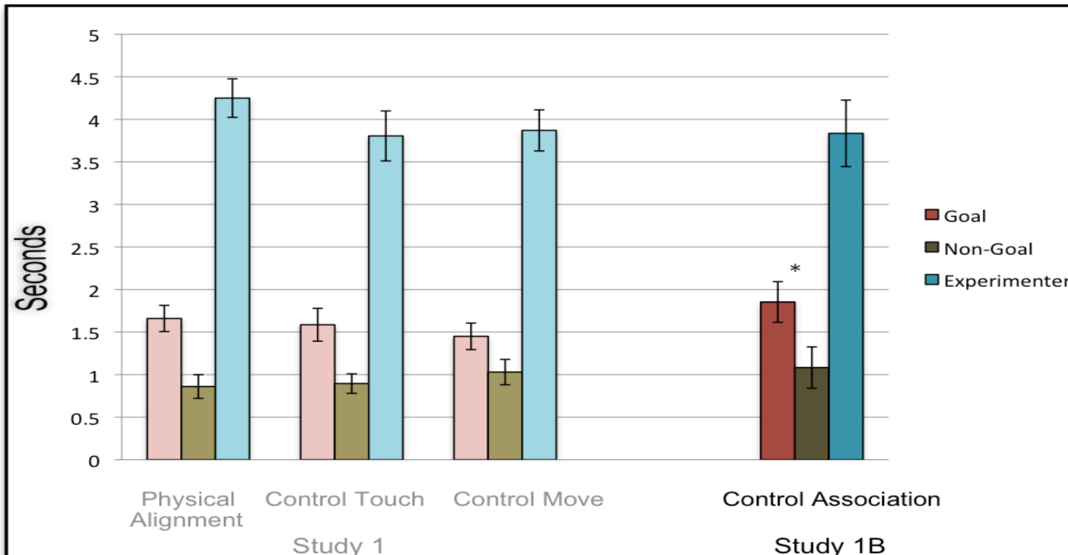


Figure 3.3. As in Study 1, infants in Study 1B spent significantly more time attending to the experimenter's goal than the non-goal. *$p < .001$

Additionally, neither attention to the experimenter nor to her goal during test trial demonstrations was related to infants' imitation (*p*'s > .27). Infants in this study did not differ from any condition in Study 1 in their attention to the goal or the experimenter during test trials (*p*'s > .32).

Infants in this study spent longer attending to both the experimenter and the claw during familiarization than infants in any condition in Study 1 (*p*'s < .001). This was due to the fact that the experimenter encouraged infants to attend to the toy and left the toy and claw in front of the infant for a longer period of time (until the infant acted or for approximately 30 seconds). This extra time did not seem to play a role in goal imitation, as neither attention to the event or attention to the experimenter during familiarization trials were related to goal imitation (*p*'s > .17).

Discussion

The findings from this study demonstrate that an association between claw and toy was not driving infants' imitation in the *physical alignment condition* in Study 1. In Study 1B, infants had the chance to associate each toy they played with in familiarization with the claw but this did not lead them to choose the toy paired with the claw in test trial demonstrations. This supports the notion that infants in the *physical alignment condition* in Study 1 did more than merely form an association between the claw and toys. Instead, they extracted the relevant goal information and used this information to guide their goal imitation.

Study 2

Study 1 demonstrated that physical alignment facilitated the extraction and imitation of the goal of a novel tool use action in 7-month-old infants. Control conditions from this study suggested that cues about the functional properties of the claw, engagement with the claw, and associative factors did not drive infants' imitation. Although findings from this initial study suggest that interaction with the experimenter wielding the claw did not drive infants' responses (see description of the *control touch condition*), Study 2 provides a more rigorous test of the effects of social contingency.

Johnson and colleagues (e.g., Johnson, Shimizu, & Ok, 2007) have proposed that socially contingent interaction is a salient cue to agency that infants use to interpret actions as goal-directed. Their work has shown that, early in the second year of life, infants follow the gaze and recognize and imitate goals of agents (even unfamiliar, novel agents) that interact with them (or an experimenter) contingently.

For example, in one study (Johnson et al., 2007), 12-month old infants were first introduced to a novel green oval-shaped object as either an "agent" or a "non-agent." In the agent condition, infants saw the object interact contingently with an experimenter in a conversation-like manner by beeping in response to an experimenter's talking. In the non-agent condition, the object made the same beeping noises, but the experimenter did not interact with the object; thus, there was no contingency. Then, in a habituation paradigm, infants saw the object approach one of two toys repeatedly until they were habituated. As in the

Woodward (1998) paradigm described in the introduction, the placement of the toys was switched during test trials and the object moved along a different path to reach the same goal (old-goal trials) or moved along the same path to a new goal (new-goal trials). As described previously, a novelty response (longer looking) to the new-goal trials in this paradigm indicates that infants interpreted the movement during habituation as directed toward a particular goal (e.g., Woodward, 1998). Only infants in this study who saw the novel object interact in a contingent manner with the experimenter prior to the habituation paradigm (and not those who heard the beeps sound in a non-contingent manner) then viewed the object's movement as goal-directed in the habituation paradigm. Thus, 12-month-old infants in this study used social contingency as a cue to agency and recognized the goal structure between the "agent" and its preferred toy.

Social contingency is inherent in the type of social alignment addressed in this dissertation. Aligning one's own actions with another's necessitates engaging with the social partner in a contingent manner. This social contingency might act as a cue to agency and thus facilitate goal extraction. There are two reasons, however, that it seems unlikely that this factor drove infants' responses in Study 1. First, studies in which socially contingent interactions have served as a cue to goal-directed actions have all been conducted with infants 12 months of age and older (Johnson, Slaughter, & Carey, 1998; Johnson et al., 2007; Shimizu & Johnson, 2004). It is not known whether these same benefits play similar roles for younger infants. Second, infants in the *control touch condition* in Study 1 had the opportunity to engage with the experimenter using the claw during familiarization and did not benefit from this social interaction. Although the experimenter and infant did not engage in conversation or scripted socially contingent interactions, this engagement would likely play a similar role as a cue to agentive actions.

In Study 2, infants in a control condition were given the opportunity to engage in a socially contingent game with the experimenter (using the claw) but, during the game, the claw did not hold a toy with which the infant could align his or her goals. In this way, a differentiation between social alignment and social contingency was created. Through this study, I examined whether social contingency alone (without alignment) was enough to drive infants' imitation of the experimenter's goal when using a claw.

Infants participated in one of two conditions in Study 2: *contingent aligned* or *contingent nonaligned*. The test trials in both of these conditions were identical to test trials in Study 1. In both conditions, infants engaged in a contingent game with the experimenter during familiarization. Infants in both conditions saw and had the chance to interact with the claw, the experimenter's hand, and each of the toys. The only factor that varied between these two conditions was whether the experimenter passed infants each toy with the claw or her hand prior to the socially contingent game. In the *contingent aligned condition*, after physically aligning their reaches with the claw's, infants played a socially-contingent game with the experimenter's hand before test trials. In the *contingent nonaligned* condition, infants were passed toys by the experimenter and then played the socially-contingent game with the experimenter using the claw before test trials.

This game (described below) gave infants the opportunity to engage with the experimenter using the tool in a socially contingent manner. Assuming physical alignment was the vital component driving infants' goal imitation in Study 1, infants in the *contingent aligned condition* should imitate the experimenters' actions with the tool and infants in the *contingent nonaligned condition* should not.

Methods

Participants. Forty full-term 7-month-old infants (6.5-7.5 months) participated in this study. Twenty infants participated in each of two conditions: *contingent aligned* (11 males; *M* age = 6;28) and *contingent nonaligned* (10 males; *M* age = 6;27). Infants were recruited from the Washington, DC metropolitan area through mailings and advertisements. Twelve additional infants began the study but were not included in final analyses due to side preference (*n* = 11), or inactivity or inability to complete the procedure due to crying (*n* = 1). The sample of infants was 18% African-American, 12% Asian, 40% Caucasian, 5% Hispanic, and 25% multiracial.

Procedure. This study took place in the same room, using the same setup and materials as Study 1. Test trials (both demonstrations and toy-choice) were identical to all conditions in Study 1. The nature of infants' familiarization with the claw and toys differed as described below.

In the *contingent aligned condition*, infants were passed each toy by the experimenter with the claw, as in the *physical alignment condition* in Study 1.

This allowed infants the chance to simultaneously compare their reach with that of the experimenter's reach with the tool (infants did so on approximately 80% of trials on average). In this study, however, each infant was passed the toys through one of two small tunnels (approximately 32 cm in length and 20 cm in diameter) covered in marble contact paper, at the end of which were blue felt pieces blocking the view through the tunnel (see Figure 4.1). Toys were alternately passed through the left and right tunnels. After infants were passed each of the 12 toys, they participated in a "peek-a-boo" game in which the experimenter tapped inside both tunnels and then peeked her hand out of the end of one of the two tunnels. No toys were presented during the game. The experimenter reached her hand through each tunnel three times (in pseudorandom order). The child could watch and/or reach for the experimenter's hand during this game.

The *contingent nonaligned condition* allowed infants to engage with the experimenter using the claw in a socially contingent manner but did not allow infants to align their goals with the experimenter's tool use actions. Infants in the *contingent nonaligned condition* were passed each of the toys through the tunnels by the experimenter's hand (without the claw). They were then introduced to the claw in a socially contingent "peek-a-boo" game matched to the game infants in the *contingent aligned condition* engaged in with the experimenter's hand.

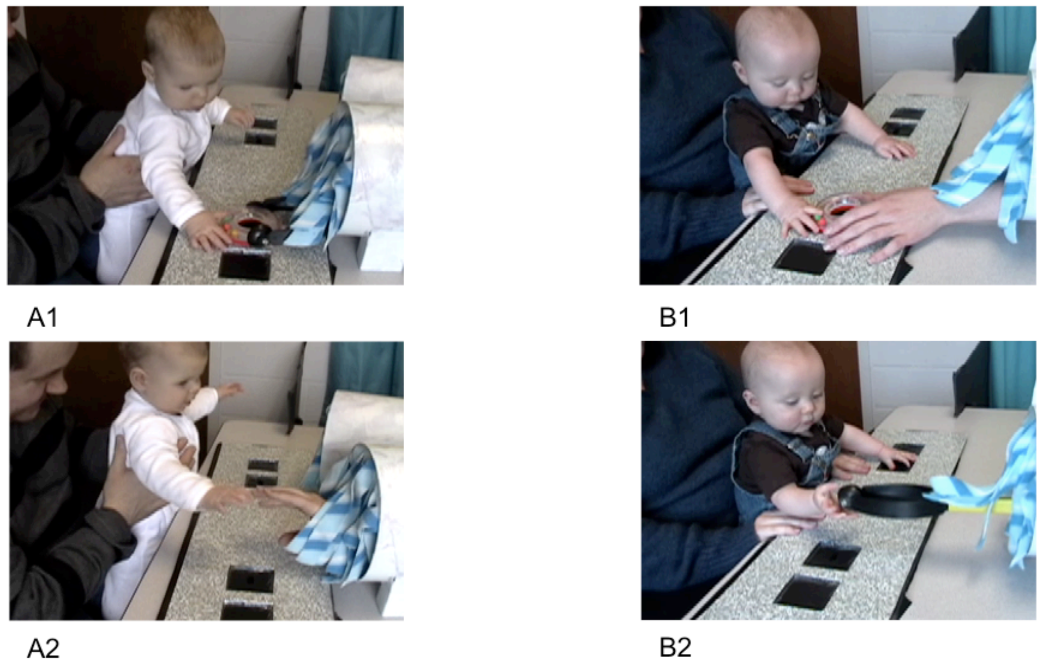


Figure 4.1. Infants in the *contingent aligned condition* in Study 2 physically aligned their reach for the toy with the claw's reach (A1). They then played a socially contingent peek-a-boo game with the experimenter's hand (A2). Infants in the *contingent nonaligned condition* were first passed each toy by the experimenter (B1) and then played the socially contingent game with the claw (B2).

Results

Main analyses examined the proportion of test trials on which infants chose the same toy as the experimenter. An initial independent samples t-test indicated that goal-imitation did not differ significantly by condition (see Figure 4.2; $t(38) = .15$, $p = .88$). Infants did not imitate the experimenter's goal more or less than would be expected by chance in either condition (*contingent aligned:* $t(19) = 1.16$, $p = .26$; *contingent nonaligned:* $t(19) = 1.30$, $p = .21$). At first glance, these findings appear to contrast with Study 1 in that infants in the *contingent* *aligned condition*, as a group, did not imitate the experimenter's toy-choice above chance levels.

There are, however, several aspects of Study 2's paradigm that may have made it difficult for infants to compare their reach with the experimenter's tool use action. For example, in this study, the experimenter passed each toy to the infant (with or without the claw) through one of two tunnels. Because these tunnels were sitting directly in front of the experimenter, infants were unable to see the

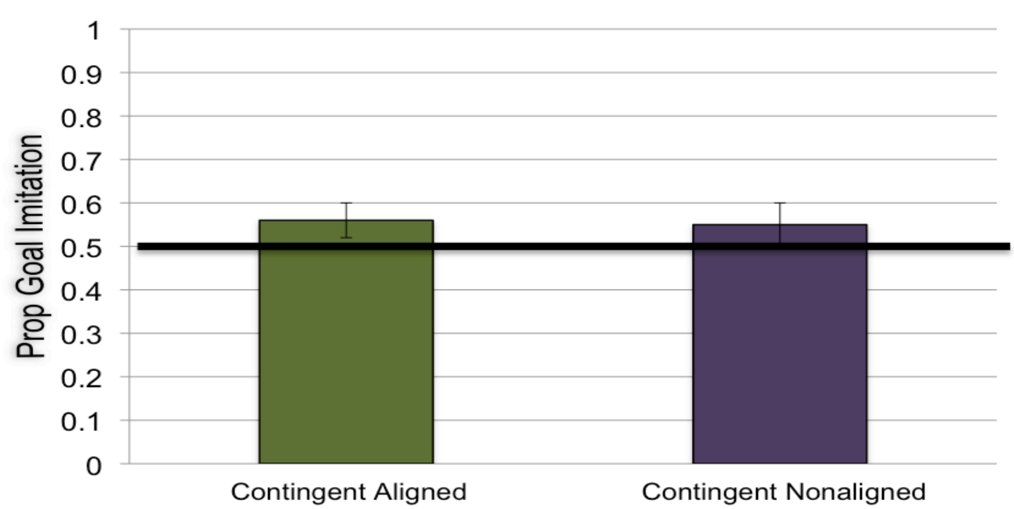


Figure 4.2. Goal imitation did not differ between conditions. Infants did not differ from chance in their imitation in either condition.

experimenter's hand on the claw during physical alignment (as they could in Study 1). This perceptual block between the experimenter and claw may have made it challenging for infants to recognize the actions as enacted by the experimenter. Both the marginal correlation with attention to experimenter in the *physical alignment condition* in Study 1 and the null results in the *control* *association condition* in Study 1B indicate that the experimenter's actions on the tool were a critical piece of the comparison process in Study 1. Because I aimed to examine infants' interpretation of the experimenter's actions when using the tool and not the tool's actions (independent of the experimenter), lack of visual access to the experimenter's control over the claw could present a critical problem.

One way to probe whether lack of exposure to the connection between the experimenter and the claw prevented infants from comparing action goals is to assess whether there were benefits of attention to the experimenter during familiarization trials. As in Study 1, I examined infants' attention to the experimenter, claw, and toy during familiarization trials for each condition. In the *contingent aligned condition*, infants' attention to these aspects of the event, and also to the tunnel, were measured while the experimenter passed the toys to the infants with the claw. In the *contingent nonaligned condition*, infants' attention to the same aspects (experimenter, claw, toys, tunnel) was measured during the socially contingent game.

Infants in the two conditions did not differ in total amount of time attending to either the experimenter or the claw during familiarization (p's > .6). There was also no significant linear relation between attention to the experimenter or claw during familiarization and infants' imitation during test in any condition (p's > .12). I hypothesized that the lack of perceptual continuity between the experimenter and the claw might make gaze shifts between the experimenter and the claw a more important factor than amount of attention paid to the experimenter alone (because gaze shifts allow infants to relate information about the claw back to the experimenter). In order to examine this possibility, I measured the number of gaze shifts from experimenter to claw during the familiarization trials. On average, infants shifted their gaze from the experimenter to the claw or tunnel approximately 8.18 times during familiarization and this number did not differ significantly between conditions, $t(38) = 1.10$, $p = .28$.

The number of gaze shifts was marginally related to infants' goal imitation in the *contingent aligned condition* ($r = .39$, $p = .093$) but was unrelated to goal imitation in the *contingent nonaligned condition* ($r = -.26$, $p = .27$). Inspection of the scatterplot (see Figure 4.3A) suggested a logarithmic relation might exist between these factors in the *contingent aligned condition*. In fact, a significant logarithmic relation was revealed between goal imitation and gaze shifts from experimenter to claw during familiarization trials, $F(1,18) = 4.24$, $p = .05$. This relation is in accordance with the hypothesis that infants in the *contingent aligned condition* needed to make a minimal number of gaze shifts between the experimenter and the claw on which she was acting in order to learn about her actions through alignment. This relation, though marginal in the *contingent nonaligned condition,* was in the opposite direction, $F(1,18) = 3.53$, $p = .076$ (see Figure 4.3B). This implies that gaze shifts between experimenter and claw throughout a socially contingent game (during which infants could not align their goal with the experimenter's) did not lead infants to imitate during test trials.

Due to the a priori hypothesis that shifting gaze between the experimenter and claw might help infants interpret the goal of the experimenter's actions in the

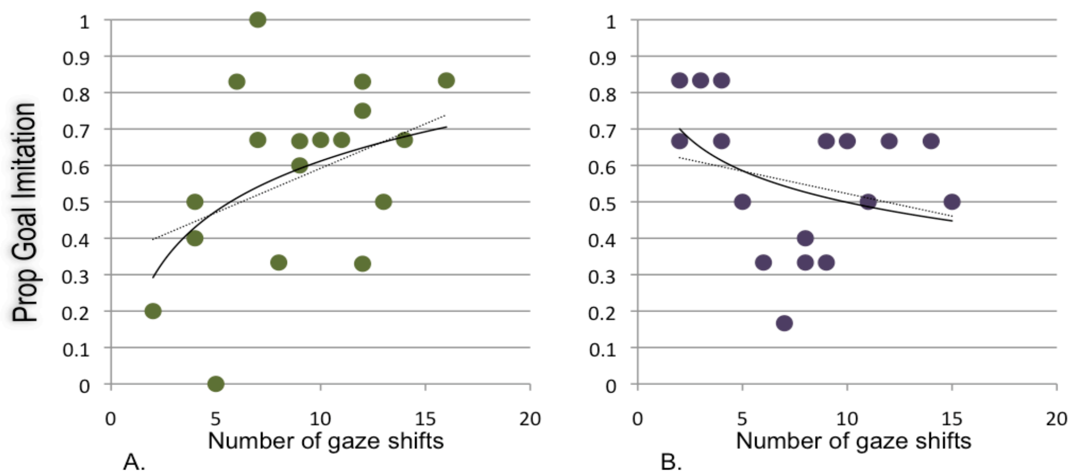


Figure 4.3. Number of gaze shifts to the claw or tunnel was positively correlated with goal imitation in the *contingent aligned condition*. The data were best described by a logarithmic relation (A; *p = .05).* There was no relation between gaze shifts and imitation in the *contingent nonaligned condition* (B).

contingent aligned condition and the logarithmic relation between these two factors, I created a median split of the number of gaze shifts between experimenter and claw and explored whether infants' imitation differed from chance depending on whether they were above or below median in number of gaze shifts during familiarization. One-sample t-tests indicated that infants who were below the median in gaze shifts did not differ from chance in goal imitation ($t(8) = -.075$, $p = .94$) but infants who were above the median in gazes shifts imitated the experimenter's actions significantly more than would be expected by chance, $t(10) = 2.36$, $p = .04$ (see Figure 4.4). Neither group differed from chance in the *contingent nonaligned condition* (*p*'s > .19).

