Cognition 121 (2011) 1–11

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Infants' understanding of actions performed by mechanical devices

Ty W. Boyer*, J. Samantha Pan, Bennett I. Bertenthal

Indiana University, Department of Psychological and Brain Sciences, IN, United States

ARTICLE INFO

Article history:
Received 11 January 2010
Revised 27 May 2011
Accepted 31 May 2011
Available online 1 July 2011

Keywords:
Action perception
Infancy
Covert imitation
A-not-B error
Cognitive development

ABSTRACT

Recent research suggests that 9-month-old infants tested in a modified version of the A-not-B search task covertly imitate actions performed by the experimenter. The current study examines whether infants also simulate actions performed by mechanical devices, and whether this varies with whether or not they have been familiarized with the devices and their function. In Experiment 1, infants observed hiding and retrieving actions performed by a pair of mechanical claws on the A-trials, and then searched for the hidden toy on the B-trial. In Experiment 2, infants were first familiarized with the experimenter and the claws but not their function. In Experiment 3, infants were familiarized with the function of the claws. The results revealed that search errors were at chance levels in Experiments 1 and 2, but a significant proportion of the infants showed the A-not-B error in Experiment 3. These results suggest that 9-month-old infants are less likely to simulate observed actions performed by mechanical devices than by human agents, unless they are familiarized with the function of the devices so that their actions are perceived as goal-directed.

1. Introduction

The perception and representation of others' actions is crucial for understanding our social world. During everyday social exchanges we are able to effortlessly understand others' actions, implicitly know their intentions and desires, and automatically shape responses to these behaviors. Recent evidence suggests that infants begin to understand at least the goal-directed nature of actions by the second half of the first year, and perhaps even earlier (e.g., Csibra, Gergely, Bíró, Koós, & Brockbank, 1999; Király, Jovanovic, Prinz, Aschersleben, & Gergely, 2003; Luo, 2011; Luo & Baillargeon, 2005; Woodward, 1998, 1999; Woodward & Sommerville, 2000).

Many social neuroscientists suggest that there are neural mechanisms specialized for understanding and responding to observed actions (Decety & Sommerville, 2004; Frith & Frith, 2006; Grèzes, Frith, & Passingham, 2004; Saxe, Xiao, Kovacs, Perrett, & Kanwisher, 2004). These specialized mechanisms may help explain infants' precocious ability to understand others' actions. One unresolved issue, however, is whether the mechanisms involved with interpreting actions are reserved specifically for human actions or are applicable to a wider range of events. Press, Bird, Flach, and Heyes (2005) suggest that because humans have mental states and machines, mechanical devices, and other inanimate objects do not, a cognitive mechanism that responds specifically to human actions may be invaluable for inferring others' thoughts and discriminating animate from inanimate beings. Some researchers have suggested this is a crucial building block of social-cognitive development (Barrett, Todd, Miller, & Blythe, 2005; Rakison & Poulin-Dubois, 2001; Woodward, Sommerville, & Guajardo, 2001).

Several studies report evidence suggesting that infants' understanding of human actions does not extend to non-human agents. Woodward (1998), for instance, habituated infants to an experimenter reaching for one of two objects on a stage, then switched the objects' locations and

---

* Corresponding author. Address: Department of Psychological and Brain Sciences, Indiana University, 1101 E. Tenth St., Bloomington, IN 47405, United States. Tel.: +1 812 856 0814; fax: +1 812 855 4691.

E-mail address: tywboyer@indiana.edu (T.W. Boyer).

0010-0277/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.cognition.2011.05.012

measured looking times to the experimenter reaching for the original goal-directed object in its new location versus the other object in the previous location. Six-month old infants dishabituated to the agent reaching for the new object in the old location, but not to the old object in the new location. When a rod or mechanical claw was substituted for the experimenter, infants did not show differential looking to the two events. These results suggest that infants understand the actions of another person as goal directed, but do not understand the actions of an inanimate agent as goal directed. Similarly, Daum and Gredebäck (2011) found that infants are sensitive to the direction indicated by a hand grasp action by 7-months of age, but are not sensitive to the direction of a grasping claw device. Legerstee and Markova (2008) and Meltzoff (1995) reported that 10- and 18-month-old infants imitate the goal-directed intentions of a human actor, but they do not imitate analogous actions performed by a mechanical device. Likewise, a few studies demonstrate that adults do not respond the same way to actions modeled by non-human agents, such as robots or mechanical devices, as they do to actions performed by a human agent (Kilner, Paulignan, & Blakemore, 2003; Press et al., 2005; Tsai & Brass, 2007).

By contrast, a number of studies demonstrate that by 5-months of age infants use self-propulsion cues (Luo, Kaufman, & Baillargeon, 2009), and by 12-months use rational path selection cues (Csibra, 2008; Gergely, Nádasdy, Csibra, & Bíró, 1995) and a history of goal attainment (Kuhlmeier, Wynn, & Bloom, 2003) to guide their understanding of the actions of simple two-dimensional geometric shapes. For example, Luo (2011) and Bíró and Leslie (2007) showed, in adaptations of the Woodward (1998) paradigm, that at 3-months and 6-months, respectively, infants are sensitive to the goal-directed actions exhibited by a non-human agent if a sufficient set of animacy cues are present (e.g., self-propulsion, action variation with equifinality, and causal action-effect relations). Using the same paradigm, Hofer, Hauf, and Aschersleben (2005) reported that 9-month-old infants are sensitive to goal-directed actions executed by mechanical claws after a brief familiarization period where they were shown how the claws are operated by a human experimenter. These findings converge with those from adults who interpret the actions of moving geometric shapes as animate if their behavior involves certain sorts of motion, such as pursuit, avoidance, and goal-directedness (Gao, Newman, & Scholl, 2009; Heider & Simmel, 1944; Scholl & Tremoulet, 2000; Tremoulet & Feldman, 2000).