As in Study 1, I also evaluated infants' attention to the experimenter and the two toys during test trial demonstrations. Independent samples t-tests indicated that attention to the goal and experimenter did not differ between conditions (p's > .6). In both conditions, infants spent significantly more time attending to the experimenter's goal than the non-goal (p's < .001; see Figure 4.5). Attention to the experimenter's goal or to the experimenter during test trials

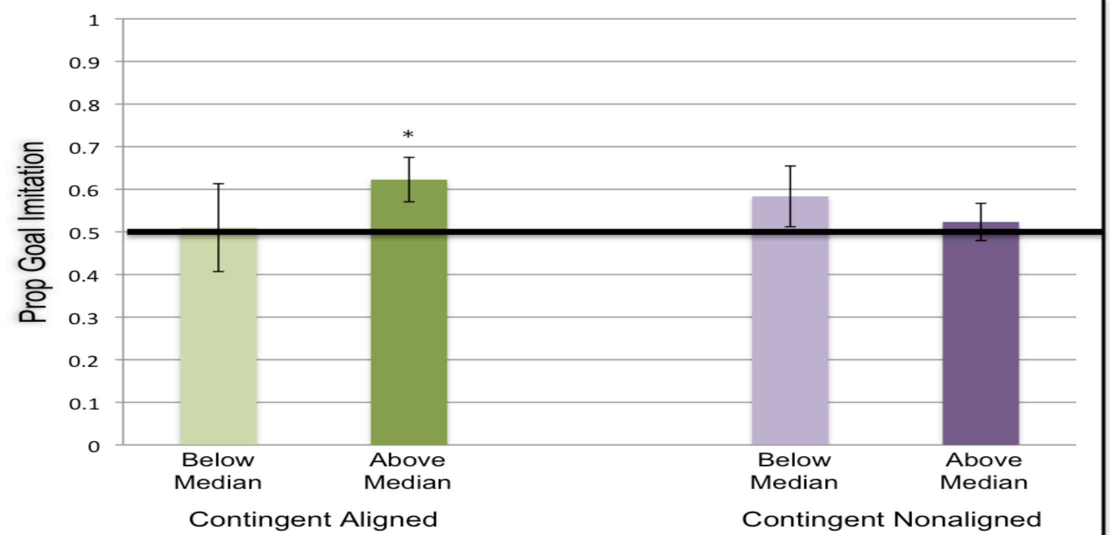


Figure 4.4. Only infants above the median in number of gaze shifts to the claw or tunnel in the *contingent aligned condition* imitated the experimenter's goal significantly more than would be expected by chance. *p = .04

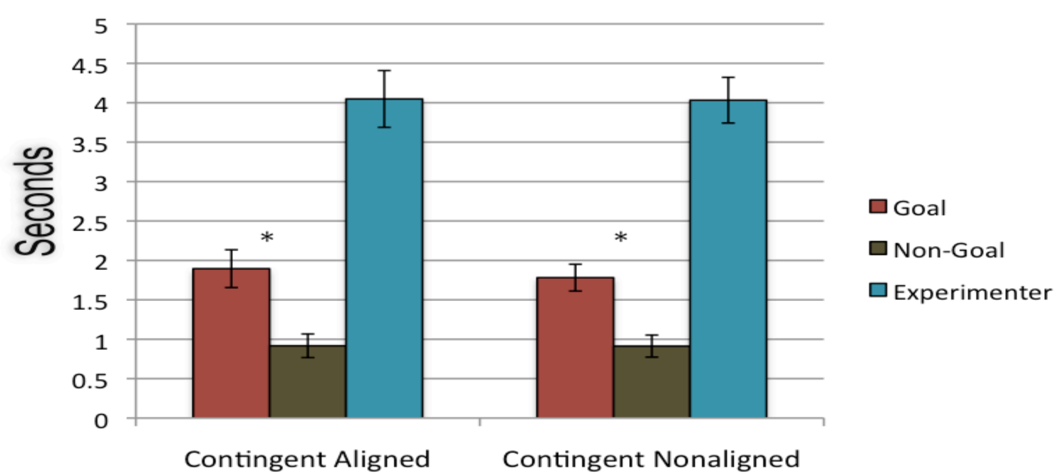


Figure 4.5. Infants in both conditions spent significantly more time attending to the experimenter's goal than the non-goal. *p < .001

was not related to goal imitation in any condition (*p*'s > .40). Additionally, attention to the goal during test trials did not differ between infants who were above or below the median in gaze shifts during familiarization in either condition (*p*'s > .10). Attention to the experimenter during test trials did not differ between these two groups in the *contingent aligned condition* (*p* = .57), but it did significantly differ for infants in the *contingent nonaligned condition,* $t(18) = 3.36$, *p* = .003. Infants in the *contingent nonaligned condition* who were above the median in gaze shifts during familiarization spent more time attending to the experimenter during test trials (*M* = 4.80s, *SD* = 1.14) than infants below the median in gaze shifts (*M* = 3.26s; *SD* = .90), suggesting a consistent tendency to attend (or not attend) to the experimenter across familiarization and test trials for particular infants. Despite this difference, neither attention to the experimenter or goal during test trials was related to goal imitation in either condition for infants with above or below the median gaze shifts (*p*'s > .07).

Discussion

The *contingent aligned condition* in this study provided a modified replication of the *physical alignment condition* from Study 1. Seven-month-old infants in this study who actively shifted their visual attention between the experimenter and the claw that she held during physical alignment later imitated the experimenter's tool use actions during test trials. This demonstrates that infants who were able to make the connection between the experimenter and her tool use actions during familiarization were able to apply this information during test trials to interpret the goal of her actions and imitate her toy choice.

An important question raised by these results is why gaze shifts between experimenter and claw during familiarization trials was critical for infants in the *contingent aligned condition*. Infants who were below the median in gaze shifts did not differ from chance in their imitation during test trials. This finding is in accordance with the marginal correlation between attention to the experimenter during familiarization and goal imitation for infants in the *physical alignment condition* in Study 1. In Study 1 infants in the *physical alignment condition* were above chance in their goal imitation as a group. In the current study, though a similar relation seemed to play a role, the group as a whole did not imitate significantly above chance levels. As discussed in the results section briefly, the logarithmic cutoff (and effect of median split) is likely due to the fact that comparison in Study 2 was made more difficult by the perceptual disconnect created by the tunnels.

The central question addressed in this study was whether engagement in a socially contingent interaction with the experimenter using the claw was sufficient to drive infants' goal imitation during test trials. The fact that infants in the *contingent nonaligned condition* did not imitate the experimenter's toy-choice in test trials regardless of number of gaze shifts during familiarization or any other attentional factors indicates that social contingency was not sufficient to drive goal imitation. This is in accord with the finding that infants in the *control touch condition* in Study 1 did not benefit from interacting with the experimenter holding the claw during a short engagement session.

As mentioned in the introduction, evidence concerning the benefits of social contingency for infants younger than 12 months of age is currently lacking. Thus, the fact that 7-month-old infants in this study did not benefit from socially contingent interaction with the experimenter using the claw does not contradict any previous findings. It is possible that, closer to 12 months of age, infants could benefit from social contingency in this paradigm. The findings indicate, however, that socially contingent interaction during social alignment was not driving infants' imitation in the *physical alignment condition* in Study 1 or the *contingent aligned condition* in Study 2. Instead, infants' goal imitation in these studies depended on infants comparing familiar and novel actions and interpreting the goal of the experimenter's action (and not just the movements of the claw).

Study 3

The first two studies provide the first evidence that a domain general cognitive learning mechanism, structure mapping, plays a powerful role in early social learning. In these studies, 7-month-old infants extracted and imitated the goal of a novel tool use action through comparing this action with a familiar action for which they initially recognized the goal. These findings demonstrate that conditions that support analogical learning (i.e., physically aligning familiar and novel actions to allow simultaneous comparison) support infants' detection of the relational similarities of familiar and novel goals.

As implemented in the above studies, however, social alignment differs from the manipulations used with older children and adults for nonsocial tasks in that infants were active participants in the alignment of actions. In nonsocial domains, both exemplars to be compared are typically external to the individual comparing them. Study 3 investigates whether active participation in physical alignment was important for infants' responses to others' actions in the current manipulation. There are both theoretical and empirical reasons to suggest active participation might be particularly beneficial in the social domain.

As noted earlier, it has been hypothesized that comparisons involving ones own actions are especially informative (e.g., Barresi & Moore, 1996; Meltzoff, 2005; Tomasello & Moll, 2007). Consistent with this hypothesis, learning to produce a particular action aids infants' interpretation of another person's goal when viewing the same action performed in a habituation paradigm (Sommerville et al., 2005). Observing the statistical properties and regularities of another individual performing the action prior to participating in the habituation paradigm, however, does not provide the same benefits (Gerson & Woodward, in preparation; Sommerville et al., 2009). Additionally, as discussed earlier, research indicates that joint engagement with an experimenter helped 14-month-old infants later recognize and remember which toys that particular experimenter had seen, whereas observing the experimenter jointly engage with another experimenter did not provide the same benefit (Moll et al., 2007).

These considerations suggest that in the current context, alignment of novel tool use actions with infants' own actions might be particularly informative. On the other hand, children and infants tested in other domains benefit from comparing exemplars they have only observed (e.g., Gentner, 2003; Oakes, Kovack-Lesh, & Horst, 2009). Whether one's own actions are uniquely powerful sources of information for analogy is an open question (see Gerson & Woodward, 2010 for a discussion).

In Study 3, I addressed this issue by comparing the effects of aligning novel tool use actions and one's own actions with the effects of observing others' aligned (familiar and novel) actions. In this study, 10-month-old infants took part in one of three conditions. Like 7-month-olds, infants at 10 months do not demonstrate robust understanding of tool use actions as goal-directed (Cannon & Woodward, 2010; Jovanovic et al., 2007; Sommerville & Woodward, 2005), and so an initial question is whether they similarly benefit from engagement in physical alignment at this age (as seen at seven months). Additionally, I aimed to contrast this active experience with observational experience of physical alignment. One group of infants was given the chance to actively engage in physical alignment (*active condition*). This was a direction replication of Study 1 but with 10-month-old infants. In another condition (*observational condition*), infants observed the same events. These infants viewed an experimenter pass each of the toys to a second experimenter using the claw. This gave infants the opportunity to observe the physical alignment of a familiar (grasp) and novel (tool use) action. A third group of infants underwent the same procedure as control touch infants from Study 1 in order to assure that 10-month-old infants would not recognize and imitate the goal of the tool use action without the benefit of either participating in or observing alignment.

I hypothesized that active experience would be uniquely beneficial and that only infants in the *active condition* would imitate the experimenter's toy-choice. If, however, observing physical alignment provided the same benefits, infants in both the *active* and *observational* conditions should imitate the experimenter's toy choice. Regardless of the results in the *observational condition,* I expected infants in the *control touch condition* to respond at chance levels (as 7-month-old infants did in Study 1).

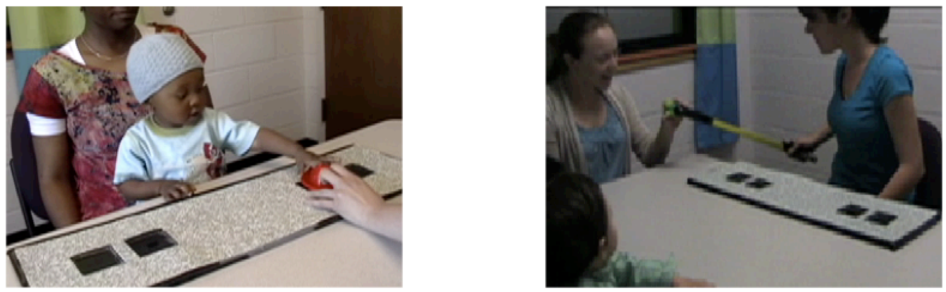
Methods

Participants. Data was coded for 48 full-term 10-month-old infants (9.5-10.5 months). Sixteen infants participated in each of three conditions: *active condition* (8 males; *M* age = 9;28), *observational condition* (7 males; *M* age =

9;25), and *control touch condition* (8 males; *M* age = 9;29). Infants were recruited from the Washington, DC metropolitan area through mailings and advertisements. Ten additional infants began the study but were not included in final analyses due to side preference (*n* = 8), inactivity or inability to complete the procedure due to crying (*n* = 1), or parental interference (*n* = 1). One infant in the *active condition* was an outlier in attention during test trial demonstrations (was more than three standard deviations below the mean in attention to the experimenter's goal in this study and also different from infants across all previously reported studies; see coding scheme in Study 1) and was thus removed from reported analyses. The sample of infants was 4% Hispanic, 31% African-American, 52% Caucasian, 2% Asian, 6% multiracial, and 5% unreported.

Procedure. The procedure for both the *active* and *control touch* conditions exactly matched the procedure for these conditions in Study 1. Infants in the *active condition* aligned their reaches with the claw's reach for the toy on approximately 70% of the 12 trials. The *observational condition* took place in the same room with the same materials and set-up as the other conditions, with the following variations.

The familiarization phase in the *observational condition* began with the experimenter passing the infant each of the toys on alternate sides of the tray (as in the control conditions in Study 1). After infants saw each of the toys, a second experimenter (E2) then appeared to the first experimenter's (E1) right. E1 passed each toy to E2 using the claw (see Figure 5.1). E2 grasped the toy with her hand and said “thanks” (or thank you) in an excited tone to engage the infants’



A. B.

Figure 5.1. Infants in the *observational condition* were passed each toy by the experimenter (A). They then observed E1 passing each toy to E2 with the claw (B).

attention. She shifted her gaze between the infant and the toy as she held the toy for a couple of seconds. If the infant was not attending at the beginning of her movement, E1 tapped near the toy or said “hi” or “look” to the infant. In this way, it was ensured that the infant observed the physical alignment of E1’s grasp for the toy with the tool and E2’s grasp for the toy with her hand. Infants were extremely attentive to the event. Following this familiarization, E2 left the room, and test trials transpired as in all other conditions. Coders again assessed infants’ toy-choice (a second, reliability coder agreed on 96% of trials) and measured infants’ attention to the claw, toys, and experimenter(s) during both test trials (two coders’ judgments were strongly correlated; r’s > .96) and familiarization (two coders’ judgments were strongly correlated; r’s > .95).

Results

Primary analyses concerned the proportion of trials on which infants chose the experimenter's goal toy. A one-way ANOVA indicated that infants' goal imitation differed by condition, $F(2, 44) = 5.17$, $p = .010$ (partial $\eta^2 = .19$; see Figure 5.2). Due to the hypothesis that infants in the *active condition* would

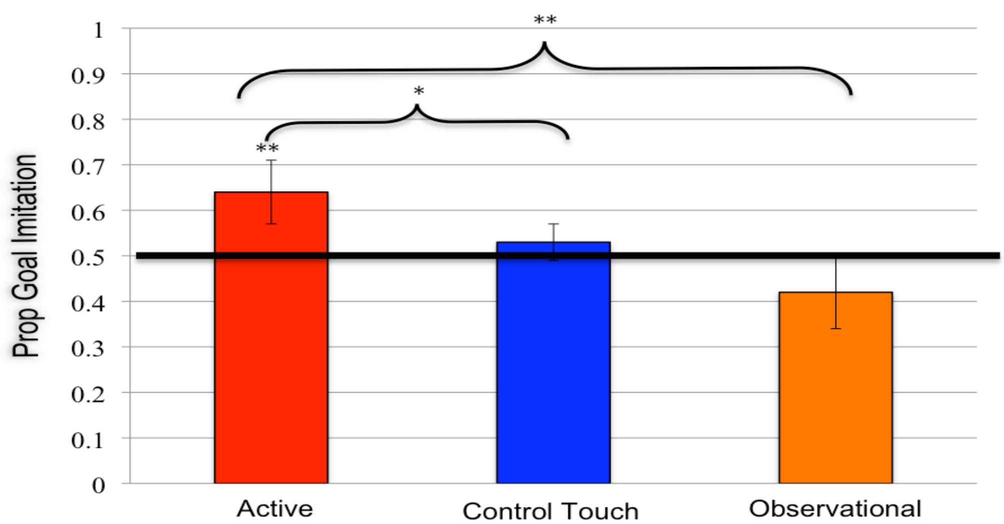


Figure 5.2. Infants in the *active condition* imitated the experimenter's goal significantly more often than would be expected by chance. They differed in their goal imitation from infants in the other two conditions. * $p = .068$ ** $p \leq .01$

imitate the experimenter's goal more than infants in the *observational condition*, a priori tests were conducted using LSD to evaluate pairwise differences among the means. These comparisons revealed that infants in the *active condition* chose the goal toy significantly more often than infants in the *observational condition* ($p = .003$). Infants in the *control touch condition* were marginally different from infants in the *active condition* in their goal imitation ($p = .068$) and did not differ from infants in the *observational condition* ($p = .18$). Infants in the *active condition* selected the goal toy more often than would be expected by chance, $t(14) = 2.98$, $p = .010$, replicating the finding in *the physical alignment condition* in Study 1. Infants in the *observational* and *control touch* conditions did not differ from chance in their choices (t's < 1.25).

I once again examined infants' attention during both the test trials and the familiarization period. As in Study 1, attention to the goal and experimenter during test trial demonstrations did not differ between conditions (p's > .25). In all three conditions, infants spent significantly more time attending to the experimenter's goal than the non-goal (p's ≤ .002; see Figure 5.3). Additionally, neither attention to the experimenter or to her goal was related to infants' goal imitation in any condition (p's > .19).

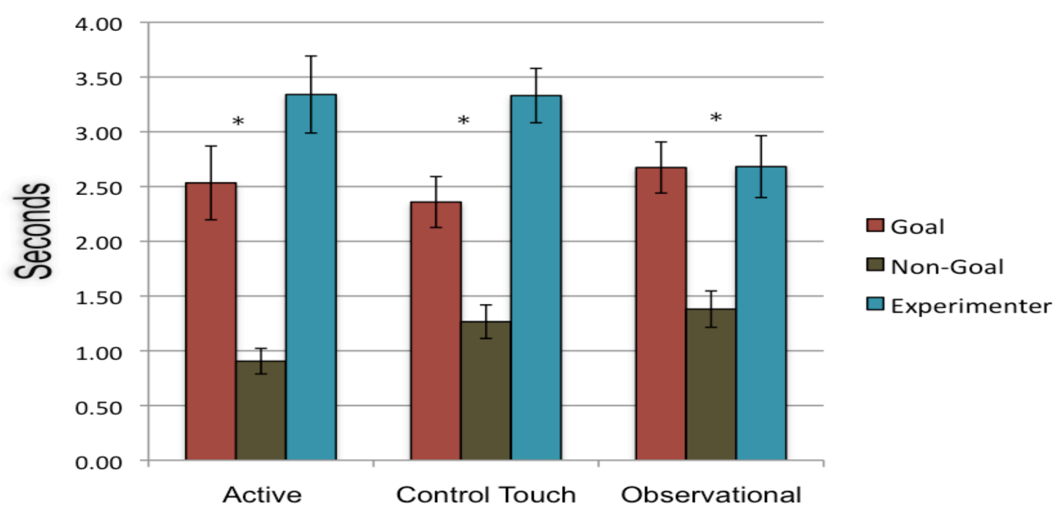


Figure 5.3. Infants in all three conditions spent significantly more time attending to the experimenter's goal than the non-goal. *$p \leq .002$

Additionally, I examined infants' attention to the experimenter and events during familiarization. Infants in the three conditions differed significantly in their attention to the claw and its actions, $F(2,42) = 47.84$, $p < .001$. Followup LSD comparisons showed that infants in the *active* and *observational* conditions did not differ from one another in their attention to the claw ($p = .59$). Infants in the *control touch condition*, however, differed significantly from both conditions (p's $< .001$). Infants in the *control touch condition* spent less time watching the claw than infants in the other two conditions. Infants in the three conditions also differed in their attention to the experimenter(s), $F(2, 42) = 20.61$, $p < .001$. Infants in the *control touch condition* spent the least time attending to the experimenter. Not surprisingly, infants in the *observational condition* spent significantly more time looking at the two experimenters than infants in either of the other two conditions spent looking at the one experimenter (p's $< .03$). Despite these differences, neither attention to the event or attention to the experimenter(s) was related to goal imitation in any condition (p's $> .19$).

Discussion

Results from the *active condition* in this study replicated findings from the *physical alignment condition* in Study 1 and demonstrate that active engagement in physical alignment aids recognition of the goal of a novel tool use action at 10 months of age. Lack of goal imitation in the *observational condition* indicates that infants of this age did not recognize and imitate the goal of the tool use action even when they observed the same exact physical alignment between a familiar and novel action as the one in which infants in the *active condition* engaged.

These findings are in accordance with findings demonstrating that active production of actions and participation in joint engagement helps infants learn about the goals and knowledge states of others (Moll et al., 2007; Sommerville et al., 2005; Sommerville et al., 2008). They indicate that, similarly, analogy is a particularly powerful mechanism when one is actively engaged in the action that is to be compared. Unlike the observation of physical alignment, which might initially provide information “at the surface” (e.g., the causal nature of actions), engagement in physical alignment seems to provide unique information about the underlying goal structure of the actions in the physical alignment (see Gerson & Woodward, 2010). Acting as an agent requires representing one’s goals at some level. To coordinate complex actions and obtain a goal, individuals must continually represent the goals that structure their actions and adjust their actions as needed to attain the goal. This information could potentially be recruited during physical alignment in order to compare one’s own goals to those carried out by a social partner.

The fact that infants did not benefit from simultaneous comparison of two exemplars out in the world stands in contrast to findings reviewed in the introduction suggesting that infants can extract and generalize relations through analogy that is external to the self in domains like categorization and physical reasoning (e.g., Oakes & Ribar, 2005; Wang & Baillargeon, 2006). This raises the question as to whether the benefit of active engagement for analogy is unique to the social domain. As discussed earlier, several researchers have hypothesized that comparisons between the self and other are critical to learning about the goals and actions of others in development (Barresi & Moore, 1996; Meltzoff, 2005; Tomasello, 1999).

Although active engagement in physical alignment may be uniquely beneficial at the origins of its application to action understanding, the observation of physical alignment is likely beneficial at some point in development. For example, in the study by Moll and colleagues (2007) described above, although 14-month-olds did not learn about an experimenter's knowledge states from observing joint engagements, 18-month-old infants *were* able to learn from the observation of the same event. Exploring the mechanisms that help infants attain the capacity to benefit from the observation of analogous actions is an important task.

In Study 4, I provide a further test of the structure mapping hypothesis in this domain by assessing whether factors known to facilitate relational extraction in other domains (e.g., object and action categorization) could play a similarly beneficial role in the extraction of goal-relations during the observation of physical alignment. In this study, I examined whether spoken labels during the observation of aligned familiar and novel actions (as in the *observational condition* from Study 3) assisted 10-month-old infants in extracting and imitating the goal of novel tool use actions.

Study 4

Based on findings from Studies 1 through 3, I have argued that active engagement in physical alignment facilitates comparison and mapping of goal-relations from familiar to novel actions. The findings thus far, however, do not establish whether infants gained a conceptual representation of the experimenter's goal or simply responded through motor learning. An explanation that contrasts with conceptual learning is that the motor system could have initiated a motor response to reach for the toy the experimenter reached for with the claw because it was trained to reach for the toy the claw held during physical alignment. This would lead infants to choose the same toy as the experimenter after physical alignment training but not in cases in which the experimenter's grasp of the toy was not immediately followed by the infant's reach for the toy.

In Study 4, I address whether infants gained a conceptual understanding from comparison rather than, or in addition to a motor representation, by examining whether infants could learn the goal of the tool use action when they observed physical alignment (between a grasp and tool use action) while the two experimenters engaged in alignment verbalized matched labels for their goals. If infants imitate the experimenter's goal after hearing both experimenters label the goals of their grasping and tool use actions during familiarization, this would imply that infants were responding based on conceptual, rather than motor, representations. Evidence indicates that infants use labels as conceptual markers as early as the first year of life. Additionally, structure-mapping theory posits that labels should aid comparison; evidence for the benefits of labels on comparison processes has been found in both preschoolers and infants.

Words guide conceptual learning in infants as young as four months (Ferry, Hespos, & Waxman, 2010). In a study by Ferry and colleagues, infants familiarized to members of a particular category (e.g., animals) with a consistent novel noun (e.g., blicket) showed a novelty preference (looked longer) to test stimuli in a different category (e.g., vehicles). For example, if infants heard the word *blicket* as they were presented with pictures of a cow, a horse, and a giraffe, they then looked longer in test trials to a picture of a car than to a picture of an elephant. Despite the lack of perceptual similarity between category members, labels helped prelinguistic infants form conceptual categories.

Importantly, labels were unique in this respect. If infants heard a tone during the presentation of each picture rather than a label, they did not form the relevant category and respond to the novel object during test trials. Therefore, heightened attention due to sounds associated with objects did not drive category formation. Instead, labels proved to be a unique conceptual marker (see also Fulkerson & Waxman, 2006).

Aside from aiding categorization, recent work indicates that labels highlight relational similarities and facilitate relational extraction in the first year of life. As described in the general introduction, a novel verb facilitated comparison of consecutively presented exemplar and led 10-month-old infants to extract the common spatial relation between exemplars (Pruden et al., 2006). Thus, labels act as cues to focus infants' attention on relational similarities (see Loewenstein & Gentner, 2005 for an example with preschoolers).

In accord with this finding, Waxman and colleagues (Waxman & Leddon, 2011) propose that the link between novel labels and conceptual development is a function of words promoting comparison among exemplars. They suggest that words "fuel the acquisition of the rich relations that characterize our most powerful concepts" (p. 26). Importantly, if labels help infants succeed in extracting goal relations, this would indicate that infants gained a conceptual understanding of the similarity between goals rather than having simulated an experimenter's action through co-activation of motor programs.

Within an intentional action, there are two different features that could be labeled in order to help draw attention to the goal relation. The intentional action itself (i.e., the verb) is inherently relational, as discussed in the introduction. The goal-object of the action (i.e., the noun) also has relational content. Pruden and colleagues' (2006) work is one example showing that a novel verb helped 10-month-old infants categorize actions. Research by Gentner and colleagues (e.g., Loewenstein & Gentner, 2005) citing the benefits of labels on structure mapping often uses relational terms (e.g., above, below, between). Most work supporting the facilitative role of labels for forming conceptual categories in young infants, however, has used nouns as labels (e.g., Ferry et al., 2010; Fulkerson & Waxman, 2006). It is commonly acknowledged that infants map nouns to words earlier than they map verbs to actions (e.g., Gentner, 1982). Because of this bias, I use nouns (the goal object's basic name) as labels in the current study.

In order to address whether labels played a unique role as conceptual markers or whether the common sound associated with each object (vocalized by both experimenters) was sufficient to aid infants in goal extraction, a control condition was conducted. In this condition, infants heard both experimenters express matched vocalizations toward each toy. The vocalizations ("ooh"s) were not words and thus should not serve as conceptual markers. If labels provide a unique benefit for comparison due to their conceptual nature, rather than serving a simple attentional function, infants should only imitate when the vocalization they hear during physical alignment is a label and not when it is a non-label vocalization.

Study 4 was identical to the *observational condition* in Study 3, with the addition of either a label or a non-word vocalization during the passing game between E1 and E2. Rather than E2 thanking E1 for each toy, both experimenters instead labeled or "ooh"-ed at each object. Because providing a novel label (e.g., dax) for familiar objects (for which infants might already know the label) might confuse or distract infants, each object was labeled with its basic category name (e.g., elephant, car, block, ring). Infants saw both experimenters repeat a common label or a common sound for each object while the experimenters physically aligned their actions. If the label facilitates comparison of the two observed actions and non-word vocalizations do not, infants in the *labeling condition* should imitate the experimenter's goals during test trials and infants in the *non-word vocalization condition* should not.

Methods

Participants*.* Thirty-two full-term 10-month-old infants (9.5-10.5 months) participated in one of two conditions: the *labeling condition* (*n* = 16; 8 males; *M* age = 9;28) or the *non-word vocalization condition* (*n* = 16; 7 males; *M* age = 9;29). Because all labeling was done in English, all infants (in both conditions) had to hear English at least 75% of the time in order to be included in this sample. Infants were recruited from the Washington, DC metropolitan area through mailings and advertisements. An additional 15 infants started the study but were not included in analyses due to side preference. The sample of infants was 16% African-American, 6% Asian, 56% Caucasian, 3% Hispanic, and 16% multiracial, and 3% unknown.

Procedure*.* The familiarization phase began with the experimenter passing the infant each of the toys on alternate sides of the tray (with her hand)*.* After infants saw each of the toys, a second experimenter (E2) then appeared to the first experimenter's (E1) right. E1 passed each toy to E2 using the claw while saying "A (turtle), here, a (turtle)" (in the *labeling condition*) or "Ooh, here, ooh" (in the *non-word vocalization condition*) as she passed each toy. As E2 grasped the toy with her hand, she said "A (turtle), thanks, a (turtle)" or "Ooh, thanks, ooh" (in the *labeling* and *non-word vocalization* conditions, respectively). In the *labeling condition*, the experimenters named each object by its basic title (e.g., turtle boat, block, plane) and both experimenters used the same label for each object. Both experimenters emphasized the label as they spoke. In the *labeling condition*, the experimenters (engaging in the two different actions) thus similarly labeled the goal of their actions. In the *non-word vocalization condition*, both experimenters similarly attended to the toys and vocalized toward them, but they did not use a word label. If the infant was not attending, E1 tapped near the toy or said "hi" or "look" to the infant. In this way, it was ensured that the infant observed the physical alignment of E1's grasp for the toy with the tool and E2's grasp for the toy with her hand during vocalizations.

Following this familiarization, E2 left the room, and the test trials transpired as in the previous studies with one exception in the *labeling condition*. In this condition, the experimenter used the label as she reached for the toy with the claw during test trial demonstrations (e.g., "A turtle, ooh, a turtle"). In the *non-word vocalization condition*, the experimenter used the same vocalization as in previous studies (saying "ooh" twice).

Coders assessed infants' toy-choice (a reliability coder agreed on 96% of trials) and measured infants' attention to the claw, toys, and experimenter(s) during both test trials (two coders' judgments were strongly correlated; r's > .95) and familiarization (two coders' judgments were strongly correlated; r's > .94). After testing, parents were asked to fill out the Level Two MacArthur Bates Communicative Development Inventory short-form (Fenson, Pethick, Renda, Cox, Dale, & Reznick, 2000) in order to assess infants' receptive and productive vocabulary.

Results

Main analyses examined the proportion of test trials on which infants chose the same toy as the experimenter. An initial independent samples t-test indicated that goal-imitation differed significantly by condition (see Figure 6.1;

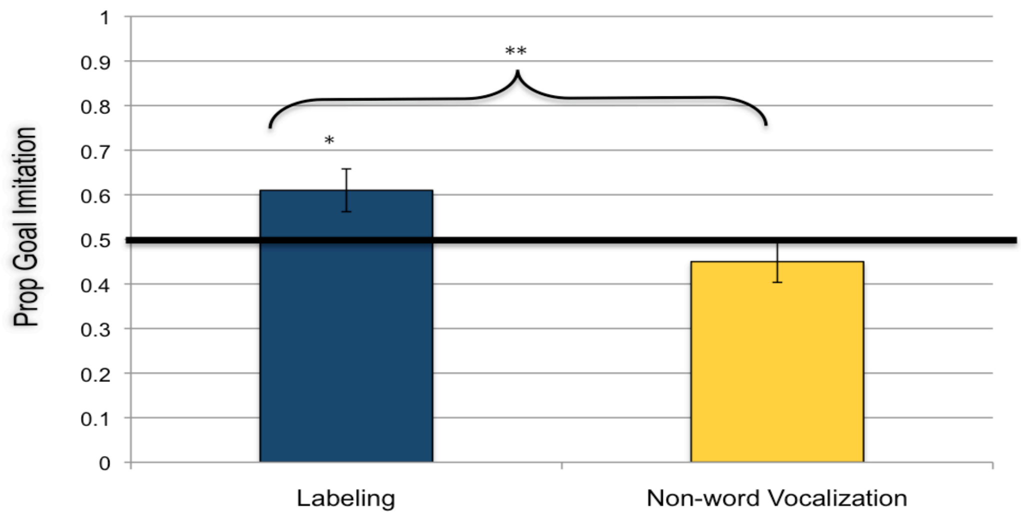


Figure 6.1. Infants in the *labeling condition* imitated the experimenter's goal significantly more often than would be expected by chance. They differed in their goal imitation from infants in the *non-word vocalization condition*. * p = .035, ** p= .02

$t(30) = 2.43$, $p = .02$). Infants in the *labeling condition* imitated the experimenter's goals significantly above more often than would be expected by chance, $t(15) = 2.32$, $p = .035$. Infants in the *non-word vocalization condition* did not differ significantly from chance level in their goal imitation, $t(15) = -1.14$, $p = .27$.

Further analyses examined goal imitation in these conditions relative to both the *active* and *observational* conditions from Study 3. A one-way ANOVA with proportion of trials imitating experimenter's goal as the dependent variable and condition (*active, observational, labeling,* and *non-word vocalization*) as the between subjects variable indicated that infants in these four conditions differed significantly in their imitation, $F(1,3) = 3.95$, $p = .012$. Posthoc LSD comparisons indicated that infants in the *labeling condition* differed significantly in their imitation from infants in the *observational* and *non-word vocalization* conditions ($p = .014$ and $p = .024$, respectively). Infants in this condition did not differ from infants in the *active condition* ($p = .79$). Infants in the *non-word vocalization condition* also differed significantly from infants in the *active condition* ($p = .012$) but did not differ from infants in the *observational condition* ($p = .83$).

In order to examine whether any individual differences within each condition were due to variability in infants' receptive vocabulary, I examined possible correlations between infants' goal imitation and scores on the MCDI Level I short-form (Fenson et al., 2000). Vocabulary was not related to infants' goal imitation within either condition (r's < .15). Thus, receptive vocabulary did not drive infants' performance in the *labeling condition.*

I examined infants' attention to the experimenters and passing events during familiarization in order to see whether the label versus vocalization affected how infants attended to the event. Infants in the two conditions did not differ in their attention to the experimenters ($p = .44$) or the claw/toy ($p = .21$). Further, attention to the experimenters or the claw/toy was not related to goal imitation in either condition (r's < .18).

Finally, I assessed infants' attention during test trial demonstrations to see whether the differences during familiarization and/or the label during the experimenter's toy choice in test trials changed infants' attention to the relevant aspects of the event. As in previous studies, neither infants' attention to the experimenter or her goal differed between conditions (p = .49 and p = .75, respectively). In both conditions, infants spent more time attending to the experimenter's goal than the non-goal (p's < .001; see Figure 6.2). Attention to the experimenter or her goal was not related to goal imitation in either condition (p's > .14).

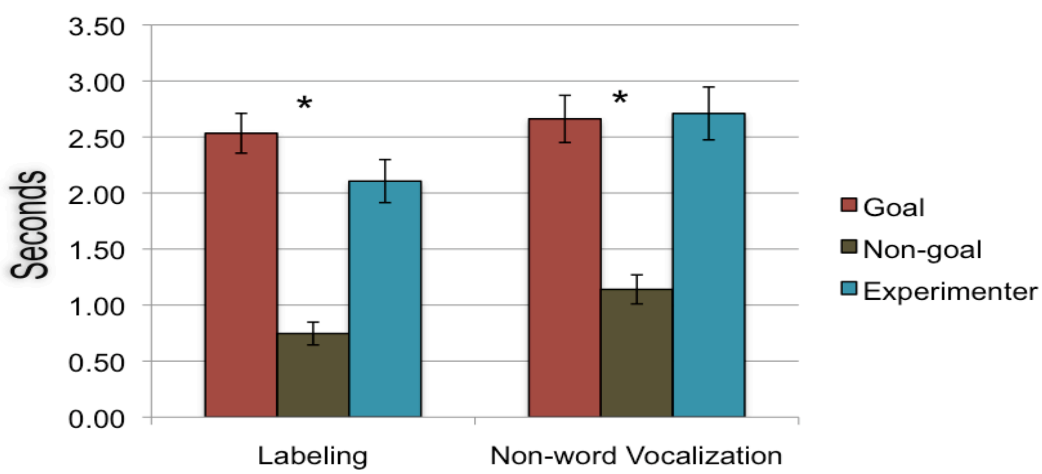


Figure 6.2. Infants in both conditions spent significantly more time attending to the experimenter's goal than the non-goal. *$p \leq .001$

Discussion

Results from this study indicate that 10-month-old infants can extract the goal-relations of a novel action (i.e., tool use) through observation of physical alignment of this action aligned with a familiar action (i.e., a grasp) when they are given a verbal cue (i.e., a label) to focus on the relational aspect of the action (the goal of the action). These findings are impressive in that only a minor variation differentiated the *labeling condition* in this study and the *observational condition* in Study 3. Infants *saw* the same exact familiarization events and test trials during Study 3 as they did in the *labeling condition* in the current study, yet infants who did not *hear* both experimenters label their goal during alignment did not extract this goal relation and imitate during test trials.

Further, infants in the current study who saw the same events and similarly matched vocalizations (both experimenters producing the same non-word sound) imitated the experimenter's goals at similar rates to infants in the *observational condition* from Study 3. Differences in imitation between the two conditions in the current study were not driven by the way in which the different kinds of vocalizations influenced infants' attention during either the familiarization or test trials. Infants in the two conditions did not differ in their attention to the experimenter(s), claw, or goal toy during any phase of the experiment. Their attention to each of these aspects was unrelated to their goal imitation in either condition. Rather than influencing quantitative attentional differences, this indicates that words provided a unique conceptual cue that facilitated relational extraction.

Although labels were more beneficial for relational extraction than non-word vocalizations, infants did not necessarily need to understand the meaning of the labels in order for the label to act as a conceptual marker. In fact, infants' vocabulary level was unrelated to their rates of imitation in the *labeling condition*. This is in accordance with previous research indicating that words act as conceptual markers prior to infants' understanding of the semantic content of the words (e.g., Ferry et al., 2010).

With respect to the work presented in this dissertation, the findings from the current study shed light on the interpretation of the former studies. Aside from the *labeling condition*, no other condition (in any study) in which the infant did not actively engage in a goal-directed action while observing the new action enabled relational extraction. If infants only imitated in cases in which they were actively engaged, findings could be described in terms of a purely motor mechanism. Motor activation seems to play some role given that infants benefited from active engagement before observation (without any additional cues) and that infants needed the initial capacity to produce and recognize the goal of grasping actions in all cases. Despite this important role, however, findings from the current study imply that infants did not only expand a motor representation but instead gained a conceptual understanding of similarities between goals through comparison.

Several open questions remain concerning when and why labels help infants compare and extract relational similarities. In the *labeling condition* in the current study, infants heard E1 label each toy during familiarization and then heard the goal toy's name repeated during test trials. It is currently unknown whether infants would have imitated the experimenter's goal had she not used the label during test trials. In the *non-word vocalization condition*, infants also heard the same sound for each object during familiarization and test trials and this did not lead to goal imitation. This implies that a common vocalization during familiarization and test trials was not sufficient to drive goal imitation. It still does not address whether infants could have mapped the label from familiarization onto test trials without the reminder.