Currently, there is no clear consensus in the literature. Some researchers suggest that infants' understanding of others' actions and attributions of their intentions is specialized for the observation of human actions, while others suggest extension to non-human agents. There are, however, notable differences between the reported studies. Specifically, researchers who have reported that infants' understanding of actions extends to non-human agents have tended to provide infants with additional experience observing the agents act. For instance, it was only after infants had visual experience of a wooden rod moving freely (i.e., through self-propulsion), reaching for an object from multiple angles of approach, and lifting an object from a surface numerous times, that Bíró and Leslie (2007) were able to demonstrate that 6-month old infants are sensitive to the intentions of a non-human agent. Three-month old infants tested by Luo (2011) required similar "rich behavioral information" (p. 459). Accordingly, a key question in examining infants' understanding of the actions of human and non-human agents becomes, to what degree is previous visual experience necessary? In order to address this issue, the current experiments were conducted with mechanical devices, while varying the amount and form of previous experience infants had with the devices.

Our perspective on this issue is informed by the direct-matching hypothesis (Rizzolatti & Craighero, 2004; Rizzolatti, Fogassi, & Gallese, 2001), which suggests that observed actions are mapped directly onto our motor representation of the same action; an action and its effects are understood when its observation leads to simulation by the motor system (i.e., representing the actions of others through covert imitation). This hypothesis is a descendant of James's (1890) and Greenwald's (1970) ideomotor theories and Prinz's (1997) common coding theory. Interest in this approach heightened with the discovery of mirror neurons in primates, which discharge when a monkey either performs an action or observes another perform that action (Rizzolatti et al., 2001). Recent electrophysiological (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995), neuroimaging (Decety et al., 1997), and behavioral (Bertenthal, Longo, & Kosobud, 2006; Brass, Bekkering, Wohlschläger, & Prinz, 2000) studies support the suggestion that a homologous mirror neuron system is functional in humans.

Several studies provide preliminary evidence that infants may be using motor representations to interpret others' actions in the form of correspondence between how they interpret others' actions and the actions they perform themselves. Sommerville, Woodward, and Needham (2005), for instance, reported that 3-month-old infants provided with active experience performing a target action understand a similar observed action as goal directed, whereas infants not given the motor experience do not. Similarly, Daum, Prinz, and Aschersleben (2011) found that the actions 6-month old infants are able to perform covaries with how they interpret others' performance of those actions; specifically, infants who are able to perform a more advanced thumb-opposite grasp are better able to differentiate another person performing a palmar from a thumb-opposite grasp. Sommerville, Hildebrand, and Crane (2008) found that 10-month old infants' previous active experience using a tool to retrieve out of reach objects increased their subsequent understanding of a person using the tool to perform a goal-directed action. Lastly, Sommerville and Woodward (2005) found that 10-month-old infants' ability to solve a means-ends task is predictive of their understanding of another person performing a similar task. Thus, these findings show that infants' understanding of goal-directed actions is facilitated by their own motor experience, sometimes limited to just a few minutes before testing.

As a complement to the preceding studies showing how motor experience facilitates action understanding, Longo and Bertenthal (2006) presented evidence that the actions infants observe influence the actions they themselves perform. Infants were tested with a modified version of Piaget's A-not-B task. In the canonical version of this task, infants see an object hidden at an initial location (A), and then search for it. After repeated search trials at A, the experimenter, in plain sight of the infant, hides the object in a second location (B), and allows the infant to search for it. Between 8 and 12 months, infants continue searching at A rather than at B. This A-not-B error is one of the most replicable findings in developmental psychology (Marcovitch & Zelazo, 1999; Wellman, Cross, & Bartsch, 1986). Whereas Piaget (1937/1954) suggested that this is due to infants' fragile object understanding, other accounts emphasize the role of working memory constraints, inhibitory control deficits, or incorrect spatial coding of the hidden object (Bremner & Bryant, 1977; Cummings & Bjork, 1983; Diamond, 1985). More recent evidence suggests that repeated reaching to A establishes a response bias or motor memory that results in perseverative reaching to the same location (Diamond, 1990; Diedrich, Thelen, Smith, & Corbetta, 2000; Smith, Thelen, Titzer, & McLin, 1999; Thelen, Schöner, Scheier, & Smith, 2001; Zelazo, Reznick, & Spinazzola, 1998). This interpretation has been formalized with Dynamic Field Theory modeling (DFT; Clearfield, Dineva, Smith, Diedrich, & Thelen, 2009; Spencer, Dineva, & Smith, 2009) showing that the history of reaches to the A-location results in an association of sufficiently strong net activation with that location that the infant returns there, despite an initial activation to reach to the B-location on the B-trial.

Longo and Bertenthal (2006) exploited this perseverative reach finding to test if 9-month-old infants interpret others' actions through covert imitation. In their version of this task, one group of infants was administered the canonical test, and one group was administered an observation only test, where they observed the experimenter repeatedly hide and find the object on the A-trials, and then were given the opportunity to search only on the B-trial. The results revealed that infants showed the A-not-B error not only after searching at the A-location, but also after repeatedly observing the experimenter search at that location. Interestingly, in this passive observation condition, the search error occurred only if the experimenter modeled an ipsilateral as opposed to a contralateral reach. Longo and Bertenthal (2006) attributed this result to infants' tendency to reach primarily with their ipsilateral hand at this age (Bruner, 1969; van Hof, van der Kamp, & Savelsbergh, 2002), which suggests their motor representation for a contralateral reach was not as well developed, and thus was less likely to be simulated. Taken together, these findings suggest that infants covertly imitate the experimenter's actions on the A trials, which biases them to search at the same location on the B trial. Moreover, these findings rule out a purely attentional account for the A-not-B error, because infants were as likely to attend to the A-location during contralateral as during ipsilateral reaches.

In this study, we test whether the covert imitation of others' actions extends to the observation of actions performed by mechanical devices, using the modified version of the A-not-B paradigm of Longo and Bertenthal (2006). If infants do not make the A-not-B error after observing the mechanical devices repeatedly hide and retrieve an object, then this would suggest that covert imitation is limited to human actions. Several previous studies (e.g., Bíró & Leslie, 2007; Hofer et al., 2005), however, suggest that some brief motor and/or visual experience with a mechanical device is sufficient to improve infants' understanding of the goal-directed nature of actions performed by the device. If infants' covert imitation of nonhuman actions is also modulated by experience, then the likelihood of it occurring should covary with infants' familiarity with the device.