Another intriguing query is whether the form of the label used in this study mattered for its functionality as a conceptual marker. In this work, nouns were used as labels because naming one's goal is inherently relational in that it draws attention to the relation between the agent and her goal. Another word form that might also be effective is verbs. For example, both experimenters could similarly name the goal-directed action in which they are engaged (e.g., I'm *daxing* it) in order to draw infants' attention to the fact that their actions are relationally similar. The study described in the introduction by Pruden and colleagues (2004, 2006) supports the notion that verbs might help infants extract relations as well, though this should be directly tested for the case of goal-directed actions.

An additional issue is whether the benefits in the *labeling condition* depended on the interaction between the observation of physical alignment and labels or independent contributions from each of these factors. I hypothesize that the label drew infants' attention to the relevant aspects of the actions that infants then compared. Because I did not conduct a condition in which infants heard the labels without viewing alignment, however, it is possible that infants were able to extract the goal from hearing the labels without needing to also view the physical alignment. This question is being addressed in an ongoing study.

General Discussion

Together, the current findings indicate that the opportunity to simultaneously align one's own goal-directed grasps with an experimenter's goal-directed tool use actions led 7- and 10-month-old infants to then selectively respond to the goal structure of the experimenter's tool use actions. Consistent with several theoretical proposals (e.g., Barresi & Moore, 1996; Meltzoff, 2005; Tomasello, 1999), these findings suggest that conditions that promote comparison of infants' own actions and goals with those of others are particularly informative for infants' understanding of others' goals. Because the critical information that infants would derive from such comparisons is relational in nature, namely that an agent's action is directed toward a goal, I hypothesize that comparison facilitated infants' detection of relational similarities between their own actions and the experimenter's claw actions throughout these studies. That is, I propose that physical alignment supported infants' interpretation of the tool use events because it helped them see the analogy between their own goal-directed actions and those of the experimenter using the claw.

In Study 1, 7-month-old infants who actively participated in physical alignment (aligned their reach for a toy with that of an experimenter using a claw) later imitated the goals of the experimenter's actions when she used the claw to reach for one of two toys. In contrast, infants who engaged with the claw or viewed the claw's functional properties but did not simultaneously align their reach with the novel goal-directed action did not imitate the experimenter's goals. Study 1B provided a further control condition, indicating that infants who viewed an iterative presentation of each toy with the claw did not imitate the goals of the experimenter’s tool use actions through the formation of an association between the claw and each toy with which infants had the chance to play.

Findings from Study 2 emphasize the importance of infants’ attention to the experimenter during the alignment event and suggest that infants learned not about the tool’s goals but instead about the experimenter’s goals while using the tool. Those infants who attended to both the experimenter and claw benefited from engagement in physical alignment, providing a replication of the *physical alignment condition* findings from Study 1. This study further demonstrated that socially contingent interactions with the experimenter and claw were not sufficient to drive goal imitation and cannot explain imitation in the *physical alignment condition* in Study 1. Combined, these studies suggest that physical alignment was the key component driving goal imitation.

Once the benefits of active engagement in physical alignment were established, Study 3 moved on to contrast active engagement with observation of physical alignment in 10-month-old infants. In this study, infants who actively engaged in physical alignment later imitated the experimenter’s goals, thus replicating the benefits of physical alignment with older infants. Infants who observed the physical alignment of a familiar and novel action did not imitate the experimenter’s goals, suggesting that active engagement in physical alignment is, at least initially, more beneficial than the observation of aligned actions for extracting common goals.

Finally, Study 4 addressed whether one factor previously shown to facilitate comparison would help infants extract a novel goal when observing physical alignment. Goal labels spoken during infants' observation of alignment aided infants in extracting the goal of the novel action, suggesting that infants formed a conceptual representation of the goal. Importantly, non-word vocalizations did not provide the same benefit, indicating that labels uniquely drew attention to the goals to be compared.

There are several aspects of the event viewed during physical alignment that infants could have learned from and/or compared. As discussed in Studies 1 and 2, many lower level mechanisms for learning were ruled out by control conditions. Although infants learn about the goals of actions from functional information in some cases, it was not helpful in the current work (*control move condition,* Study 1). Additionally, infants did not benefit from engaging with the claw (*control touch condition,* Study 1). In Study 1B, learning an association between the claw and the toy it was presented with was not sufficient to drive goal imitation. Study 2 further suggests that engagement in social contingency during the physical alignment was not the critical cue driving goal imitation. Study 3 added to this conclusion by showing that observing an experimenter engage in a socially contingent manner with another experimenter (using the claw) did not influence infants' later goal imitation. The *observational condition* and *non-word vocalization condition* in Studies 3 and 4 provide additional support that cues of association or functionality were insufficient to drive goal imitation. The null findings across these control conditions and the fact that attention to the claw and toys (during both familiarization and test trials) within and across all conditions and studies was not related to infants' goal imitation suggests that neither attentional nor associational mechanisms drove infants' goal imitation in the *physical alignment condition* in Study 1, the *contingent aligned condition* in Study 2, the *active condition* in Study 3, or the *labeling condition* in Study 4.

As described above, physical or causal properties of the tool did not drive infants' goal imitation in test trials. Infants in the *control move condition* in Study 1, the *observational condition* in Study 3, and the *non-word vocalization condition* in Study 4 all had the opportunity to view the casual properties of the tool. If learning the causal link between the tool and toys provided sufficient information for infants to extract the goal of the experimenter's actions with the tool, infants in all of these conditions should have imitated. In actuality, none of these groups imitated the experimenter's goals.

A distinct, though related, question regards whether it was necessary for infants to understand the causal nature of the experimenter's actions in order to compare the tool use actions to the familiar grasping actions. Due to the importance of attention to the experimenter in Studies 1 and 2, it seems minimally necessary for infants to recognize the causal link between the experimenter acting on the claw and the claw's grasp of each toy. Research indicates that 7-month-old infants are capable of distinguishing between causal and non-causal events categorically (Oakes, 1994) and recognizing that events in which hands and inanimate objects move in synchrony together are causal (Saxe & Carey, 2006). In the current work, infants would not need to understand support or movement capabilities of the claw actions because, during test trials, the experimenter reached for the toy with the claw but did not move the toy.

Although, for reasons described above, I do not believe causal understanding plays an important role in this work, adapting the familiarization trials such that the experimenter's actions were not causally related to passing the toy could directly assess this issue. For example, if the experimenter first passed the mat (with the toy on it) to the infants and then reached for the toy without moving it, would infants still imitate the experimenter's toy choice during test trials? I suspect they would. A further question to probe in future research concerns whether infants can learn about new causal events through physical alignment (see *Breadth of knowledge* for related questions).

Together, the current findings add to a growing literature suggesting an important role for comparison in cognitive learning during the first year. They also raise several questions concerning the extent to which comparison influences infants' action understanding. In order to gain a better understanding of the mechanisms at play in the current research, I discuss 1) the breadth and depth of knowledge gained from comparisons, 2) the role of shared attention in the comparison process, 3) whether comparisons were implicit or explicit, 4) further tests of the comparison process, and 5) opportunities for comparison.

Nature of Goal Representation

Breadth of Knowledge.

Mapping to Novel Actions and/or Mental States. As discussed above, tool use was used in this series of studies as an example of what I believe is a broader phenomenon. Although these studies only provide direct evidence that infants were able to learn about the goals of tool use actions through alignment, it is likely that the same mechanism could be used to learn about the goals of other actions throughout development. How comparison processes benefit recognition of the goals of more complex and abstract actions (e.g., multi-step sequences, object-directed attention, actions produced by unfamiliar agents), and eventually mental states, should be addressed in future research.

Due to the social nature of physical alignment in the current studies, emotion recognition and understanding represent a category of mental states for which the role of comparison processes could be important. It has been proposed that comparison processes play an important role in emotion understanding and empathy (Barnes & Thagard, 1997). Assuming this perspective, it follows that physical alignment of one's own emotions with another's should facilitate understanding of that individual's emotional state. Whether or not this would occur through a similar process as that evidenced in the current studies is unknown.

One difference between the alignment of instrumental actions and facial expressions is the information that is visually accessible. Infants in the current studies could observe the two actions being enacted during physical alignment and compare them visually. Someone displaying an emotional expression, however, has no visual access to his or her expression (unless there is a mirror present, of course). This lack of simultaneous perceptual access to the two expressions and the need to compare an internal state to another's external expression might make alignment of emotions relatively difficult. It is possible, then, that comparison of emotional expressions emerges later in development than comparison of instrumental actions. If it does come about later in development, a training study could be conducted (prior to the recognition of a particular emotion) that elicits specific emotions in a child as the child sees the same emotion expressed by an experimenter. The child's understanding of that emotion could then be assessed in a social referencing or habituation paradigm and contrasted with children who see the experimenter express a mismatched emotion. The development of comparisons of goals in relation to comparisons of emotions should be examined further.

Context Specificity. Another avenue of inquiry concerns the breadth of knowledge gained through the comparison process when aligning two actions (regardless of whether those actions are instrumental or emotional expressions). The current studies did not assess whether infants learned about the specific goals of the particular tool, toys, and experimenter with which they engaged during the alignment or gained a more general representation of the goal-relation between an individual and a goal object. Whether they would recognize the goal behind tool use actions produced by a different individual or with a different tool (e.g., a cane) after engaging in physical alignment with an experimenter using a claw is an important question.

If comparison processes do *not* initially induce a broad representation, how do infants move beyond initially context-specific knowledge? One possible mechanism of generalization is progressive alignment, a form of structure mapping (discussed in detail below) that helps individuals move from local to more distant structural matches (see *Further tests of comparison*).

A limitation of the current study is that the alignment training involved socially coordinated actions and infants' responses in the goal imitation paradigm could not differentiate between whether infants viewed the experimenter's tool use actions in terms of the social goal of toy exchange or in terms of the experimenter's individual goal of grasping the toy. It is possible infants learned that the goal of the game was to reach for the toy that the experimenter reached for, rather than having learned the individual goal of the experimenter's tool use action. In both cases, infants would have learned a goal rather than an associative response. The question is simply a matter of whether they learned a collaborative or an individual goal.

Studies 1 and 3 cannot answer this question, because in both studies, infants who were actively engaged in the toy passing game were the infants who later imitated the experimenter's goal with the claw. Study 2 demonstrated that social contingency was not driving goal imitation, but this does not rule out the possibility that infants learned about a social goal during physical alignment in these studies. The *labeling condition* in Study 4 indicated that infants did not necessarily need to be engaged in the “game” themselves in order to learn a goal, but this does not resolve whether they extracted a social or individual goal from viewing the two experimenters’ actions.

A different dependent measure that is external to the game is necessary in order to address this issue. For instance, after engaging in physical alignment with the experimenter using a tool, a habituation paradigm could assess infants’ recognition of the experimenter’s goal when using a tool. If infants recognized the experimenter’s goal in a habituation paradigm in which no action on the toy was necessary on the part of the infant, this would imply that infants learned an individual goal rather than the social goal of a passing game.

Further, in the goal imitation paradigm, recognition of the experimenter’s goal was revealed through infants’ toy choice, but whether the infant recognized that the experimenter was not interested in the tool itself but rather used the tool as a means to retrieve the toy was not addressed. Adapting this training for inclusion in a habituation paradigm would help address this issue. Infants could be habituated to an experimenter acting on one of two tools in order to reach one of two goals. In test trials, then, whether or not infants recognize that the experimenter’s goal was the toy rather than the tool could be examined by switching the pairing between the toy and the tool (see Sommerville & Woodward, 2005). This would address whether infants truly understood the higher-order goal structure of the means-end action.

Despite the many advantages of habituation paradigms, they are limited in that they assess infants' responses to novelty (e.g., a novel goal) rather than assessing expectations prior to an event outcome. Eyetracking provides a way to assess infants' (goal) predictions prior to viewing the tool use action carried out during test trials. In a study by Cannon and Woodward (under revision), 11-month-old infants who saw a hand reach for one of two objects on a screen later predicted that the hand would reach for the same object in a new place rather than a new object in the same place (as indicated by eye saccades to the goal object without hand movement toward either object). In contrast, when these infants saw a claw choose between objects, they reliably predicted that the claw would go to the same location rather than the same goal after the toys' locations were swapped. Combining this paradigm with alignment training would address whether engagement in physical alignment leads to accurate goal prediction for tool actions before this prediction would otherwise be established and revealed.

Breadth of Attribution to Novel Agents. A further question concerning the breadth of this mechanism more generally is whether comparison only supports inferences about human actions or might also support analysis of any event in which one entity moves toward another, regardless of whether a human agent is involved. It is of note that the action-goal infants learned about in this series of studies was a novel kind of *human* action. In each of the current studies, infants always saw an *experimenter* act on a toy with a tool. The marginal correlation between infants' attention to the experimenter during familiarization and their imitation in the *physical alignment condition* in Study 1 and the significance of gaze shifts between the experimenter and the claw actions in the *contingent aligned condition* in Study 2 both hint at the fact that, particularly early on, attending to the social agent is advantageous for interpreting the goals behind novel actions. Whether infants could also map the goals from physically aligned actions to novel, nonhuman agents is an open question.

It must be noted that older infants and adults can reason about the goals of non-human agents (e.g., Bíró & Leslie, 2007; Gergely & Csibra, 2003). Progressive alignment could once again provide a mechanism for mapping familiar goal-relations to novel agents. This possibility is described in more detail below (see *Progressive alignment*). The possibility that infants use progressive alignment to extract the goals of novel, unfamiliar, or abstract actions provides a new perspective concerning how infants might develop the capacity to extract goals of abstract events. Future research is needed to reveal whether analogy processes play a role in this extension.

Perception and Production? Finally, the scope of the benefits of physical alignment could also extend to aiding infants not just in recognizing the goal of novel actions but also in learning to perform novel actions. In the current work, the claw that the experimenter manipulated would be unwieldy for young infants to use as a tool. Whether infants could learn to perform new actions through physical alignment should be assessed using novel actions that are more feasible for young infants (e.g., pulling on a cloth to retrieve a toy).

Chen and colleagues' study (Chen et al., 1997), described in the introduction, implied that infants learned to solve cloth pulling problems through comparison between modeled examples and those problems given to the infant. Current work in our laboratory suggests that cueing infants to attend to the goals rather than the means of means-end actions helps infants learn to solve cloth pulling problems more readily and efficiently (Gerson & Woodward, in preparation). One hypothesis for explaining this finding is that comparisons between the goal structures of multiple problems helped infants solve the problems. Combining physical alignment with a dependent measure designed to assess infants' improvement in problem solving would provide a more direct test of whether comparison helps infants solve problems.

Potential relation to mirror neuron system. The prospect that comparison might lead to motor learning raises the question of whether alignment training would change neural representations of both produced and observed goal-directed actions. Recently, the mirror neuron system (MNS) has been a hot topic of discussion and inquiry across a number of domains, including action understanding, motor development, and empathy. Mirror neurons were first discovered to fire both to the production and observation of object-directed actions in nonhuman primates (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992). Since their discovery, neuroimaging and electrophysiological findings suggest that a similar mirror system is present in humans (Rizzolatti & Craighero, 2004). Some important features of this system are that it: 1) is responsive both to produced and observed actions, 2) is particularly sensitive to goal-directed actions, and 3) is shaped by experience and motor expertise (Calvo-Merino, Grezes, Glaser, Passingham, & Haggard, 2006; Järveläinen, Schürmann, & Hari, 2004). Because of these features, this system is a candidate neural mechanism for the reported behavioral link between one's own and others' actions. Hypothesized physiological markers of this system have recently been identified in infancy (Shimada & Hiraki, 2006; Southgate, Johnson, El Karoui, & Csibra, 2010; Southgate, Johnson, Osborne, & Csibra, 2010).

Whether the findings in the current work are unique from or related to the MNS cannot be answered by the current work. Research by Ferrari and colleagues (Ferrari, Rozzi, & Fogassi, 2005), however, suggests that physical alignment between familiar and novel actions may indeed change neural responses (i.e., responses of the MNS) to observed events. In this work, the authors found mirror neurons that fired when monkeys observed a tool use action (a tool reaching for food) they had never performed themselves (with a tool). Similar mirror neuron activity was found when the monkeys reached for food themselves (without a tool). During this study, the monkeys' previous experience viewing the tool actions coincided with interactions in which they retrieved a piece of food from the end of the tool (thus simultaneously grasping the same object as the tool, just as in our current study). It is possible, therefore, that subsequent mirror neuron activity during tool use observation was the result of having acted on the same goal as the tool during previous encounters.

Whether physical alignment of goal-directed actions alters neural responses to novel actions in human infants should be examined. If so, this would suggest that the MNS plays some role in the learning that takes place in the current studies. This would not, however, determine that neural representations of motor learning entirely explain infants' actions. As described in the discussion section of Study 4, infants are doing more than motor mirroring when they imitate the experimenter's goal. Instead, they gain a conceptual understanding of the novel action. Differences in MNS activity after active engagement in alignment versus observation with labeling would be expected.

I hypothesize that neural representations of goal-directed actions could be a stepping stone for infants' developing action understanding rather than the sole mechanism of goal representation throughout development. The structural level of description infants gain through mirroring could provide an initial representational kernel for the subsequent development of intentional action knowledge. Abstraction and application of goal knowledge to novel actions could occur both through motor mirroring (as in Ferrari et al., 2005) and comparison processes like those described in this dissertation. Comparisons between familiar and novel actions offer the opportunity for individuals to move beyond initial neural mapping and gain more abstract and conceptual representations.

The Role of Shared Attention in the Comparison Process

As described in the introduction, my proposal is not the first to theorize that engagement with social partners plays a role in the development of intentional action knowledge. Tomasello (1999) has hypothesized that infants undergo a "nine month revolution" at which point in development they begin to engage in triadic interactions (shared attention on an object) and come to understand others as intentional beings. He suggests that engagement in shared attention helps infants conceptualize first and third person perspectives concurrently.

Barresi and Moore (1996) have proposed a more direct mechanistic account of the link between engagement in triadic interactions and intention understanding. Much like my account, they suggest that sharing attention on an object with a partner allows the infant to physically align the focus of his or her attention (the attentional goal) with that of the social partner. Findings from the current studies demonstrate that physical alignment between one's own and a social partner's instrumental actions facilitates recognition of the other's goals and suggests that this occurs before infants systematically engage in joint attention.

Lack of relations between goal imitation and attention to the experimenter or her goal during test trials across studies suggests that joint action, rather than joint attention, drove comparison in this work. Still, this does not imply that shared attention played no role in how infants benefited from engagement in physical alignment. The fact that attention to the experimenter (or gaze shifts between the experimenter and claw) was correlated with imitation in Studies 1 and 2 implies that shared attention influenced infants' ability to interpret the experimenter's actions and benefit from alignment. Because this relation was marginal in Study 1, this finding should be replicated before any firm conclusions can be reached about the role of attention to the experimenter during physical alignment. The significant relation in Study 2 may be because attention to the experimenter is particularly important in this paradigm due to the perceptual discontinuity between the experimenter and claw created by the tunnels.

The relation between attention to the experimenter during alignment and rates of goal imitation during test trials was not found in any of the studies conducted with 10-month-olds. This may be due to the fact that infants begin to engage in shared attention more robustly beginning around 9 months of age (as described earlier; e.g., Tomasello, 1999). It must be noted that shared attention, as I define it in this work, does not require that infants recognize that they are sharing attention with the experimenter. Instead, I focus on looks to the experimenter and gaze shifts between relevant aspects of the event. These attentional capacities are likely related to joint attention skills such as gaze following and engagement in triadic interactions, which, as stated earlier, develop between 9 and 12 months (Tomasello, 1999). Because 7-month-old infants do not, as a group, actively engage in shared attention or triadic interactions, they likely vary greatly in their inclination to shift gaze between a social partner and an object of attention.

At seven months, infants who are more likely to engage in shared attention or attend to relevant aspects of an event seem more able to engage in the process of comparison and benefit from it. At this younger age, infants might need to rely more on attention to the experimenter than older infants. Individual differences in attention to the experimenter or number of gaze shifts might not be as critical at ten months. One hypothesis is that infants can gain the same information from less time looking at the experimenter at ten months (perhaps because of their propensity to follow gaze; Brooks & Meltzoff, 2005), though this question was not addressed in the current research.

The source of individual differences in the tendency to engage in shared attention at seven months of age is beyond the scope of this work. Some previous research on this topic suggests that early experiences with caregivers may play a role in the development of joint attention. The infants' active engagement in interactions likely plays a role too. In fact, longitudinal findings indicate that more frequent simultaneous action on an object with a social partner at six months of age leads to more engagement in shared attention at nine months (Gaffan, Martins, Healy, & Murray, 2010). Because engagement in joint action precedes engagement in joint attention developmentally, joint action itself may play an important role in the development of shared attention. These two types of interactions could then facilitate comparisons between the self and other both independently and convergently.

Further, although attention during test trials was unrelated to goal imitation in any study, examining differences across studies suggests that there is a shift in attention throughout development: across studies, older infants spent more time attending to the experimenter's goal and less time attending to the experimenter than did younger infants (see Figures 2.5, 2.8, 3.5, 4.3, and 5.2). Despite the fact that variability in attention to the experimenter or to the goal toy did not drive goal imitation in either age group or in any condition, this shift in attention to the meaningful aspect of the action is consistent across studies and thus worth exploring. One possible explanation is that 10-month-old infants are better at gaze following (Brooks & Meltzoff, 2005) and are more likely to shift their attention from the experimenter to the focus of her gaze during test trial demonstrations: the goal. This shift in increased attention to the goal occurred across all conditions regardless of infants' goal imitation. Therefore, it was not driving infants' responses; instead, it likely reflects a shift in infants' gaze following capabilities that may make the comparison process more effective at the group level. Because of this developmental phenomenon, future research could assess whether infants physical alignment during joint attention episodes (rather than joint action) helps infants learn about the goals of object-directed attention. For example, if the experimenter passed toys to the infant with her hand after gazing at the toy from several angles first, would this help infants align their grasp with the experimenter's attentional state? This could be tested by seeing whether the infant would choose a toy the experimenter gazes at (but does not touch) during test trials.

Implicit versus Explicit Comparison

It is unlikely that infants are aware of the active process of comparison from which I propose they benefit in these studies. The notion that this process may be implicit, however, does not make it less meaningful. As Baillargeon (2004) has pointed out concerning findings from violation of expectation studies (in which looking times, rather than an overt behavior by the infant, are used as a dependent measure), infants could engage in implicit or unconscious processing though still "engaging in…appropriate reasoning and inferential processes (p. 422)."

A substantial literature suggests that adults' goal pursuit and decision making is influenced by factors of which the individual acting is largely unaware (e.g., Bargh, 2002; Chun, Kruglanski, Sleeth-Keppler, & Friedman, 2011). Priming studies indicate that adults are influenced by words denoting a certain attitude (e.g., cooperation versus competition) and often unconsciously adopt others' goals when viewing another's actions. One proposal as to why individuals unconsciously adopt others' goals is that people routinely align their own preferences and judgments with others' (Jones, DeBruine, Little, Burriss, & Feinberg, 2007).

Markman and Gentner (2005) suggest that comparison processes are constantly active. They propose that the process and/or outcomes of comparison need not be conscious. Instead, nonintentional similarity comparisons drive attention allocation, which can then, in some cases, influence higher-level cognitive processes. In support of the notion that the process need not be explicit, many of Gentner and colleagues' findings (see Gentner, 2003 for a review) have demonstrated spontaneous comparison in preschoolers without explicitly indicating to the children that they should compare during these tasks.

This is not to say that individuals never engage in explicit comparison. Literature discussed in the introduction concerning the difficulty adults sometimes have mapping analogies between perceptually dissimilar instances makes it clear that a conscious effort must be put forth in at least some cases. Although I do not view explicit awareness as necessary for this task, it is likely helpful for more demanding tasks.

Although I suggest infants in this study aligned and shared their goals with the experimenter without conscious awareness of engaging in this process, adults might instead use top-down inference if they were asked to participate in this task. They might, for example, think about whether the experimenter wanted the toy, wanted to show them something about the toy, or wanted to share the toy with them when she reached for the toy during test trial demonstrations. These diverging interpretations, though potentially useful and informative in everyday interactions with others, could prevent the adult participant from imitating the experimenter's toy choice. For example, they might instead choose the opposite toy so as not to compete with the experimenter. If adults engaged in a cognitively demanding task simultaneously with engagement in this task, they might resort back to automatic processes and choose the same toy as the experimenter.

Further Tests of the Comparison Process

The current findings indicate that comparison plays a role in infants' developing knowledge of others' goal-directed actions. Further, findings from Study 4 indicate that common labels act as cues for infants to compare in the domain of action understanding. According to structure mapping theory, in addition to labels, perceptual similarity, progressive alignment, and expertise all support comparison. If the findings in these studies were in fact a function of structure mapping, then these factors should all facilitate infants' comparison of goals. This generates testable hypotheses about when each of these factors might support comparison that facilitates action learning.

Perceptual similarity enables relational extraction in that it drives individuals to mentally align and compare exemplars, leading to the discovery of structural similarities (Gentner, 2003). Progressive alignment both relies on and helps individuals overcome initial ties to perceptual similarity by beginning with initial comparison of perceptually similar exemplars and leading to mapping the structure of these exemplars to structurally matched but perceptually dissimilar exemplars (Gentner, 2003). Expertise within a particular domain also plays a role in relational extraction. According to Gentner (1988), children undergo a "relational shift" in which they begin to engage in analogies with a more relational focus within a particular domain once they become more familiar with that domain.

Perceptual similarity. Although perceptual (surface) features of exemplars sometimes distract individuals from extracting relational similarities, they can also play a facilitative role. When exemplars can be matched based on perceptual similarity initially, this mental alignment can then facilitate comparison of deeper commonalities and differences, including relations. In the study by Chen and colleagues described in the introduction (Chen et al., 1997), 10-month-old infants, unlike 13-month-olds, were initially unsuccessful at transferring the solution to the multistep means-end problem from one example to another. The authors proposed that representations of the procedure might initially be tied to the specific tool or toy seen in the example modeled by the experimenter. In a followup study, surface similarity was maintained across trials and the perceptually matched goals (toys) or tools across examples aided 10-month-old infants in making an analogy and led them to transfer solutions from one problem to the next by the second trial (as the older infants had done without this additional cue).

There are several ways in which perceptual similarity might facilitate comparison both during participation in and observation of physical alignment. For example, during engagement in physical alignment, a claw may be easier to align with the infant's actions than a tool that is perceptually less similar to a hand (e.g., a cane or stick) because the claw shares some surface features with a hand grasping (it opens and closes like a hand). The fact that infants saw the same toys during physical alignment and test trials might also have helped infants map goal relations from one segment of the testing session to the next. Whether perceptually dissimilar tools and/or toys would make this task more difficult could easily be assessed with slight variations in the current paradigm.

Progressive alignment. Progressive alignment provides one route through which comparison of perceptually similar exemplars could lead to more abstract representations. In studies examining the benefits of progressive alignment with preschoolers, exemplars that progressed from closely related matches (e.g., perceptually matched) to less similar examples (of the same structural relation) facilitated abstraction of the relation in the more abstract cases. For example (Kotovsky & Gentner, 1996), when preschoolers were asked to match exemplars based on a pattern (e.g., shape1-shape2-shape1), they were only able to abstract this A-B-A pattern independent of domain (e.g., patterns varying by shape versus size: square-triangle-square versus big-small-big) after they were first able to compare a series of exemplars from within one domain (e.g., triangle-circle-triangle, rectangle-star-rectangle, etc.)

In the current work, assuming the perceptual similarity between the claw and the infant's hand, these surface features could initially help infants compare these actions; it could then be used in progressive alignment to aid infants in generalizing their representation of the goal of the experimenter's actions to new tools. If infants were first passed a series of toys with the claw and were then passed toys with a perceptually dissimilar tool (e.g., a stick with a cup on the end to hold the toy), they might learn the goal of future actions produced with the stick from mapping the goal-relation from the claw example to the new tool. Similarly, if the goal relation retrieved in the current work is initially tied to the specific toys seen during alignment training, multiple sets of perceptually similar toys might help infants map their goal representation onto novel toys during test trials.

Further, as mentioned in the above section on breadth of knowledge, progressive alignment could help infants map familiar goal-directed actions produced by humans to novel and increasingly abstract agents. If infants saw a series of structurally matched actions carried out by familiar agents (e.g., humans) and then saw these same actions (matched in goal relations) acted out by novel agents, such as animated shapes, they might be able to map their goal representations from the familiar to abstract agents. This raises the possibility that infants could learn about the goals of abstract shapes (e.g., Gergely & Csibra, 2003; Hamlin, Wynn, & Bloom, 2007; Kuhlmeier, Wynn, & Bloom, 2003) through analogy with human actions.

Expertise. The significance of expertise for relational extraction is evident in that adults without experience in the relevant domain have trouble aligning pertinent similarities. For example, in a study by Chi and colleagues (Chi, Feltovich, & Glaser, 1981), participants were asked to categorize a set of physics problems. In this task, categorizing based on the equations needed to solve the problem was more meaningful and useful than categorizing based on surface similarities. Despite this, novices in physics sorted the problems according to similarity in surface features (e.g., the objects involved in problems or the literal physicals terms used). Only physics *experts* organized the problems according to the principles needed to solve them (e.g., problems using the Law of Conversation of Energy versus Newton's Second Law). Further, a study conducted by Rattermann and Gentner (1998) found that four and five year old children's ability to recognize similar causal relations was positively related to their causal knowledge. These findings support Gentner (1988) and Goswami's (2001) theories that expertise within a domain leads to a relational shift and suggest that individuals with more experience in the domain of interest are more likely to benefit from the process of comparison and thus recognize relations and generalize appropriately.

In infancy, the effect of expertise on relational reasoning is less established. A study by Adolph (1997) is suggestive that experience in the motor domain is related to transfer of knowledge from one situation to another. In this work, experience (length of time) producing a particular motor act (e.g., crawling), controlling for age, predicted adaptive responding to new situations (through transfer of knowledge about how to act in a novel locomotor task). The ability to adaptively respond to new locomotor challenges requires reasoning about oneself in relation to the environmental context and thus requires relational reasoning. Direct evidence is still needed, however, that infants' experience within a domain exerts an effect on infants' relational abstraction in that domain.

If expertise does facilitate relational extraction, as infants become more expert in producing intentional actions, they should more readily generalize their action representations. This hypothesis is closely tied to the link between infants' action production and their action understanding reviewed in the introduction. It suggests that training infants to produce a novel action could help them both learn about this particular action and eventually generalize knowledge gained about this action to perceptually dissimilar instances of the action.

Once infants become more "expert" at producing and understanding a particular action, viewing someone else produce a perceptually dissimilar but structurally matched action should help infants extract the goal of the novel action. The more experience an infant has producing and/or observing actions, the better the infant should be at generalizing this knowledge. If infants were given the chance to physically align their reaches with a series of perceptually similar tools and objects, they might then be able to extract the relation between an agent and her ultimate goal (a toy) independent of the type of tool used. In this way, experience acting as an agent, familiarity with particular actions, and alignment of perceptually similar examples could interact.

Opportunities for Comparison of Intentional Actions

The social knowledge gained from comparisons during joint action with a social partner is especially intriguing given the ecological validity of this process. Opportunities for comparison during social interactions are widespread in infants' everyday world rather than being confined to the laboratory setting. When infants engage in joint play, they often act on toys simultaneously with a social partner. Triadic interactions, in which two individuals (e.g., a mother and her child) share attention on an object, increase greatly during play at the end of the first year of life. These opportunities for shared attention allow the infant to physically align his or her attention on the same goal as a social partner (see Barresi & Moore, 1996).

Another important opportunity for comparison occurs during collaborative activity. When social partners engage in two distinct actions in order to achieve the same goal, the collaborative partners align their two actions and this alignment could facilitate the extraction of the common intentional relation. That is, comparing one's own action and goal with one's collaborative partner could help an individual extract the goal of his or her social partner's action. In the current work, an adult social partner (i.e., the experimenter) scaffolded joint action by initiating the action and providing the infant with a toy for which it was assumed the infant would want to grasp. Through the development of more complex social and cognitive capacities, infants and children eventually become able to engage in more active collaborations (e.g., Meyer, Hunnius, Paulus, &

Bekkering, 2010) that could provide rich opportunities for alignment and social learning.

Joint play, joint attention, and collaboration are ubiquitous throughout early development and could jointly or independently provide rich opportunities for social learning through comparison. Though all infants experience these different forms of social play, individual differences in the form the play takes might affect the nature and frequency of the comparison process. Joint attention episodes are initially supported and driven by adult social partners (Bakeman & Adamson, 1984). Because of this, variability in the tendency for a caregiver to engage an infant in shared attention could play a role in infants' action understanding.

In support of this hypothesis, research by Brune and Woodward (2007) indicates that 10-month-old infants are variable in their ability to recognize the goal of object-directed attention. That is, when infants saw an experimenter attend to a particular object in a habituation paradigm, only some infants at this age showed a novelty response when the experimenter looked toward a different object in test trials. Intriguingly, variability in infants' responses in this habituation paradigm was related to infants' participation in supported joint attention during free play with a caregiver.

A study by Hofer and colleagues (Hofer, Hohenberger, Hauf, & Aschersleben, 2008) provides additional support for the notion that individual differences in caregiving styles relate to variability in action understanding. In this research, 6-month-old infants of mothers who were moderately controlling in their play styles (during a free play session coded using the CARE-Index; Crittenden, 1988) were better at recognizing the goal of an intentional action (as assessed in a habituation paradigm) than infants of sensitive or unresponsive mothers. Because moderately controlling mothers are less likely to be attuned to their infants' needs and interact contingently with them, the controlling mothers are more instructive in their play and show more goal-directed actions to the infants. Parents who are controlling of the play environment tend to draw infants' attention to their actions rather than allowing the infant to engage in active exploration on his or her own (Lawson, Parrinello, & Ruff, 1992). This type of behavior creates an atmosphere in which parents act on objects simultaneously with their infants frequently, for example, when showing a child goal-directed actions on toys with which the child is playing. Perhaps it is these more frequent instances of joint action that facilitated action understanding in this group.

In both of these examples, variability in action understanding was related to differences in how caregivers interacted with the child. In Western societies, interactions with caregivers play a prominent role in infants' everyday life and are an important source for learning about others in their environment. In other cultures, however, adults are less likely to actively interact and engage in play with their children. Instead, siblings and peers are the prominent partners in joint play and joint attention and children typically observe adults' actions rather than engaging with them (Gaskins & Paradise, 2010). How these differences across cultures influence action understanding has yet to be examined. Future research should consider the role of individual variability (e.g., through observation of free play sessions) in infants' everyday experiences both with different caregivers within Western society and across cultures to examine how these discrepancies in play influence action understanding.

Conclusion

The current findings suggest a means by which infants could overcome initial limits on their action understanding. They provide evidence for the long proposed hypothesis that opportunities for comparison during social interactions help infants glean insights into the goals behind actions they have never seen or performed themselves. Critically, this mechanism likely has a broad impact on infants' action knowledge because joint action is pervasive in everyday social life. Well before infants engage robustly in joint attention with others, they engage in joint action, for example, when taking a toy from a parent. The current findings suggest that these everyday experiences provide rich learning opportunities for infants. This work provides a basis for examining the scope and breadth of the benefits of comparison processes in the social domain. It generates several new and exciting hypotheses concerning opportunities for developing action understanding during social interactions and suggests a path of inquiry that could reveal new insight into the imperative and much debated query of how humans develop their rich social understanding of others.

Appendix A: The Development of Infants' Action Understanding: Structure Mapping as a Mechanism of Generalization

Perceiving and understanding others' intentional actions is vital to communicating and interacting with others. When we see someone perform an intentional action, we can infer the goal behind the action and use this information to predict the person's future actions. For example, when we see someone kick a soccer ball in a game, we perceive this as an intentional relation between the kicker and the ball. We can then use this information to predict the kicker's future actions (i.e., that the kicker will likely continue to kick the ball toward a goal). Without recognizing the relation between the ball and the agent, we cannot make any assumptions or predictions about future actions on the ball. If an opposing team member gets possession of the ball, for example, the former expectation would be disrupted: this new person would likely attempt to kick the ball in the opposite direction. It is thus the relation between the agent and his or her goal that is critical to extracting meaning from actions and applying this meaning to social reasoning.

Barresi and Moore (1996) defined an intentional relation as the relation between an agent and his or her goal. According to Barresi and Moore, intentional relations involve an actor, directed activity, and an object or event that is the focus of that directed activity. The ability to identify these kinds of intentional relations and thus draw meaning from others' behavior is vital to human functioning across several domains. As human adults, the majority of our observations and interactions are filtered through our intention reading. Adults relate stories to others according to goals and plans (Trabasso, Stein, Rodkin, Munger, & Baugh, 1992), parse events into actions based on goals (Zacks, Tversky, & Iyer, 2001), and rely on an understanding of others' goals in everyday reasoning and interactions (Dennett, 1987; Heider, 1958; Malle, Moses, & Baldwin, 2001; Shipley & Zacks, 2008). The propensity to view others' actions as intentional seems automatic and intuitive to us and is universally present in adults (Lillard, 1998; Norenzayan & Nisbett, 2000).

Infants are sensitive to the relational structure of some actions, specifically familiar instrumental actions, from early in life. Further, as will be reviewed below, learning from self-produced experience seems to play a role in early sensitivity to others' goals. Infants' sensitivity to intentional relations becomes broader and richer over the course of the first year of life. For example, infants understand a reach for an object before they understand a reach that involves a tool as a means to retrieving the object (Sommerville & Woodward, 2005; Woodward, 1998). This development implies an important role for learning. This review focuses on how this development occurs.

A central challenge for infants' early social and cognitive development is detecting the intentional relations that structure others' actions. We first present evidence that infants understand intentional relations early in life and examine initial mechanisms of this social knowledge. Then, we focus on how this initial knowledge develops over time. Due to the fact that the generalization of goal relations is central to expanding knowledge about intentions, we focus on this aspect. Analogical learning mechanisms have been shown to support the detection and generalization of information about relational structure in a number of cognitive domains. We review a theory for relational abstraction first proposed by Gentner (the structure-mapping theory; Gentner & Markman, 1997) and evidenced in work with preschoolers. We then propose that this same mechanism functions in infancy, and further, as a system used in the generalization of infants' action understanding. We discuss the implications of this proposal and the current state of empirical evidence needed to support it.

Early Social Cognitive Knowledge

Evidence from several different paradigms indicates that infants have an initial understanding of others' actions as intentional within their first year. As one example, a habituation study by Woodward (1998) demonstrated that six-month-old infants understood the intentional relation between an agent and an object in an object-directed grasp. In this study, infants were habituated to an event in which a person reached for one of two toys on a stage (see Figure A1). After

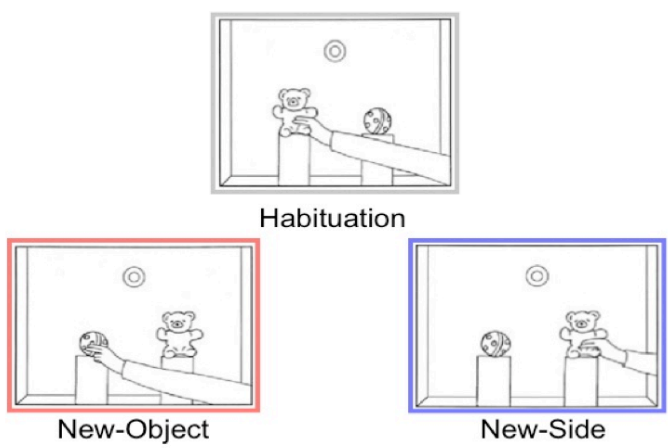


Figure A1. Habituation paradigm used in Woodward (1998) habituation, the placement of the two toys on the stage was switched. Then, infants viewed test events in which the arm took a different path to reach the same toy as in habituation (old-goal trials) or reached along the same path for a different toy (new-goal trials). Six-month-old infants showed a novelty response (looked longer) to new-goal, but not old-goal, test events, indicating that they viewed the goal-relation as more important than the physical path. Importantly, infants' understanding of the action was based on more than mere association. When infants viewed an inanimate rod produce these same actions, they did not systematically look longer at either test event. Instead, their perception of this action rested on an understanding of the *intentional relation* between the agent and her goal.