These two issues were addressed in three experiments conducted with 9-month-old infants who observed an object hidden and retrieved by a pair of mechanical claws. In Experiment 1, the claws were unfamiliar and the experimenter was not visible. Prior to testing infants in Experiment 2, infants were familiarized with the experimenter without the claws or were familiarized with the experimenter and the claws but did not see how the claws were operated. In Experiment 3, infants were familiarized with the experimenter and observed him operate the claws to reach for a set of objects. If infants are not capable of covertly imitating the actions of the mechanical claws, then a significant percentage of infants showing search errors is not expected in any of the experiments. If, however, infants are capable of covertly imitating the actions of the mechanical claws once they are sufficiently familiarized with them, then they are expected to show the search error in Experiments 2 and/or 3, depending on the type of familiarization required.

2. Experiment 1

This experiment tests whether infants search correctly or incorrectly in the observational version of the A-not-B task when a pair of mechanical claws is substituted for a human experimenter. In essence, this is a direct replication of the experiment conducted by Longo and Bertenthal (2006) except that the infants observe a pair of mechanical claws hiding and finding the object and the experimenter is not visible.

2.1. Method

2.1.1. Participants

Thirty-nine-month-old infants participated ($M = 271$-days, $SD = 13$-days; 17 females, 13 males). An additional eight infants were tested, but were excluded due to fussiness (1), unintentional revealing of the toy (4),[1] refusal to search (2), or experimenter error (1).

2.1.2. Materials

The apparatus consisted of a brown cardboard box top (41 × 32 × 4.3 cm) with two cylindrical wells (12 cm diameter) set into it (12.7 cm apart). A similar apparatus with a single well in the center of a box top was used for training

---

[1] The hidden toy was revealed under the lid without an infant intentionally searching for it. If, for instance, an infant lifted the front end of the apparatus, both of the well lids might be displaced, or if an infant banged on the boxtop, the toy might begin to rattle.

trials. Cylindrical lids with spherical wooden knobs (3.5 cm diameter) were used to cover the wells. The apparatus was presented on a table with a foam board wall at the back to occlude the experimenter and a curtain hung 45 cm above the table surface to block the infant's view of the experimenter's hands and arms operating the claws. The experiment was conducted with a pair of 80 cm mechanical claws that could grab objects with two suction cupped pincer digits (see Fig. 1). A toy that produced a rattle noise when shaken was used on the test trials, and another toy was used during the training trials. The session was filmed from a digital video camera located away from the table and to the infant's side, resulting in a full view of the infant and the hiding apparatus.

2.1.3. Procedure

Infants were seated on their caregiver's lap in front of the stage. Four training trials were administered with the single well apparatus, using the procedure of Longo and Bertenthal (2006) and Smith et al. (1999). On the first training trial, the toy and lid were each grasped with one of the mechanical claws and placed on top of the box on either side of the well. The apparatus was slid forward, and the infant was allowed to grasp the toy and/or lid. The sliding of the box forward after placement with the claws was repeated on all subsequent training trials. On the second training trial, the toy was placed in the well and the lid was placed adjacent to the well. On the third trial, the toy was placed in the well and was partially covered with the lid. On the final trial, the toy was placed in the well and was completely covered by the lid. No infant failed to remove the lid and grasp the toy on the final training trial. The experimenter then removed the single well apparatus, replaced it with the two-well apparatus, and administered the hiding and search trials.

During the test phase, the experimenter extended the claws from behind the curtain, which then grasped the toy and rattled it to draw the infant's attention, placed it between the wells, retracted the claws behind the curtain, and waited 3-s. Next, the experimenter extended the claws and again grasped the toy with one claw, rattled it, removed the A-well lid with the other claw, placed the toy in the A-well and covered it with the lid, retracted the claws, waited 3-s, then retrieved the toy and placed it between the wells. This hiding and search procedure was repeated six times. Finally, the experimenter hid the toy in the B-location, retracted the claws and waited 3-s, then slid the apparatus forward using the claws and allowed the infant to search. The experimenter consistently grasped the toy with the claw operated by his right hand and grasped the lid with the claw operated by his left hand, but the position of the A-location was counterbalanced across infants.

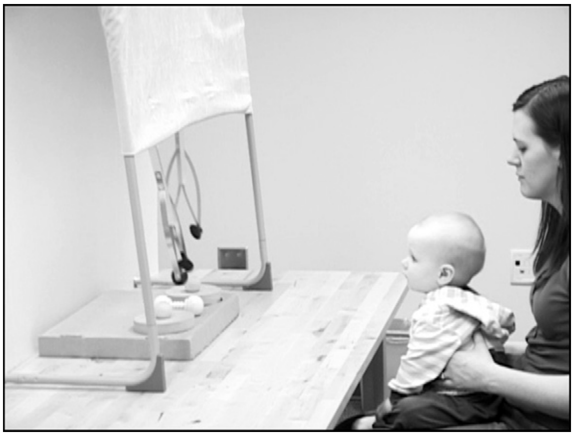

Fig. 1. Example of an infant observing the mechanical claws grasp the toy (Experiment 1).

2.1.4. Coding

Each infant's manual search behavior during the B-trial was coded as correct or incorrect from the video of the session. In addition, although infants could not reach far enough to contact the box top containing the hidden toy on the A-trials, they were not prevented from trying. In order to ensure that any attempts to reach for the hidden toy on the A-trials did not bias infants' performance on the B-trial, we coded each infant's number of attempts to reach on the A-trials. We also coded looking times to the A- and B-locations frame-by-frame (specifically coding looking to the A- and B-locations on the apparatus, either with the lid covering the well or while the lid was being held and the toy was being placed in the well) during the A-trials, during the 3-s delay immediately after the toy was hidden at the B-location, and following the movement of the box to within reach of the infant.[2] Looking times were independently coded by two observers, and 21% of the trials were coded by both observers to establish inter-rater reliability, $r = .97$, $p < .001$.