It is often the case that an infant's understanding of a concept can be detected in habituation studies before the infant is able to act on this knowledge (see Baillargeon, Spelke, & Wasserman, 1985; Spelke, Breinlinger, Macomber, & Jacobson, 1992). In the domain of intention understanding, however, the ability to act on an understanding of others' goals seems to closely follow an initial understanding of this concept (as demonstrated through habituation studies). In a study conducted by Hamlin, Hallinan, and Woodward (2008), when seven-month-old infants saw an experimenter reach for and grasp one of two toys they systematically chose the same toy as the experimenter. In contrast, they did not choose a toy the experimenter touched with the back of her hand (a more ambiguous action). Thus, evidence suggests that infants detect intentional relations and can act on this knowledge early in life (see also Bíró & Leslie, 2007;

Brandone & Wellman, 2009, Gergely, Nadasdy, Csibra, & Bíró, 1995; Mahajan & Woodward, 2009; Sodian & Thoermer, 2004; Wellman & Phillips, 2001)

Intentionality spans a wide variety of actions, ranging from object-directed grasps (like that demonstrated in Woodward's [1998] paradigm) to actions that are part of abstract, overarching goals (e.g., reaching for one's keys may serve the ultimate goal of driving to the store in order to buy flour and make a cake). Not only do infants understand actions like a hand's grasp (as reviewed above), but they also come to understand the more complex acts (object-directed attention, means-end actions, unfamiliar actions, actions produced by unfamiliar agents, failed attempts to achieve goals, and more) within the first year and a half of life (Bíró & Leslie, 2007; Brandone & Wellman, 2009; Gergely & Csibra, 2003; Sodian & Thoermer, 2004; Sommerville & Woodward, 2005; Woodward, 1999, 2003; Wellman & Phillips, 2001). Infants do not, however, demonstrate an understanding of this entire array of behaviors as intentional from the onset.

Infants succeed in abstracting the relation between an agent and his or her goal object in a grasping action by six months (or three months when given training; Sommerville et al., 2005; Woodward, 1998) but do not succeed at detecting the relation between an agent and the object of her gaze until twelve months of age (Woodward, 2003). Additionally, infants recover the goal-relation of familiar events (e.g., those produced by hands) earlier and with fewer cues than they recognize this relation for less familiar events (e.g., those produced by inanimate objects; Bíró & Leslie, 2007; Woodward, 1998).

This developmental change in infants' sensitivity to intentional relations highlights the need to investigate the learning mechanisms in place that facilitate this broadening of social cognitive knowledge. One important contributor to early action knowledge that has been previously suggested is self-produced experience. We review the evidence supporting this mechanism in the following section.

Developmental Mechanisms of Action Understanding

One explanation for the pervasiveness and early emergence of action understanding is that it is the result of universal early experiences. Researchers have suggested that critical abilities common to particular species may be a function of early experiences that are assured (or "expected") in the species' environment (Gottlieb, 1991; Greenough, Black, & Wallace, 1987; Marler, 1991). One way experiences can be guaranteed early in life is through production of the experience by the organism itself.

It has long been proposed (e.g., Baldwin, 1897; Piaget, 1953) that an individual's actions in the world drive cognitive development. Intuitively, it seems highly plausible that one may gain insight into another's goals and intentions by acting as an intentional agent oneself. We might imagine that others have similar internal states to our own when they are exhibiting external states that match behaviors we have engaged in ourselves. Meltzoff (1995) has proposed a "like me" account of understanding other agents, in which the actions of others and the self are innately coupled through a common body schema. According to his framework, infants recognize other humans as “like” themselves, are driven to imitate them, and directly match their own actions and mental states with those of other agents. Other researchers have proposed slightly different accounts as to particular mechanisms but are in agreement that experience influences the understanding of others (see Barresi & Moore, 1996; Tomasello, 1999; Woodward, 2005).

In support of these hypotheses, infants tend to understand particular actions as intentional around the same time they are first able to produce these same actions themselves (e.g., grasping; Bertenthal & Clifton, 1998; Rochat, 1989; Woodward, 1998). Correlational studies have also found that at time points when infants are variable in both their motor and cognitive abilities, their ability to produce particular actions is positively related to their ability to understand the intentional relations of these actions (Brune & Woodward, 2007; Sommerville & Woodward, 2005; Woodward & Guajardo, 2002). Intervention studies add to this support and demonstrate a causal influence of experience on action understanding.

In one such study, Sommerville, Woodward, and Needham (2005) examined the influence of action production on action understanding in three-month-old infants. At this age, infants are both unable to produce well-organized reaches on their own and incapable of understanding a reach as object-directed in others. In the study, infants were trained to produce object-directed grasps (using Velcro-covered mittens) and were then tested on their ability to understand the intentional relation between an agent and the object of her grasp.

Infants who were given experience producing reaches with Velcro mittens and Velcro-covered toys in a short, three minute session were then able to understand this action as object-directed when produced by an experimenter in a habituation paradigm (modeled after the Woodward [1998] study described above). Importantly, the knowledge infants gained from this experience did not concern which objects were present or how things moved but instead relied upon encoding the goal-relation of the event.

A study by Gerson and Woodward (in preparation) provides evidence that the effects of the Sommerville et al. (2005) study were not simply due to infants' visual exposure to their own object-directed actions during training but were instead based on their active experience producing actions. These findings support the notion that self-produced activity is unique in its influence on infants' initial understanding of others' actions as intentional. Additional work provides supporting evidence that the unique benefits of active experience hold true for slightly more complex actions in older infants (means-end actions; Sommerville, Hildebrand, and Crane 2008; Woodward, Mahajan, Sommerville, Eisenband, & Gerson, in preparation).

In addition to the correlational and intervention evidence indicating a connection between action production and understanding, recent neural evidence supports a direct neural link between these two functions. Mirror neurons were first discovered to fire both to the production and observation of object-directed actions in nonhuman primates (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992). Since their discovery, neuroimaging and electrophysiological evidence (Rizzolatti & Craighero, 2004) have led to the hypothesis that a similar mirror system is present in humans. Some important features of this system are that it: 1) is responsive both to produced and observed actions, 2) is particularly sensitive to goal-directed actions, and 3) is shaped by experience and motor expertise (Calvo-Merino, Grezes, Glaser, Passingham, & Haggard, 2006; Järveläinen, Schürmann, & Hari, 2004). Because of these features, this neural mechanism seems likely to play a role in the reported behavioral link between one's own and others' actions. Recent evidence indicates that such a system might be in place in infancy (Shimada & Hiraki, 2006; Southgate, Johnson, El Karoui, & Csibra, 2010; Southgate, Johnson, Osborne, & Csibra, 2010). Although more developmental work is needed in this area, if in place early in infancy, this may be one piece of the puzzle as to how infants first understand actions as intentional. An unanswered question raised by these collective findings is how infants broaden their initial action knowledge to generalize these insights to new events. In the following section, we turn to this question.

The Generalization of Action Knowledge

If we were limited to understanding goals only when we had performed the relevant action ourselves, we'd never become fully competent social perceivers. As adults, we understand the intention behind several actions we have never produced ourselves and can extend our knowledge of intentional actions to novel situations. For example, when adults viewed animated geometric objects move around a screen in a seemingly non-random fashion, they created elaborate stories about the actions and intentions of these shapes (Heider & Simmel, 1944). One possible route of generalization is that self-produced actions create representations that then develop into more abstract action concepts. We consider this possibility in the remainder of this review.

As reviewed above, infants learn about the relational structure of some goal-directed actions by acting themselves. In this way, their own actions seem to give them unique insight into intentional relations. As infants learn to reach or use a tool to attain a goal, they come to view events involving these actions as being structured by an intentional relation (Gerson & Woodward, in preparation; Sommerville et al., 2005, 2008). Without this experience, infants do not focus on the relational nature of these events. The question, then, is whether and how infants generalize this insight to new events. Can the results of active learning help infants see goal relations in a broader range of events? Initial data from ongoing studies in our laboratory suggests that generalization is not immediate after one brief training session such as those that have been used in previous intervention studies. Therefore, we examine cognitive mechanisms that could support generalization given the right kinds of learning contexts.

The problem of generalization is not unique to the domain of action understanding. Every aspect of cognition encounters the challenge of being sensitively and appropriately generalized once initially learned. Additionally, generalization must be based on more than mere surface similarities. In the domain of interest in this review, for example, perceptual similarity is not guaranteed across different instances of similar actions. Grasping a ball appears quite different from using a lacrosse stick to attain a ball, but both of these actions have the same goal of retrieval. Critically, infant cognition does not just exist at the surface-level. Instead, infants learn to generalize based on more than perceptual features (and sometimes even ignoring surface-level similarities in favor of deeper, less obvious similarities).

The ability to note relational similarities is clearly relevant to infant's action understanding, as described above, but it is also essential in several other domains. A few examples demonstrating the importance of relational detection in other domains include spatial reasoning (relations such as in, on, and under), logical-mathematical reasoning (relations such as greater than, less than, and sum of), and biological reasoning (relations such as parent of, offspring of, prey, and predator). Detecting relations is also a vital precursor to analogical reasoning across these and other domains (Gentner, 2003). Analogical reasoning is vital to all cognitive development because it allows one to project inferences to new situations based on previous examples. Thus, it is of utmost importance to uncover how individuals come to recognize relational similarities in order to comprehensively understand learning. One hurdle to matching instances based on similar relations is that relational similarities are initially harder to align than perceptual similarities. Additionally, perceptual differences in relationally similar events make the task of detecting the relational similarities even more difficult.

Because it is essential to prioritize relations rather than surface features across several domains, we recruit a domain-general theory that accounts for the development of relational detection at varying levels of abstraction. We first review evidence for Gentner’s structure mapping theory, a proposed domain-general mechanism used in analogy formation (Gentner, 2003). Gentner and colleagues’ work has particularly focused on preschool children’s relational reasoning in spatial representations and semantic tasks. Because of the limited evidence for this mechanism in infancy, I first argue that infants have the necessary capacities that are assumed by this theory. Then, we propose how this mechanism could take effect in infants’ social knowledge of intentional relations.

The Structure Mapping Theory

Structure mapping is a domain-general mechanism that permits learners to move beyond recognizing surface similarities and instead prioritize relational similarities (Gentner, 2003). Structure mapping facilitates alignment, comparison, and abstraction of relations found in patterns and events in adults and preschoolers. This mechanism allows individuals to discover the similarities and differences between exemplars by “determining the maximal structurally consistent alignment between their representations” and then comparing these representations (Gentner, 2003, p. 201). Structurally consistent alignments are cases in which each element of a representation has a corresponding element in another representation. For example, if a toy (hidden object) is hidden under a cup (hiding place), a structurally consistent representation has an element that matches each of these features (e.g., a different toy [hidden object] might be hidden under a bowl [hiding place]). If the new representation has greater or fewer elements (e.g., a cup with no toy or a bowl, cup, and toy) the two representations cannot be structurally matched. The act of structurally aligning representations allows one to subsequently extract the richest and deepest relational match between the representations.

Often, representations match according to both perceptual (or concrete) similarity and relational similarity. In these situations, initial alignment based on the concrete features aids individuals in abstracting commonalities at multiple levels (perceptual and relational levels) that might not be apparent without the aid of the initial perceptual match. In the example described above, it is easiest to first match a toy hidden under a cup to a new instance of a different toy hidden under another cup. Once the match is made on this concrete level (toy as hidden object and cup as hiding place), one could compare the instances and note that, beyond perceptual similarity, the same relation exists in both cases as well (i.e., *A* under *B*). Extracting this relational similarity would then allow one to recognize the instance of a toy hidden under a bowl as an example of this same relation despite the lack of concrete similarity. Structure mapping allows individuals to understand a relational pattern as distinct from the objects with which it is first associated, thus aiding in the process of creating more complex analogies.

Given the processes involved in structure mapping, several factors are predicted to (and have been shown to) support structure mapping: (1) the opportunity to compare, (2) expertise in the relevant domain, (3) verbal labels that highlight relational properties, and (4) pre-existing constraints that highlight some kinds of relations over others. In the following sections, we briefly illustrate the evidence for effects of these factors on structure mapping in children and adults.

Opportunities to Compare

The process of structure mapping largely relies on engagement in comparison. Once similar instances are aligned (often through matching of perceptual features), the process of comparing the instances leads to the abstraction of relational similarity. In support of this hypothesis, Gentner has found that the simultaneous presentation of exemplars that are both perceptually and structurally similar facilitates children’s ability to detect relational similarities between the exemplars.

For example, Loewenstein and Gentner (2001) presented three-year-old children with a model room (the *hiding room)* in which they were shown where a bone was hidden. They were then asked to find the bone in a spatially identical (though perceptually dissimilar) model room (the *finding room;* the furniture was in the same spatial relation but shaped differently). The children initially had difficulty applying the relational information (where the bone was hidden in relation to other items in the room) from one exemplar to another and were thus unable to find the hidden bone in the second room. Children given the chance to compare two perceptually similar hiding rooms (the furniture in the room was not only in the same spatial relation but was similarly shaped as well; see Figure A2) were then able to apply the relational information from these examples to the new, perceptually dissimilar finding room.

Figure A2. Hiding rooms and finding room in Loewenstein and Gentner (2001). Source: Article by Loewenstein and Gentner in Journal of Cognition and Development (2001).

The opportunity to simultaneously compare the two rooms resulted in better performance than the same comparison process across time. Through this process of simultaneous comparison, children were able to represent the relational similarity between exemplars independent of the perceptual features with which the relation was first associated and thus map it onto a novel exemplar despite the lack of surface similarity.

Loewenstein and Gentner (2001) suggest that the surface similarity between the model rooms was key to promoting comparison. The children in the above-reviewed study were first able to match the two hiding rooms according to their surface similarities. Once the rooms were aligned along this dimension, the alignment promoted the comparison of other shared dimensions of the rooms (the similar spatial relations).

Although results in Loewenstein and Gentner's (2001) study show that simultaneous comparison yields the highest detection of relations, *progressive* *alignment*, in which similar events are presented in close temporal proximity, further allows children to abstract higher-level relations. For example, Kotovsky and Gentner (1996) found that first aligning items based on relatively concrete relations facilitated 4-year-old children's subsequent ability to discern the higher-order relational structure between the items. When children were trained to match examples of the relation small-big-small through the serial presentation of several examples of this relation, 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; see Figure A3).

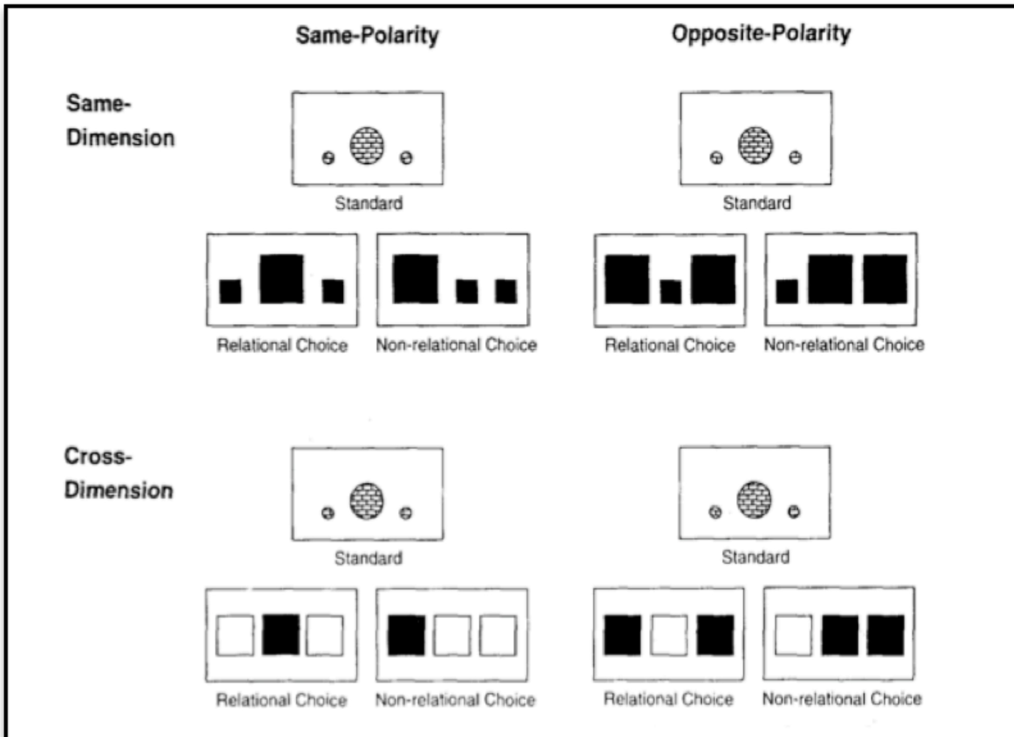


Figure A3. Same and cross-dimension mapping relations in Kotovsky and Gentner (1996). Source: Article by Kotovosky and Gentner in Child Development (1996).

Importantly, children's ability to transition their understanding of the relation from within to across dimensions was reliant upon the alignment of within dimension similarities. When children were shown a series of A-B-A pattern examples from within the same dimension (e.g., big-small-big) before they were shown cross-dimensional examples of this pattern (e.g., shaded, not shaded, shaded), they were able to map their understanding of the relation from the initial dimension to the novel dimension. In contrast, children who saw an intermixed set of both within and cross-dimension examples in random order were not able to extract the similar relation. Therefore, progressively aligning within dimension examples allowed the children to extract the A-B-A relation independent of the dimension. This likely occurs through a similar process of comparison.

The process of comparing representations both simultaneously and across time has been evidenced as useful to abstracting relational similarity. This ability to shift from a featural to relational focus is facilitated by other factors as well. In the next section, we review evidence that experience within a particular domain influences children's detection of relations within that domain.

Expertise

In order for the process of comparison to support the abstraction of relational similarities, children must focus on the relations, rather than other features (of which there are usually many), during alignment. In fact, children undergo a "relational shift" in which they begin to engage in analogies with a more relational focus within a particular domain once they become relatively more familiar with that domain (Gentner, 1988). The shift to a relational focus occurs at varying time points in different domains based on the amount of experience one has in the domain. Therefore, the relational shift is not developmentally driven but is instead expertise-driven.

This is emphasized by the fact that, in some domains, even non-expert adults have trouble aligning pertinent similarities. For example, in a study by Chi and colleagues (Chi, Feltovich, & Glaser, 1981), participants were asked to categorize a set of physics problems. In this situation, categorizing based on the equations needed to solve the problem is more meaningful and useful than categorizing based on surface similarities. Despite this, novices in physics sorted the problems according to similarity in surface features (e.g., the objects involved in problems or the literal physicals terms used). Only physics *experts* organized the problems according to the principles needed to solve them (e.g., problems using the Law of Conversation of Energy versus Newton's Second Law).