2.2. Results and discussion

The coding of infants' searches on the B-trial revealed that only 12 of the 30 infants (40%) searched incorrectly at the A-location when the toy was hidden at B (see Fig. 2). By contrast, Longo and Bertenthal (2006) reported that a significant majority of infants (70%) committed the search error after observing an experimenter manually hide and retrieve an object. Reaches toward A during the A-trials were quite infrequent ($M = .83$ reaches across the six A-trials, $SD = 1.17$), and a comparison of infants who searched correctly vs. incorrectly revealed no difference in the number of times infants reached toward the A-location during the A-trials, $t(27) = 1.64$, $p = .11$. In fact, infants who searched correctly on the B-trial reached toward the A-location more frequently ($M = 1.1$ reaches, $SD = 1.4$) than those who made the A-not-B error ($M = .42$, $SD = .67$).

Table 1 summarizes the looking time results. During the A-trials, infants who searched correctly on the B-trial looked at the A-location less than those who committed the A-not-B error, but this was only a marginally significant difference, $t(27) = -1.82$, $p = .08$. Infants did not look at the B-location much during the A-trials, and there was no difference between those who searched correctly and

---

[2] The video record for one of the infants who searched correctly was lost, and therefore reaches and looking times could not be calculated for this infant.

Fig. 2. The number of infants who searched correctly at the B-location or searched incorrectly at the A-location in each experiment.

those who committed the A-not-B error, $t(27) = 1.25$, $p = .22$. During the 3-s delay immediately after the object was hidden at the B-location, infants who searched correctly and those who committed the A-not-B error did not differ in how long they looked at either the B-location or A-location, $t(27) = .76$, $p = .45$ and $t(27) = -1.08$, $p = .29$, respectively. This comparison confirms that infants who committed the search error did not do so because they had not been attending to B during the delay. By contrast, there was a significant difference in infants' visual attention during the search phase. Infants who searched correctly spent more time looking toward the B-location than infants who committed the A-not-B error, $t(27) = 3.73$, $p = .001$, and conversely, spent less time looking toward the A-location, $t(27) = -2.69$, $p = .01$.

Taken together, these results converge to show that infants did not search nor attend consistently to either the A- or the B-location on the test trial. Infants' visual attention on the A-trials showed a trend toward biasing their search on the B trial, but this result was nonsignificant and not replicated in either of the two subsequent experiments. Lastly, infants' visual attention during the B-trial simply confirmed that they looked in the direction that they searched during this phase of the experiment. These findings are thus consistent with previous studies showing that infants are not as sensitive to goal-directed actions executed by mechanical devices as those performed by human agents (Hofer et al., 2005; Woodward, 1998), and tend not to imitate mechanical device actions (Legerstee & Markova, 2008; Meltzoff, 1995).

Table 1
Infants' visual attention toward the A- and B-locations as a function of correct vs. incorrect (A-not-B error) search on the B test trial (in sec).

Experiment	Search	A-trials		3-s Delay		Search	
		A	B	A	B	A	B
1	Correct	32.2	1.6	0.3	1.5	2.2	5.7
	Incorrect	38.1	0.9	0.4	1.2	5.1	1.2
2	Correct	38.2	1.7	0.2	1.5	0.5	3.6
	Incorrect	35.9	1.7	0.2	1.3	3.7	0.2
3	Correct	32.2	1.7	0.3	1.1	0.8	3.9
	Incorrect	34.1	1.7	0.2	2.0	3.4	1.0

Although these results are consistent with the suggestion that infants understand human and mechanical agents differently, there is an alternative interpretation. In the current experiment, the mechanical claws were unfamiliar to the infants and certainly had little resemblance to the hands and arms of a person. Given this unfamiliarity, infants may have been, on the one hand, more interested in the claws than the hiding of the toy, or, on the other hand, they may have simply been somewhat uncomfortable with the entire test procedure and possibly wary of this unfamiliar mechanical device hiding and searching for the toy (see Hofer et al., 2005). As such, they may have devoted insufficient attention to where the toy was hidden, and this would explain their random search performance on the B-trials. The next experiment addresses these issues by including a familiarization phase designed to make infants more comfortable with the experimental situation and familiar with the mechanical claws.

3. Experiment 2

At the beginning of this experiment, infants were familiarized with the testing situation in one of two ways: (1) They were familiarized with the experimenter but not the mechanical claws, or (2) they were familiarized with the experimenter and the mechanical claws, but were not shown how the claws could be used by a person to assist in reaching for objects. Also, infants could see the experimenter's hands operating the claws during the training and search trials. Conceivably, the visibility of the hands might reduce the 'strangeness' of the claws by suggesting that they function as a tool controlled by a human agent.

3.1. Method

3.1.1. Participants

Thirty-nine-month-old infants participated ($M = 279$-days, $SD = 12$-days; 13 females, 17 males). An additional five infants were tested, but were excluded due to fussiness (2), looking away during the B hiding event (1), simultaneous search at both locations (1), or experimenter error (1). Fifteen infants were assigned to a no claws-familiarization condition and 15 infants were assigned to a claws-familiarization condition.

Fig. 3. Example of an infant observing the mechanical claws grasp the toy with the experimenter's hands visible to the infant (Experiments 2 and 3).

3.1.2. Materials

The materials from the previous study were used. The curtain, however, was raised from 45 cm to 90 cm above the apparatus, providing an opening such that infants could see the experimenter's hands operating the claws (see Fig. 3). Infants could not see the experimenter's arms, torso, or face. An additional seven toys were used during the familiarization phase.