Gentner has found support for the effects of expertise on the relational shift in both adults and children. In one study (Loewenstein, Thompson, & Gentner, 1999), adult participants were given examples of potential negotiation strategies. Graduate management students were three times more likely than undergraduates (studying in various fields) to compare and draw an analogy from two training cases in order to incorporate tactics from these examples into their negotiation. This is likely due to the fact that the graduate students in business school had a great deal more expertise with negotiation, allowing them to see the relational similarities between examples earlier than students with less experience in this field. Additionally, a study conducted by Rattermann and Gentner (1998) found that four and five year old children's ability to recognize similar causal relations was positively related to their causal knowledge. Together, these findings suggest that individuals with more experience in the domain of interest are more likely to benefit from the process of comparison and thus recognize relations and generalize appropriately.

Labels

In addition to alignment, comparison, and expertise, relational language aids in the initial registration of relations because relational labels invite one to compare instances that one might not be inclined to compare without this cue. Research by Gentner and colleagues (e.g., Loewenstein and Gentner, 2005) supports this hypothesis in showing that, along with progressive alignment, young children perform better on spatial mapping tasks involving relational similarities when they are presented with overt spatial language during the task.

For example, in a series of studies by Loewenstein and Gentner (2005), preschool aged children played a matching game similar to the example previously reviewed (e.g., Loewenstein & Gentner, 2001) in which the detection of relational similarities was key to success. In these studies, children were shown a tall box with a shelf in the middle (creating three places onto which cards were placed: under the box, on the middle shelf, or on top of the box). They were told this box was the "*hiding*" box. They were also shown an identical box that was called the "*finding*" box. One of the three cards placed in the hiding box had a star on it. After seeing the placement of the card in the hiding box, children were asked to find the card in the same place in the finding box.

This task required the children to note the spatial relational similarities between the hiding and finding boxes and find the card that was in the same relative position. When three-year-old children were given spatial relational language during the hiding (e.g., “I’m putting this *under* the box”), they performed significantly better than children who were not given this information (e.g., “I’m putting it *here*”). By four years of age, children no longer needed these labels in order to succeed in the task. When the task was made more difficult by cross-mapping the objects (so that children had to overcome preference for perceptual matches in favor of spatial matches), however, older children (four and five years of age) once again benefited from the spatial language.

Loewenstein and Gentner (2005) believe that older children do not necessarily need language as an aid for simple tasks because they have internalized the language used by younger children. The older children, who were able to perform simple spatial mapping tasks without the aid of language, regained benefits from language when the task was made more difficult because it helped make up for the increased cognitive load that interfered with their ability to internalize speech.

Relational language thus helps children focus their attention on the important aspects of an event or exemplar during the process of comparison. In fact, there are often several physical and relational aspects to which individuals could attend within every representation. In addition to the use of language to focus attention on the important aspects of an event, there are also constraints that must be in place in order for structure mapping to be used sensitively and effectively.

Constraints

One problem with the current account is that not *all* analogies are productive, and thus, constraints are needed to limit the number of analogies one makes. Gentner and Medina (1998) argue that similarity is naturally constrained when one relies on structural similarity during comparisons. Matching systems that have higher-order constraining relations make “a better analogical match” than matching relations that are unconnected to one another because those based on higher-order relations are often more sound matches and less likely to be based on coincidence.

Additionally, Gentner and Medina (1998) hypothesize that knowledge about a domain helps children benefit from more systematic structures. This may be one reason expertise is a beneficial factor in analogizing. In support of this hypothesis, a great deal of evidence indicates that young children use knowledge about particular domains (e.g., biological knowledge, folk physics, number) to constrain generalizations sensitively and appropriately across a variety of domains (see Gelman, 2003; Gelman & Kalish, 2006; Mandler & McDonough, 1996). As one example, children recognize artifacts such as vehicles as distinct from living beings such as animals and constrain generalizations about each of these domains appropriately. Conceptual knowledge could help constrain generalizations by directing attention to the appropriate kinds of relations within a particular domain. With these constraints in place, children should be more likely to compare exemplars within a specified category than across categories and thus extract more relevant and appropriate relations.

In this section, we reviewed evidence that structure mapping guides children's abstraction of relational similarity. We discussed evidence for several features of this mechanism and noted factors that aid the process of analogy. Thus far, support for structure mapping has been reviewed for preschoolers and adults in a non-social domain. In order to extend this proposal to the domain of interest, we next review evidence that infants have the necessary precursors to make use of this mechanism.

Precursors for Structure Mapping in Infancy

Whether or not infants can and do engage in structure mapping in the domain of intentional action understanding is an open question. In order to entertain the notion that infants are able to engage in (and benefit from) comparison, some precursors must first be supported. Infants must have the initial ability to detect relational properties before they can benefit from structure mapping. We review evidence that infants do in fact notice relational properties across a variety of domains. Beyond this, we discuss whether the factors found to influence the detection of relations in older children and adults also play a role in infancy. We note evidence that the same factors that facilitate structure mapping in preschool children could also play a role in infancy, namely: (1) the opportunity to engage in comparison, (2) expertise in the relevant domain, (3) the use of verbal labels to highlight relational properties, and (4) pre-existing constraints.

Detection of Relations in Infancy

In the domain of action understanding, infants as young as six months selectively attend to intentional relations (as reviewed above; e.g., Woodward,1998). Because structure mapping is a domain-general mechanism, it is important to verify that the ability to note relations is also domain-general. In fact, detecting relational properties is a pervasive aspect of infant cognition. Infants display impressive abilities to detect spatial relations, physical relations, causal relations, and relational rules (Casasola, Cohen, & Chiarello, 2003; Marcus, Vijayan, Rao, & Vishton, 1999; Quinn, 2003; Saxe & Carey, 2006).

For example, research by Casasola, Quinn, and their colleagues supports the notion that infants have the vital ability to detect spatial relations. Casasola and colleagues (Casasola et al., 2003) conducted a looking time study showing that 6-month-old infants understood the spatial relation of containment and were able to note similarities between instances of containment in order to categorize these events. Additionally, in studies conducted by Quinn (1994), infants as young as three months demonstrated an understanding of spatial relations. In one set of studies, three-month-old infants were habituated to a dot in several different locations above a line. In test trials, they saw a dot in a new position above the line or a dot below the line. Despite the fact that the dot had moved matching distances in both test events, infants dishabituated to the test event in which the dot was below the line and not the novel instance of the dot above the line, showing that they categorized instances of the spatial relation “above” (see Figure A4).

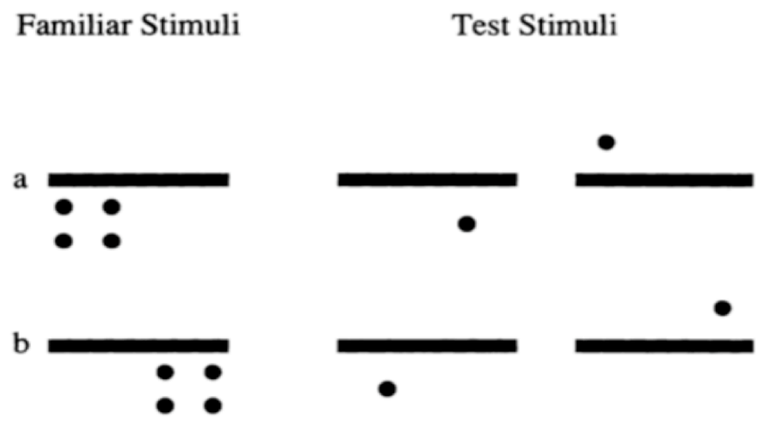


Figure A4. Examples of habituation (familiar) and test stimuli in Quinn (1994). The familiar stimuli shows all four possible locations shown to infants in the habituation trials (infants only saw one of these dots at a time). Source: Article by Quinn in Child Development (1994).

In addition to recognizing and categorizing spatial relations, a study by Marcus and colleagues (Marcus et al., 1999) demonstrated that seven months olds were able to abstract relational patterns from a string of spoken syllables. Infants were trained with three-syllable-strings involving a distinct ABA pattern (e.g., *ga-ti-ga*) or an ABB pattern (e.g., *ga-ti-ti*) and were then presented with test events that either matched this pattern (using different syllables) or consisted of a novel pattern. The infants showed a preference for the novel pattern during test events, demonstrating that they were able to abstract the relations between syllables and notice that a new pattern was different.

These are just a few examples of infants’ ability to note relations and relational similarity across several domains (see also Chen, Sanchez, & Campbell, 1997; Leslie & Keeble, 1987; Oakes & Cohen, 1990). This ability is a vital precursor to the engagement in structure mapping. Now that this preliminary skill has been established, we turn to factors supporting the functioning of structure mapping and the roles these factors play in infancy.

Comparison in Infancy

This work provides initial evidence that infants can detect relational similarities. An important question, then, concerns whether infants, like preschoolers, can use the detection of relations to engage in structure mapping. The notion that infants engage in comparison processes and use comparison to guide conceptual learning is not completely novel, though support for this hypothesis consists mostly of indirect evidence. It has been suggested that infants develop a “contemplative attitude” between three and five months (Mandler, 1992) and that they begin to actively compare stimuli between four and eight months (Fox, Kagan, & Wiskopf, 1979). In this section, we discuss whether simultaneous presentation, perceptual similarity, and progressive alignment aid in infants’ detection of relations.

Evidence indicates that simultaneous presentation of exemplars aids infants in detecting similarities. For example, in a study by Oakes and Ribar

(2005), four-month-old infants were sensitive to distinctions between categories when exemplars of the different categories were presented simultaneously. In contrast, when exemplars were presented successively (one at a time), sensitivity to the same distinctions did not emerge until six months. This demonstrates that infants are able to compare simultaneously presented exemplars and subsequently abstract relevant information from these exemplars at quite an early age.

Quinn (2003) has shown that, initially, infants' understanding of spatial relations is tied to perceptual similarity (i.e., particular objects). Representations of different types of spatial relations not only develop progressively (e.g., *above* is understood before *between*), but each type of relation also undergoes its own developmental course from concrete to abstract. For example, in Quinn's paradigm described above (Quinn, 1994), three- to four-month-old infants' understanding of the relations *below* and *above* was tied to the specific objects they viewed in familiarization. At six to seven months, however, infants had a more abstract representation of these relations that was independent of the objects involved (Quinn, 2003). Similarly, six to seven month old infants in these studies had an object-dependent understanding of the relation *between,* whereas nine to ten month old infants had an abstract, object-independent understanding of this same relation. Thus, perceptual similarity (seeing the same objects) initially aided infants' understanding of relations, but with development, detection of relations was independent of surface similarities.

Cohen and Oakes (1993) provide further evidence that infants' detection of relations is initially aided by perceptual similarity. They found that the specific agents and recipients involved in a causal relation played a role in ten-month-old infants' perception of causality. When these factors varied across examples, infants did not categorize causal events separately from non-causal events. In contrast, when the infants were given perceptual support (same agents and recipients in each action), they were able to categorize causal relations as unique from non-causal events.

Similar effects have been found in infants' own action production. The production of intentional actions is distinct from the recognition of intentional relations but is closely related in that strategically deploying one's actions relies on problem solving and representing the relational structure of the problem at hand. A series of studies by Chen and colleagues (Chen et al., 1997) demonstrate how perceptual similarities initially aid infants in generalizing their own intentional action production. In these experiments, infants engaged in analogical problem solving and were given the opportunity to generalize a learned solution to a problem across exemplars. Ten- and thirteen-month-old infants were given three problems to solve. In each of them, infants needed to remove a barrier, pull one of two cloths, and pull one of two strings in order to retrieve a toy. Thirteen-month-old infants' actions became more structured (they made initial contact with the relevant items more often) from the first to the third example of the problem. This improvement across different problems implies that the infants were able to perceive similarity in the structure of the different problems and integrate and generalize solutions to novel situations and objects.

Younger infants (10-month-olds) given the same task, however, were initially unable to transfer problem solving knowledge to new exemplars. The authors hypothesized that the lack of transfer between exemplars was due to the younger infants' inability to perceive the structural similarity between perceptually dissimilar problems. In order to aid infants' detection of the structural similarity between problems, they created a condition in which the problems infants were given either used the same goal (toy) or same tool (cloth) across examples (so there was both perceptual and structural similarity). Under these conditions, 10-month-olds successfully transferred the solution to the problem across (perceptually similar) examples.

According to the structure-mapping hypothesis, Chen and colleagues' (1997) findings are likely derived through infants' propensity to align and compare perceptually similar instances. Infants' alignment of exemplars in this example occurred sequentially rather than simultaneously. In this way, ties to perceptual similarity (in infancy), in conjunction with progressive alignment, could aid infants in abstracting relations. In contrast to Gentner's findings, however, Chen and colleagues did not assess whether infants were able to apply the learned solution to a new, perceptually dissimilar example after engaging in structure mapping (the test of their learning occurred with a perceptually similar exemplar).

Work by Baillargeon and Wang (2002) provides further evidence that infants are able to use progressive alignment (sequential presentation of multiple similar examples) to generalize initial relational understanding to new events. In the domain of physical knowledge, infants understand the relation between two objects in an occlusion event (one object hidden behind another) prior to understanding this relation in a covering event (one object covering another). Baillargeon and Wang took advantage of this decalage in understanding to demonstrate that eight-month-old infants who understood occlusion events but did not yet understand covering events could transfer knowledge about the similar relations involved in these events through alignment. When these infants were first shown an occlusion event and then shown a covering event involving the same objects, they were able to map the relation between the occluder/cover and the hidden object from the occlusion event to the covering event. According to the structure-mapping hypothesis, infants likely aligned these events based on the surface similarities and were then able to extract the matching structural relation.

Together, these findings suggest that infants are able to engage in comparison. The findings provide indirect evidence that this process aids in the detection of relations. Next, we explore another proposed facilitator of alignment. We examine the role of experience within a domain on infants' relational detection.

Expertise in Infancy

Although no direct evidence exists that expertise influences infants' perception of relations, the effects of age found in several above-reviewed studies (e.g., Bíró & Leslie, 2007; Chen et al., 1997; Quinn, 2003) could, in large part, be a function of expertise. For example, in Quinn's work (Quinn, 2003), infants were able to abstract relations, and do so independent of the objects involved, at different ages for different relations. One explanation for the independent development of particular types of relations is that infants might be able to abstract relations in contexts with which they are more familiar first. In everyday life, infants likely have greater experience with *above* and *below* relations earlier than experience with *between* relations. This could be one reason they detect and generalize above and below relations first.

Similar age effects have been found in the domain of action production. In the Chen study reviewed above, 13-month-olds were better able to carry the solution of the given problem to dissimilar exemplars than were 10-month-olds. This could be a function of 13-month-old infants' greater experience with means-end problems and subsequent improved ability to abstract the relation independent of objects. Adolph (1997) presents more direct evidence that expertise plays a role in the generalization of motor plans independent of age. She found that experience with a particular motor act (e.g., crawling), controlling for age, was the best predictor of adaptive responding to new situations (transferring knowledge about how to act in a novel locomotor task).

Although alternative factors might play a role in the effects of age found in these studies, the finding from Adolph that experience is important to locomotor behavior independent of age suggests that this might be true in other domains as well. As mentioned previously, the ability to adaptively respond to new locomotor challenges requires reasoning about oneself in relation to the environmental context. Direct evidence is still needed, however, that infants' experience plays a role in relational abstraction. Next, we examine the influence of a domain with which infants have relatively little experience. We discuss how language could play a role in structure mapping in infancy.

Labels in Infancy

The notion that language plays a facilitating role in structure mapping during infancy might, at first glance, seem unlikely. Children under two years of age are still relative novices in the domain of language, thus raising doubt that language could influence their understanding in any domain. Evidence indicates, however, that even as young as 12 and 14 months of age (when infants are just beginning to produce words on their own), infants are able to use language to support taxonomic extraction and inductive inference. And even earlier, infants can use labels as conceptual markers.

A study by Graham and Kilbreath (2007) supports the notion that infants use language to compare instances and infer commonality between them. In this work, 14- to 15-month-old children and 21-22 month old children were familiarized to the function of objects with no labels, novel word labels, or novel gesture labels. They were then given new objects that looked or did not look similar to the old objects and were either labeled with word or gesture or not labeled at all. Infants in both age groups were more likely to perform the “target actions” (actions previously demonstrated) on objects that were more similar in appearance to the familiarization objects regardless of labeling, showing they were able to use these surface features to infer deeper commonalities. Critically, both groups of infants also performed the target action on less similar looking objects in cases in which they shared a word label with the familiar object (but not without a shared label). These findings indicate that infants as young as 14 months of age were able to use labeling to note and create a concept of a category based on more than perceptual features. This could be due to the fact that the common label promoted alignment and subsequent comparison, though there is currently no direct evidence to support this hypothesis.

Support for the notion that infants are able to use labels to compare items exists in other domains as well. As one example, Feigenson and Halberda (2008) have shown that 14-month-old infants were able to use labels to parse arrays into smaller units, resulting in greater memory capacity. They propose that this effect was a function of the labels acting as cues that lead infants to view stimuli as conceptually similar to one another and allowed mental reorganization or “chunking.”

Recent evidence indicates that even younger infants are able to use labels in the domain of action understanding to transfer knowledge of an individual’s goal to a new context. Blumenthal, Yun, and Sommerville (2009) found that 10-

month-olds who saw an experimenter label her goal in one room were able to transfer their knowledge of the experimenter's preference for that particular goal-object when they viewed the same action in a new room. Infants who saw the same event without the label did not make this transfer.

Recent work indicates that infants as young four months of age are able to use labels as conceptual markers. Infants familiarized to a category with a novel noun showed a novelty preference (looked longer) to similarly labeled test stimuli that were in a new category. When categories were indicated by a tone rather than a word, infants did not show this novelty preference (Ferry, Hespos, & Waxman, 2010). Importantly, the fact that tones paired with examples of the object category did not guide infants' learning indicates that the finding with words was not just the result of concurrent sound heightening infants' attention. This result indicates that extremely young, prelinguistic infants are able to use words to guide their conceptual learning.

The fact that infants are able to use language to mark conceptual categories and facilitate transfer of knowledge within the first year of life is intriguing. This opens the door to several novel questions about how language plays a role in infants' learning earlier than previously considered. Before discussing how language and other factors influence the domain of interest, we discuss the final factor considered in reference to structure mapping, constraints.

Constraints in Infancy

Work discussed above showed that preschoolers sensitively constrain generalizations based on domain-knowledge and a priori constraints. It is important to consider whether infants are also appropriately sensitive in their generalizations. One domain in which a priori constraints have been proposed to play a role is in the domain of physical knowledge.

According to Baillargeon, infants have innate physical event categories that become more complex through the incorporation of more variables with experience. Infants understand the physical constraints of some events before they understand that the same variables must be considered in constraining other, similar events (Baillargeon, Li, Ng, & Yuan, 2008). For instance, as referenced above in the Baillargeon and Wang (2002) example, infants recognize the importance of height in occlusion events (that an occluder must be at least as tall as the object it is covering in order to hide the entire object) before they note the importance of height in containment or covering events, despite the physical similarity between these kinds of events. Baillargeon believes that infants form “event categories” of simple relations such as occlusion, containment, and covering. Infants then come to recognize the variables (e.g., size, shape, color) that enable them to predict outcomes in each of these categories independently. In this way, they initially generalize their physical knowledge of variables within an event category but not across event categories.

Constraints play a similar role in the domain of locomotor development. Evidence indicates that infants and children flexibly learn what actions can be performed under particular physical circumstances (Adolph & Joh, 2008). Their flexibility in adapting to new contexts, however, is limited. Infants can transfer knowledge of actions within, but not across, “problem spaces.” The scope of transfer is limited to the boundaries of the particular postural control system within which the infant is learning. For example, infants are able to flexibly adapt to new events (e.g., going down a ramp) using perceptual cues while crawling; once they begin to walk, however, their knowledge gained from crawling is no longer applicable. They must then relearn under what circumstances they need to adapt their behavior.

Baillargeon and Adolph examine generalization within different domains but propose similar ideas concerning the constraints of generalization in infancy. What Baillargeon refers to as “event categories” in the domain of physical knowledge is similar to Adolph’s “problem space” in her account of motor knowledge. Both researchers reach a similar conclusion: infants are flexible in their generalization of events/actions within a problem space/event category, but transfer across categories is not as flexible.

The constraints applied by infants that are summarized above are adaptive for the particular domains addressed. For example, in the locomotive domain, generalization within a problem space allows infants flexibility in their learning. The constraints that are in place are also beneficial in that the techniques and adaptive responses one learns in one problem space (e.g., crawling) might not be the most efficient and functional techniques when learning a new behavior (e.g., walking). Every domain likely has particular cases in which it is more or less beneficial to generalize versus constrain one's generalizations. Later, we will consider how this might apply to the case of action understanding.

This broad review of the evidence suggests that, like older children, infants have the necessary capacities to recruit structure mapping as a general cognitive tool in the extraction of relational similarities. Infants, like older children, detect relations across a variety of domains. They spontaneously engage in comparison, which aids their analysis of item similarity. As with older children, simultaneous presentation of items, perceptual similarity, and sequential presentation all aid in the comparison process. Indirect evidence also indicates that expertise and language facilitate the process of comparison. Finally, like older children, constraints play a role in infants' generalizations. Although direct evidence is still needed for some of these issues, the established evidence supports the possibility that structure mapping could play a similar role in infancy as in later childhood. In the final section, we examine how this mechanism could be applied to the domain of interest, action understanding.

Alignment and Action Understanding

Now that we have established the fact that infants have the capacities necessary to engage in structure mapping, we turn back to the domain of interest and examine how this mechanism could play a role in action understanding.

Assuming this proposal is accurate and structure mapping does guide the generalization of infants' initial action understanding, several hypotheses follow. In the following section, we examine hypotheses stemming from the application of structure mapping to the domain of action understanding and the state of evidence concerning each of these hypotheses. We first suggest that representations should start local and then present ideas concerning how structure mapping might play a role in the generalization of these initial representations. We hypothesize that comparison, expertise, and labeling should all facilitate structure mapping in the process of generalizing action knowledge. We then hypothesize what kinds of constraints might be in place in this domain.

Local Representations

Because structure mapping benefits from initial constraints and ties to perceptual similarity, this suggests that infants' action representations should start local and become more general given opportunities to align. Research reviewed above conducted by Woodward and colleagues (Brune & Woodward, 2007; Sommerville & Woodward, 2005; Woodward, 1998, 1999) is in concordance with this hypothesis. It demonstrates that six-month-old infants respond to changes in agent-goal relations when they view familiar agents (people and hands) performing familiar actions (e.g., a reach) but not when they view actions performed by unusual agents (e.g., claws or tubes) or ambiguous or novel actions (e.g., touching with the back of a hand).

In contrast, other researchers' findings seem inconsistent with this hypothesis. Recent evidence indicates that infants can and do sometimes interpret novel actions (e.g., touching an object with the back of the hand; Király, Jovanovic, Prinz, Aschersleben, & Gergely, 2003) and novel agents (e.g., a rod, a box, abstract shapes; Bíró & Leslie, 2007; Gergely & Csibra, 2003; Kuhlmeier, Wynn, & Bloom, 2003; Luo & Baillargeon, 2005) as goal-directed. In these studies, older infants (generally nine and twelve months of age) were tested and additional cues, such as self-propelled motion, action effects, and equifinality were a part of the actions shown to the infants. Researchers have generally proposed these findings as evidence that infants' knowledge of others' intentional actions is independent from their experience with real-world agents and actions and instead reflects innate, abstract representations of intentionality.

One alternate possibility is that infants do not actually understand the "goal" of the actions involved in these more novel examples. Instead, they could detect the spatial relation between the moving entity and the object without understanding the action as an *intentional* relation (as reviewed above, infants understand several different kinds of relations). For example, in Bíró and Leslie's (2007) studies, the additional behavioral cues might aid infants' detection of the relation between a rod and an object (e.g., the cue of equifinality creates more instances of visual pairing of the rod with the object) without requiring an interpretation of this relation as intentional. Although this habituation paradigm reveals attention to relations, it does not, in itself, reveal how infants understand this relation.

According to a different interpretation of these results, if infants are in fact detecting an intentional relation in these studies, structure mapping could play a key role. For example, Bíró and Leslie (2007) demonstrated that six-month-old infants interpreted a novel hand action (poking) as goal-directed when given the additional cue of equifinal movement (approach toward the goal object from several angles). Nine- and twelve-month-old infants interpreted this same action produced by an inanimate rod as goal-directed when given the additional cues of self-propelledness (free movement of the rod in a random motion) and action-effects (movement of the goal object). In order for six-month-old infants to understand the inanimate rod’s action as goal-directed, all three cues were necessary (equifinal movement, self-propelledness, and action-effects). These age differences are consistent with a familiar to less familiar shift over time in that infants were able to detect relations between relatively more familiar events (those with hands) with less cues and earlier than they were able to detect this relation in novel events.

The fact that infants make intentional attributions about novel hand movements before novel agent actions may be due to the ease of aligning actions produced by hands, as infants likely view more examples of actions produced by hands in their everyday lives. This alignment could foster analogy between human movements (that often possess cues of equifinality, self-propelled movement, and action effects) and the movement of the rod in these studies through the process of structure mapping. The older infants in these studies likely had more accumulated experience viewing various actions produced by hands, which could have influenced their ability to align and compare these actions. According to the proposed hypothesis, Bíró and Leslie's findings might actually be due to infants' generalization of an initially context-specific understanding of actions through structure mapping.

These hypotheses are speculative and are in need of direct evidence in order to differentiate these different explanations. Following, we review hypotheses concerning how structure mapping could take effect in the process of generalization of action knowledge, where research stands in regards to these hypotheses, and what open questions remain.

Comparison in Action Understanding

Other researchers have hypothesized that comparisons between self and other support the understanding of others' intentional actions. Meltzoff (2005; 2007) has proposed that the inherent connection between the infant's actions and the actions of others provides the basis for extending knowledge about the self to others, and vice versa. Tomasello (1999) has also suggested that infants learn about others' intentions via analogy to their own intentional states.

If structure mapping is a mechanism through which infants generalize their understanding of intentional actions, it should follow that circumstances that support alignment of exemplars within the domain of interest (in this case, intentional actions) should also support generalization. Alignment of actions could occur through comparing one's own actions with others' actions, through comparing two other individuals' actions, and through the progressive alignment of one’s own actions. The former can be viewed as similar to simultaneous comparison and the latter as similar to sequential presentation and comparison. It is important to consider when and how each of these different types of alignment might be beneficial in this domain.

There are several reasons to posit that alignment of one’s own actions with others’ could play a role in infants’ action understanding. One example of an opportunity to align one’s actions with another’s is during episodes of triadic interaction, in which two individuals jointly attend to an action or object. Infants engage in triadic interactions with caregivers and other adults increasingly between nine and twelve months of age (Tomasello, 1999).

Barresi and Moore (1996) have proposed that comparison during the physical alignment of one’s own and others’ actions during episodes of joint attention allows infants to form an analogy between self and other. Because the infant’s actions and attentional state are physically co present with the actions and attentional states of another individual during shared attention, the infant can compare these states and thus infer that the other individual likely possesses similar attentional and intentional states as oneself.

Alignment of one’s own actions is not, however, restricted to triadic interactions and there are several opportunities to align actions before nine months of age. For example, alignment of one’s own and other’s actions could occur while acting on an object at the same time as another individual, handing an object to another person, or engaging in a collaborative act with another. Each of these events provides the opportunity for infants to align their own actions and intentions with others'.

The current proposal differs from other hypotheses in the point in development at which triadic interactions (and other interactions facilitative of alignment) are proposed to play a role in action understanding. According to Barresi and Moore's (1996) hypothesis, triadic interactions are important for deriving the relation between an agent and his or her goal. In the current proposal, instances of alignment (like in triadic interactions) instead aid infants in building upon a relational representation they have already gained through other means. Aligning one's actions with others' could help infants generalize initial knowledge concerning intentional actions (already gained through self-produced experience) to new actions and objects. For example, research by Brune and Woodward (2007) provides correlational evidence that 10-month-old infants who engage in more shared attention with mothers during a free-play session are more likely to understand gaze as object-directed in a habituation paradigm.

Beginning with a relational kernel (understanding intentional relations) would be especially useful because physical alignment likely occurs in only a small portion of infants' everyday experiences with actions. Infants must be able to extract common goal structure across actions that span time. An initial self-generated action representation could help infants make use of actions that must be aligned through variability in time and give them information about the kind of relation involved in the action (e.g., a goal relation). Thus, the relational kernel allows infants to benefit from progressive alignment as well as simultaneous comparison.

According to this proposal, if infants are able to align an intentional self-produced action with an unfamiliar action, this alignment should facilitate the detection of a matching intentional relation through the structure mapping process. For example, seven-month-old infants have an established goal representation for a grasp in that they understand a grasp for an object as directed at the goal (Woodward, 1998). At this age, however, infants do not yet understand tool-use (Sommerville & Woodward, 2005). If they see an individual use a tool to retrieve a toy, they do not yet know that the person acting intended to reach the toy rather than the tool. The current proposal suggests that if infants of this age physically aligned their own reaches for a toy with a tool-use action (for example, a person reaching for a toy with a claw), they could use the alignment of their own intentional action (for which they have an action representation) with the novel action in order to abstract the intentional relation between the person holding the tool and the goal-toy. Recent findings in our laboratory support this hypothesis (Gerson & Woodward, under review).

The simultaneous alignment of one's own actions with another's and the alignment of one's own actions across exemplars and time should both play a role in facilitating comparison and extending existing action representations to new objects and actions. Future research should examine how progressive alignment plays a role in infants' understanding of actions in new contexts.

For example, current work in our laboratory is examining whether infants in Sommerville, Woodward, and Needham's (2005) "sticky mittens" study gained an understanding of an intentional reach independent of the objects involved in their training. The current proposal suggests that progressive alignment (and initial perceptual similarity) should aid infants in abstracting the relation between an agent and a goal independent of the perceptual appearance of the goal. Therefore, if the infants in Sommerville et al.'s (2005) study's experience acting on toys led them to understand another's reach for the same toys on which they'd acted, but not for novel toys, infants of this age could be given experience acting on multiple sets of perceptually similar toys. Through aligning their actions on perceptually similar objects, infants should then be able to abstract the relation between an agent and objects independent of the objects involved and thus understand another's grasp for a perceptually dissimilar object as intentional.

Further studies should examine when and how these different types of alignment play a role in infants' action understanding. Alignment of one's actions with another's, alignment of two other individual's actions, and progressive alignment of one's own actions all likely play facilitative roles in the abstraction of more complex intentional relations. How these different processes interact and independently influence action understanding is an open question. Next, we discuss how expertise might play a role in infants' alignment of intentional actions.

Expertise in Action Understanding

As previously suggested, the fact that the relational shift occurs earlier in domains with which an individual has some expertise renders plausibility to the notion that infants might extract relations in intentional actions prior to doing so in other domains. Furthermore, within the domain of action knowledge (a domain in which infants are experts at a relatively young age), infants would likely be more prone to align relations for actions with which they have greater familiarity. This being the case, as infants become more expert in producing intentional actions, they should more readily generalize their action representations. This hypothesis is closely tied to the above-summarized link between infants' action production and their action understanding. It suggests that giving infants more experience with an action for which they are beginning to build an action representation could help them generalize their knowledge about this action to perceptually dissimilar instances of the action.

Once infants become more "expert" at producing and understanding a particular action, viewing someone else produce a perceptually dissimilar but structurally matched action should become more meaningful. The more experience an infant has producing and/or observing actions, the better the infant should be at generalizing this knowledge. For example, in a study conducted by Sommerville, Hildebrand, and Crane (2008), ten-month-old infants trained to produce cane-pulling actions to retrieve a toy then understand this same action as directed at the toy when produced by an experimenter. Whether infants are able to use this experience to infer the intentional relation between an individual using a novel tool (like a claw or a cloth) and a toy is currently unknown. If infants were given the chance to interact with a series of perceptually similar tools and objects, they might then be able to extract the relation between an agent and her ultimate goal (a toy) independent of the type of tool used. If this is true, infants trained to reach for toys using a series of perceptually similar canes might then come to understand an agent's cloth-pulling actions as directed at the toy at the end of a cloth. In this way, experience acting as an agent, familiarity with particular actions, and alignment of perceptually similar examples might interact. In the next section, we consider how language could act together with all of these factors.

Labels in Action Understanding

Considering the hypothesis that labeling acts as a cue to compare exemplars, it follows that labeling intentional actions or goals of those actions should allow infants to align and compare when they otherwise might not be inclined to do so. Baldwin and Saylor (2005) have advanced a similar proposal, suggesting that language promotes comparison, which leads to structure mapping, and helps individuals align instances of behavior in order to abstract mental states and intent that are common across different action scenarios. They propose that understanding absent references (discussing things or people not present), for example, should be important to aligning instances of referent-present and referent-absent utterances in order to note the relations between these utterances and internal focuses of attention. Baldwin and Saylor's account focuses on learning internal states. We propose a similar mechanism is at play in infants' generalization of action representations.

Work conducted by Blumenthal, Yun, and Sommerville (2009) reviewed above suggests that labeling goal objects does in fact help infants generalize an actor's goal across contexts. In this example, however, it is the individual's goal (preference) rather than the understanding of this type of intentional action that is generalized. Additional studies have demonstrated that nine-month-old infants can also use labels to generalize a goal across individuals (Henderson & Woodward, under revision). In this case, it is the label rather than the goal of the action that infants are learning. Although these examples do not provide direct evidence that labels can aid infants in abstracting the goal structure of an action, they provide a promising basis for examining this question.

If labels do cue infants to compare actions when they might not otherwise do so, one would hypothesize that labeling two different actions with the same word would cue infants to align these actions and thus extract the common structure between them. For example, one could examine this question with seven-month-old infants and a novel means-end action, as in the above hypothesis that involved physical alignment. In this case, rather than physically aligning an infant's reach with a tool-use action, these two kinds of actions (a hand's reach and a tool's reach) could be given the same label, allowing the infant to compare these exemplars when they otherwise might not do so. This alignment and comparison, guided by labeling, should once again allow the infant to abstract the goal structure of the tool-use action. Labels may be one way infants' generalization of intentional actions is guided and constrained. Additional constraints are considered in the following section.

Constraints in Action Understanding

In the domain of action understanding, several factors are likely to play a role in constraining generalizations. Across domains, there are some constraints that are present in the environment itself. Certain categories of objects or events consist of clusters of similarity (e.g., similar animals tend to have several different kinds of similarities). As mentioned previously, these higher-order constraints found in the world likely guide analogy because they are more effective in analogical thinking (Gentner & Medina, 1998). In contrast, Adolph's work concerns constraints that are organized around motor schema (Adolph & Joh, 2008). These constraints are neither within the child's mind or the child's environment. Because motor development is linked to action understanding, it is possible these kinds of constraints also play a role in this domain. A third type of constraint, which we consider in more detail, is a priori constraints. According to Baillargeon (Baillargeon et al., 2008), these types of constraints exist in the domain of physical knowledge and are innate. Following, I consider the types of innate constraints that have been hypothesized to play a role in action understanding.

Researchers have proposed contrasting accounts concerning the information considered innate to infants' intention understanding. Different perspectives are in concordance in the claim that infants' innate knowledge of intentionality is activated when sufficient behavioral cues are present. These accounts differ, however, in which cues are cited as necessary to activate infants' understanding of intentionality. In this way, particular cues perceived within actions could constrain infants' interpretation of intentional actions.

As reviewed above, Bíró and Leslie (2007) suggest that infants have an innate ability to read intentions. The behavioral cues necessary for activating this understanding include self-propelled motion, equifinal movement, and action effects. One interpretation of their previously reviewed findings that six-month-olds view novel actions as intentional with the presence of all of these cues (and that slightly older infants do so with less cues) is that infants are initially constrained by these cues. They may need all of these cues to be present in order to initially understand new actions and agents as intentional. Infants' experience viewing actions performed by hands likely provides them with the prior knowledge that most of these cues are generally associated with hands. Thus, they can interpret novel actions produced by hands as intentional without the explicit demonstration of every cue prior to being able to do so with similar actions produced by novel agents.

In contrast, Gergely and colleagues (Gergely, Nádasdy, Csibra, & Bíró, 1995) propose that infants take a non-mentalistic stance and view efficiency and rational action as the necessary cues to interpreting goal-directed actions. According to this perspective, infants take a "teleological stance" concerning action and rely on the principle that goal-directed actions should be achieved in the most efficient manner possible. In this case, rational goal approach might constrain infants' interpretation of intentional actions.

In contrast to the possibility that constraints are innate and prespecified, it is possible instead that constraints in this domain are emergent. The motor system could play a role in emerging constraints. For example, in a study by Barrett and colleagues (Barrett, Davis, & Needham, 2007), 12- and 18-month-old infants demonstrated motor fixedness in that they always attempted to grasp a tool in the same prespecified way once it was learned. The same kind of constraints on motor learning may play a role in infants' action understanding.

In particular, infants may be more likely to generalize knowledge about intentional actions to motorically similar events, thus constraining their generalization of conceptually similar events that are performed differently. For example, if infants learn the intention behind a cloth-pulling means-end action, they may generalize this instance to a cane-pulling action with similar motoric demands before generalizing to a conceptually similar, though motorically different means-end event like opening a box to retrieve an object.

Ultimately, motoric limitations should not be the sole driving force in the generalization of intentional action understanding. Infants should (and do) understand actions based on conceptual information rather than motor information in the event. As discussed in great detail above, it is not the physical manifestation of the action that infants attend to in their interpretation of intentional actions initially, so it seems unlikely that they would generalize based on this information alone (e.g., from reaching to any manual action).

Instead, infants might first generalize events that are both conceptually and motorically similar. This initial constraint could then aid their generalization to motorically dissimilar events. Motorically similar actions are often more perceptually similar as well. If infants are able to understand a cloth-pulling and cane-pulling action, for example, the perceptual similarities between these two events could allow infants to progressively align these representations and thus abstract the conceptual similarity that links these two events to less similar events like opening a box to retrieve an object. The mechanisms constraining generalization of intention understanding should be systematically explored to determine to what extent a priori and emergent constraints play a role.

Conclusion

This review examined the origins of intention understanding in detail and considered the mechanisms involved in development within this domain. First, we reviewed evidence for young infants' impressive abilities to understand others' actions. We then considered how the origins of intention understanding are derived, particularly focusing on the link between infants' self-produced actions and their understanding of others' actions. The remainder of the review focused on how infants are able to use this initial kernel of relational knowledge to come to understand increasingly complex actions.

We presented Gentner’s structure mapping hypothesis as a domain-general mechanism used in the abstraction of relations, first presenting evidence for several features of this mechanism and the factors influencing the effectiveness of this process. We then argued that this same mechanism could be used in infancy. Within each of these sections, we discussed findings supporting the benefits of factors such as comparison, alignment, expertise, and language in relational detection and structure mapping. We also reviewed constraints that are in place to harness this process for its most effective and sensitive use. In cases for which no direct evidence currently exists for these features, we examined indirect evidence and discussed how and why each of these factors might still be relevant.

Finally, we applied this proposal to the case of action understanding. We posed several hypotheses concerning how this proposal would take effect in the domain of action understanding and suggested studies that could address these hypotheses. A great deal of open questions concerning the development and generalization of infants’ intention understanding remain. This proposal presents one mechanism through which infants’ understanding of others’ actions could reach more complex levels. This does not imply that other mechanisms do not also interact and influence development in this domain. Understanding others’ actions and intentions is a critical aspect of cognition and is a foundational ability for development in several other domains. Research exploring the paths through which humans eventually develop the sophisticated understanding of others that we possess as adults is vital to understanding all human cognition.

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