3.1.3. Procedure

This experiment began with a familiarization phase. Infants, their caregiver, and the experimenter sat on the floor around a collection of seven toys. In the no claw-familiarization condition, the experimenter interacted with the infant, grasped each of the toys in a fixed sequence, held each up and looked at it, and played with each using his hands (e.g., rolling two wheeled toys, squeezing a plastic squeaker toy, rattling a rattle). In the claws-familiarization condition, the two mechanical claws were scattered among the toys and, in essence, the experimenter handled them and the toys alike, but did not operate the claws (e.g., the claws were grasped by the shaft, held and looked at, and shaken as the toy rattle was). This phase lasted for approximately 2 min. Afterwards, the caregiver lifted and held the infant on his or her lap in front of the stage. The experimenter went behind the back wall attached to the table so that he was no longer visible, and then began to administer the training and experimental trials, which proceeded exactly as in the previous experiment.

3.1.4. Coding

As in Experiment 1, we coded infants' correct and incorrect searches, how many times they reached toward the A-location during the A-trials, and infants' looking times to the A- and B-locations during each phase of the experiment. In addition, we coded infants' looking times to the experimenter's hands operating the mechanical claws during the A-trials. Looking times were coded by one of two observers, and 33% of the trials were coded by both observers to establish that the coding was reliable, $r = .99$, $p < .001$.

3.2. Results and discussion

Seven of the 15 infants in the no claw-familiarization group (46.7%) and seven of the 15 infants in the claws-familiarization group (46.7%) made the A-not-B error (see Fig. 2). Combining the results from the two groups and comparing against the A-not-B error rate of Experiment 1 reveals no significant difference, $\chi^2(1, 60) = .07$, $p = .79$.

Active reaches during the A-trials were again infrequent ($M = .50$ reaches across the six A-trials, $SD = 1.00$), and there was no difference in frequency of reaching between infants who searched correctly at the B-location ($M = .25$, $SD = .77$) and those who searched at the A-location ($M = .78$ reaches, $SD = 1.2$), $t(28) = 1.48$, $p = .15$. As in the previous experiment, the likelihood of searching at the A-location on the B-trial was not related to the minimal reaching that occurred on the A-trials.

There were no looking time differences between the no claw-familiarization group and the claw-familiarization group either during the A-trials [$t(28) = -.03$, $p = .98$, looking toward A; $t(28) = .90$, $p = .38$, looking toward B], immediately after the object was hidden in the B-location [$t(28) = 1.22$, $p = .23$, looking toward A; $t(28) = .89$, $p = .38$, looking toward B], or during the search phase [$t(28) = .98$, $p = .33$, looking toward A; $t(28) = .07$, $p = .94$, looking toward B], and therefore we collapse across these groups for further comparisons.

A comparison of the looking times indicates that there was no difference between infants who searched correctly and those who made the A-not-B error when looking at either the A-location or B-location during the A-trials, $t(28) = .82$, $p = .42$ and $t(28) = -.02$, $p = .99$, respectively (see Table 1). In addition, there were no differences in the total amount of time spent looking at the experimenter's hands operating the claws between infants who made the error ($M = 5.9$ s) and those who searched correctly ($M = 5.8$), $t(28) = .05$, $p = .97$. Also, as in the previous experiment, infants who searched correctly and those who made the A-not-B error did not differ in how long they looked at either the A-location or B-location during the 3-s delay, $t(28) = .01$, $p = .99$ and $t(28) = .52$, $p = .61$, respectively. There were, however, significant differences during the search phase, and infants who searched correctly spent more time looking toward the B-location than infants who searched incorrectly, $t(28) = 6.64$, $p < .001$, and, conversely, spent less time looking at the A-location, $t(28) = -6.64$, $p < .001$.

In sum, this experiment suggests that neither increased familiarization with the experimenter nor the claws is sufficient to induce infants to covertly imitate observed actions performed by mechanical devices. Also, being able to observe the experimenter's hands operating the claws at test had little effect on infants searching. Once again, looking time measures during the A-trials and the 3 s delay were not predictive of search performance, but looking time during search was predictive of search performance. Based on finding no difference between Experiments 1 and 2, we conclude that it is unlikely that infants' performance in the previous experiment was attributable to their being uncomfortable with the experimental procedure or distracted by the unfamiliarity of the claws.

Although infants were familiarized with the appearance of the claws, it is virtually certain that they remained unfamiliar with their function, at least until they were used during the testing. Would familiarizing infants with the function of the claws increase their likelihood of showing the A-not-B search error? Previous research by Hofer et al. (2005) suggests that direct experience observing a human agent operate mechanical claws was necessary for infants to interpret them as goal-directed agents during testing. Whether this finding would generalize to the current research is an empirical question. In the Hofer et al. (2005) study, infants were tested with a habituation paradigm which demanded that they encode the observed actions, but which did not test whether infants were encoding the observed actions through covert imitation. The purpose of the final experiment was to test whether more direct experience with the mechanical claws' function would affect the likelihood that infants would covertly imitate the observed goal-directed actions of the claws.

4. Experiment 3

The goal of this experiment was to test whether infants will be more likely to commit the A-not-B search error if they are first familiarized with the function of the claws when they are operated by a human agent. This familiarization will likely increase infants' understanding that the claws are a means to an end and that they result in a goal-directed action. It is well established in the infant imitation literature that understanding an action as a means to an end increases the likelihood of the action being overtly imitated (Call & Carpenter, 2001; Elsner, 2007). It is, however, an empirical question whether the same relation applies to covert imitation.

4.1. Method

4.1.1. Participants

Thirty-nine-month-old infants participated (M = 280-days, SD = 12-days; 18 females, 12 males). An additional eight infants were tested, but were excluded due to interference with the apparatus (4), refusal to search (3) or simultaneous search at both locations (1).

4.1.2. Materials

The same materials from the previous experiment were used.

4.1.3. Procedure

As in Experiment 2, the procedure began with a 2 min familiarization phase. During this phase the experimenter reached for objects using the mechanical claws. In essence, the familiarization was the same as the no-claws familiarization of Experiment 2, but rather than grasp, hold, look at, and play with each toy with his hands, the experimenter did so with the mechanical claws. One difference was that during this phase the experimenter rolled one of the wheeled toys out of arm's reach and reached for and grasped it with one of the mechanical claws. Afterwards, the caregiver lifted and held the infant on his or her lap in front of the stage, and then the testing proceeded exactly as in the previous experiment.

4.1.4. Coding

As in Experiments 1 and 2, we coded searches, reaches during the A-trials, and looking times. Looking times were again coded by one of two observers, with both observers coding 32% of the participants. Inter-rater reliability was high, $r = .97$, $p < .001$.

4.2. Results and discussion

Twenty of the 30 infants (66.7%) committed the search error (see Fig. 2). This is significantly greater than chance ($p < .05$, binomial test), and is very similar to the result of Longo and Bertenthal (2006), where 21 of 30 infants (70.0%) showed the A-not-B error. If the results of this experiment are compared to the results from Experiment 1, the difference is statistically significant, $\chi^2(1, 60) = 4.29$, $p = .04$; a comparison between these results and those of Experiment 2 shows a trend in the same direction, $\chi^2(1, 60) = 2.44$, $p = .11$. Comparing this experiment and Experiments 1 and 2 combined reveals a significant difference, $\chi^2(1, 90) = 4.36$, $p = .037$.

There was no difference in reaching toward the A-location during the A-trials between infants who made the A-not-B error ($M = .84$ reaches, $SD = 1.0$) and those who searched correctly ($M = .56$, $SD = 1.4$), $t(26) = .55$, $p = .59$. Infants who made the A-not-B error and those who searched correctly also did not differ in how long they looked at the A-location, the B-location, or the experimenter's hands (Ms = 5.5 s and 6.8 s for those who made the error and those who searched correctly) during the A-trials, $t(26) = -.40$, $p = .69$, $t(26) = -.11$, $p = .92$, $t(26) = .66$, $p = .51$, respectively.[3] There were also no differences between infants who made the error versus searched correctly in looking times to the A- or B-location during the 3-s delay following object hiding in the B-location, $t(26) = .40$, $p = .69$ and $t(26) = -1.30$, $p = .21$ (See Table 1). As reported in the previous two experiments, there were significant looking time differences during the search phase; infants who searched correctly looked more toward the B-location than infants who searched incorrectly, $t(26) = 6.69$, $p < .001$, and less toward the A-location, $t(26) = -2.93$, $p = .007$.

Looking times and reaching behaviors in Experiments 1, 2, and 3 were compared with separate one-way analyses of variance (ANOVA). There were no cross-experiment differences in number of reaches toward the A-location during the A-trials, $F(2, 84) = .66$, $p = .52$. There were also no differences in looking times across experiments to the A-location, $F(2, 84) = 1.12$, $p = .33$, or B-location, $F(2, 84) = .49$, $p = .62$ during the A-trials (See Table 1). A final comparison revealed no difference between Experiments 2 and 3 in amount of time looking at the experimenter's hands, $t(56) = -.07$, $p = .95$.

---

[3] The video record for one of the infants who made the A-not-B error ended before the search trial, and another infant who searched correctly was not within the view of the camera during a significant portion of the A-trials, the 3-s delay, and the search phase. Looking times could, therefore, not be coded for these two infants.

These results suggest that familiarization with the function of the claws increased the likelihood that infants would covertly imitate their subsequent actions. This is in clear contrast to the results of Experiments 1 and 2, where infants were not familiarized with the claws' function and were less likely to commit the A-not-B search error. Previous research has shown that infants between 12- and 18-months are less likely to overtly imitate an observed goal-directed action if they are not shown its full set of means-end relations (i.e., the body movements, the objects, and the effects; Bellagamba, Camaioni, & Colonnesi, 2006; Bellagamba & Tomasello, 1999; Elsner & Aschersleben, 2003; Elsner, Hauf, & Aschersleben, 2007; Huang & Charman, 2005; Tennie, Call, & Tomasello, 2006; but cf. Nielsen, 2009). We conjecture that this same relation may apply to covert imitation as well, and that familiarizing infants with the function of the claws heightened the salience of the relation between the means (i.e., use of the claw to extend one's reach) and the ends (i.e., accomplishing the goal of grasping out-of-reach objects) of their actions. Whereas infants in the current experiment already had some understanding of how the claws function in performing a goal-directed action, infants in Experiments 1 and 2 did not, which reduced their likelihood of motorically simulating the actions. Relatedly, Hofer and colleagues (2005) provide support that familiarization with a mechanical device increases infants' sensitivity to its goal-directedness. The current results extend this finding by demonstrating that an increased understanding of the goal structure of mechanical device actions increases the likelihood of covertly imitating the observed actions.

5. General discussion

Recent evidence suggests that the actions infants observe others perform and their own planning and execution of these actions are represented with a common representational code (e.g., Daum et al., 2011; Sommerville & Woodward, 2005; Sommerville et al., 2005). One measure of this shared representation is evidence of the A-not-B search error following observation of someone else searching for the hidden object on the A-trials (Longo & Bertenthal, 2006). This finding suggests that infants establish a response bias to the A-location while observing the experimenter's goal-directed actions during the A-trials, which we argue is not unlike what happens when they search on the A-trials themselves. The current experiments tested whether the emergence of these shared representations are limited to human actions or extend to actions performed with a pair of mechanical claws, and whether this varies with infants' familiarity with the mechanical claws' and their function. The results reveal that infants' brief experiences observing actions performed with mechanical devices are represented not only by their visual system, but by their motor system as well, at least when testing is preceded by the observation of a similar action that primes the motor representation.

When infants in the current study had no previous experience with the claws, or had experience that did not involve a demonstration of the function of the claws, as in Experiments 1 and 2, respectively, they did not show evidence of action perception through motor representation. By contrast, infants in Experiment 3, who were familiarized with how the mechanical claws function when operated by another person, were more likely to search in the A-location, hence suggesting covert imitation. As such, these findings are consistent with previous research reporting that 9-month-old infants do not interpret the actions performed with mechanical claws as goal-directed (Woodward, 1998), unless they have first been familiarized with the claws operation by another person (Hofer et al., 2005). Importantly, the current findings go beyond previous research to reveal that familiarization with the goal-directed actions of a mechanical device specifically increases the likelihood of covert imitation of the observed actions.

Are these findings compatible with the direct-matching hypothesis? This hypothesis suggests that motor simulation decreases if observed actions are outside one's motor repertoire (Calvo-Merino, Glaser, Grézes, Passingham, & Haggard, 2005; Longo & Bertenthal, 2006; Longo, Kosobud, & Bertenthal, 2007; Rizzolatti et al., 2001). Furthermore, previous studies with adults report decreased simulation of observed actions performed by robots or mechanical devices (Kilner et al., 2003; Press et al., 2005; Tsai & Brass, 2007). The claws used here do not resemble human hands, and 9-month-old infants are motorically unable to operate the claws, both of which suggest that infants would be less likely to match their actions. Therefore, the results of Experiments 1 and 2 are consistent with previous findings with adults.

The results of Experiment 3, however, suggest that the relation between perception and action is modulated by the immediately preceding experience: after a brief familiarization with the function of the mechanical claws, which increased the salience of the means-ends relations of the claws' actions, infants tended to search in the incorrect A-location on the B-trial. This result suggests that infants' mapping of observed actions onto motor representations occurs regardless of whether or not a human agent is involved as long as there is some familiarity with the means-ends relations of the observed event. Based on the results in Experiment 3, we conjecture that infants learn very quickly to generalize goal-directed reaching actions to the claws, and thus map the observed actions of the claws to their own motor representations. Although this view is at odds with the orthodox interpretation of a direct matching system (e.g., Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti & Craighero, 2004; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996), it is consistent with recent accounts that propose a more flexible system that is able to abstract from observed actions and their effects and map this generalized information onto motor representations (e.g., Caggiano, Fogassi, Rizzolatti, Their, & Casile, 2009; Craighero, Metta, Sandini, & Fadiga, 2007).

In the current study, infants' understanding of the claws' actions benefitted from the brief demonstration of their function, but infants may have also benefitted from the claws appearing as tools rather than as independent agents. Infants begin using tools (McCarty, Cliftron, & Collard, 2001) and begin understanding that tools modulate human-object relations (Lockman, 2000) at approximately the same age as was tested here. Conceivably, infants experiences with using tools to retrieve out of reach objects (Munakata, McClelland, Johnson, & Siegler, 1997; Sommerville et al., 2008) may have contributed to their representation of the actions performed with the claws. The familiarization experience of infants in Experiment 3 may have increased their understanding of the claws as tools, which, in turn, may have contributed to their increased abstraction and covert imitation of the actions performed with the claws. Interestingly, although earlier studies reported evidence to the contrary (e.g., Rizzolatti et al., 1996), recent research indicates that with sufficient familiarization (Ferrari, Rozzi, & Fogassi, 2005) or training (Rochat et al., 2010), primate mirror neurons fire in response to the observation of actions performed with tools. One significant difference between these neurophysiological studies and the current study, however, is that this generalization requires 2 months of experience in macaques, while our results suggest it occurs after only 2 min of experience in human infants. This difference suggests that human infants are much better prepared for this experience, either because the mapping mechanism between the visual description and motor representation of the action is already more abstract, or a different mechanism altogether is available in humans. Although this interpretation is intriguing, it remains somewhat speculative because we did not test directly whether infants perceived the claws as tools or independent agents. This is an empirical question that could be tested, but for the moment remains unresolved.

One caveat concerning our interpretation is that the A-not-B error in this task is only a proxy for covert imitation and is an indirect assessment of motor activation. Indeed, a more direct assessment of the neural activation in the brain is required to provide more convincing evidence for this hypothesis. In the absence of more definitive evidence, we consider two other influential theories that have been recently advanced to explain why infants commit the A-not-B error. The Dynamic Field Theory (DFT; Clearfield et al., 2009; Diedrich et al., 2000; Spencer et al., 2009; Thelen, Schöner, Scheier, & Smith, 2001), is one alternative, which suggests that the results might be explained in terms of attention, perception, and memory for the A- and B-locations. If, for example, infants devoted more attention to the A-location on A-trials in Experiment 3 than in either Experiments 1 or 2, then they would be more likely to make the A-not-B error in Experiment 3, because they had established an attentional bias toward the A-location. Likewise, had infants in Experiment 3 devoted less attention to the experimenter's hands operating the claws than infants in Experiment 2 (i.e., because the experimenter's manual operation of the claws was less novel to them due to their experience in the familiarization phase), they would have more cognitive resources to devote to tracking the object's placement in the A-location, resulting in a stronger representation of the object in the A-location. Our results, however, revealed no differences across experiments in infants' attention to either the A-location or the experimenter's hands during the A-trials, and, therefore, there is no reason to suggest that attention is differentially biasing infants' search behavior in each experiment.

According to the DFT approach, infants in Experiment 3 may have also formed a stronger memory trace for the A-location while observing the claw reaches on the A-trials, due to an increased understanding of the claws' function from the familiarization phase. As a consequence, the strength of the activation for the A-location on the B-trial could well have been greater than what occurred in Experiments 1 or 2. Strictly speaking, this possibility is not inconsistent with the account we are proposing. Previous DFT models, however, have proposed that infants direct greater activation to the A-location due to their active reaching on the A-trials, whereas we are suggesting that infants experience greater activation toward the A-location due to the *simulation* of reaching while they observe the claws reach to the A-location. In essence, the only difference between the two views is whether reaching for the hidden object on the A-trials is covert or applies only to overt motor behavior. Interestingly, Spencer and Schutte (2004) found that observing an experimenter hide an object at one location influences 2- and 4-year old children's searches for the object in a second location. This finding thus provides additional evidence that search errors are induced not only following active reaching but also after the repeated observation of the goal-directed action.

The second alternative theory for explaining the current results is that infants in Experiment 3 formed a different set of expectations for how to behave during the B-trial as a function of the interaction they had with the experimenter. According to the pedagogical learning stance (Csibra & Gergely, 2009, 2011), infants' search errors in the A-not-B paradigm are attributable to the experimenter's ostensive and referential signals during the experiment, which bias the infant to interpret the hiding trials at the A-location as a teaching demonstration for learning some generalizable information, such as the object belongs in or can usually be found hidden at the A-location. Topál and colleagues (2008) showed that infants were more likely to commit perseverative search errors if the experimenter ostensively communicated with them than if the experimenter was non-communicative or was not visible and conducted the task from behind a curtain. Like the non-social conditions conducted by Topál and colleagues (2008), Experiment 1 involved no social interaction between the experimenter and the infant, and the results did not reveal a significant number of infants showing the search error. Thus, the findings from Experiment 1 are consistent with the natural pedagogy approach.

This approach is not, however, sufficient to reconcile the results of Experiments 2 and 3. These experiments were identical in terms of the social interaction between the experimenter and infant, and the only difference was that the claws were operated in a goal-directed fashion during the familiarization phase of Experiment 3 but not during that of Experiment 2. It is likely that the experimenter's ostensive communicative cues during the familiarization phase of Experiment 3 influenced infants' interpretation of the claws' function and that this affected their observation of the claws' actions during the A-not-B task. In order to fully explain the test results, however, the experimenter's pedagogical stance during familiarization would have had to somehow generalize to the test phase when the experimenter was not even present. Although we cannot directly refute this interpretation, we suggest that a history of covertly imitating the claw reaches on the A-trials is a more direct and parsimonious explanation. In order to evaluate the natural pedagogy approach more directly, however, it would be necessary to conduct additional experiments where social interaction and communication with infants during both the familiarization and test phases are manipulated. This is outside the scope of the current study though, and is left for future research.

In sum, previous research revealed that infants' experience performing actions affects how they subsequently interpret others' actions (Daum & Gredebäck, 2011; Sommerville & Woodward, 2005; Sommerville et al., 2005), and their observation of others' actions affects the actions they themselves perform (Longo & Bertenthal, 2006). The current experiments build upon this previous work by showing that infants' motor representations of others' actions is restricted to behaviors modeled by humans and does not generalize to actions executed with mechanical devices, unless they are familiarized with the function of the devices immediately before testing. We suggest that this familiarization increases the salience of the means-ends relations of the perceived events, which results in a stronger mapping between the perceived actions and their effects resulting in priming of infants' motor representations. In contrast to recent findings suggesting that infants' understanding of actions is improved only after direct active experience with those actions (e.g., Sommerville et al., 2008), this study reveals that even brief visual experience with previously unfamiliar goal-directed actions primes infants' motor representations of similar subsequently observed actions.

Acknowledgements

Portions of the data were previously presented at the biennial meetings of the Society for Research in Child Development, Denver, CO., April 2009. The authors wish to thank Zachary Page for assistance with data collection, Brian Donley, Natasha Benfer, and Kisan Patel for assistance with data coding, and the parents and children who participated.

References

Barrett, H. C., Todd, P. M., Miller, G. F., & Blythe, P. W. (2005). Accurate judgments of intention from motion cues alone: A cross-cultural study. *Evolution and Human Behavior, 26*, 313–331.

Bellagamba, F., Camaioni, L., & Colonnesi, C. (2006). Change in children's understanding of others' intentional actions. *Developmental Science, 9*, 182–188.

Bellagamba, F., & Tomasello, M. (1999). Re-enacting intended acts: Comparing 12- and 18-month-olds. *Infant Behavior and Development, 22*, 277–282.

Bertenthal, B. I., Longo, M. R., & Kosobud, A. (2006). Imitative response tendencies following observation of intransitive actions. *Journal of Experimental Psychology: Human Perception & Performance, 32*, 210–225.

Bíró, S., & Leslie, A. M. (2007). Infants' perception of goal-directed actions: Development through cue-based bootstrapping. *Developmental Science, 10*, 379–398.

Brass, M., Bekkering, H., Wohlschläger, A., & Prinz, W. (2000). Compatibility between observed and executed finger movements: Comparing symbolic, spatial, and imitative cues. *Brain & Cognition, 44*, 124–143.

Bremner, J. G., & Bryant, P. E. (1977). Place versus response as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology, 23*, 162–171.

Bruner, J. S. (1969). Eye, hand, and mind. In D. Elkind & J. H. Flavell (Eds.), *Studies in cognitive development: Essays in honor of Jean Piaget* (pp. 223–235). Oxford, UK: Oxford University Press.

Caggiano, V., Fogassi, L., Rizzolatti, G., Their, P., & Casile, A. (2009). Mirror neurons differentially encode the peripersonal and extrapersonal space of monkeys. *Science, 324*, 403–406.

Call, J., & Carpenter, M. (2001). Three sources of information in social learning. In E. Dupoux (Ed.), *Language, brain, and cognitive development* (pp. 211–228). Cambridge, MA: The MIT Press.

Calvo-Merino, B., Glaser, D. E., Grézes, J., Passingham, R. E., & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex, 15*, 1243–1249.

Clearfield, M. W., Dineva, E., Smith, L. B., Diedrich, F. J., & Thelen, E. (2009). Cue salience and infant perseverative reaching: Tests of the dynamic field theory. *Developmental Science, 12*, 26–40.

Craighero, L., Metta, G., Sandini, G., & Fadiga, L. (2007). The mirror-neurons system: Data and models. In C. von Hofsten & K. Rosander (Eds.), *From action to cognition: Progress in brain research* (pp. 39–59). The Netherlands, Amsterdam: Elsevier Science.

Csibra, G. (2008). Goal attribution to inanimate agents by 6.5-month-old infants. *Cognition, 107*, 705–717.

Csibra, G., & Gergely, G. (2009). Natural pedagogy. *Trends in Cognitive Sciences, 13*, 148–153.

Csibra, G., & Gergely, G. (2011). Natural pedagogy as evolutionary adaptation. *Philosophical Transactions of the Royal Society London: B, 366*, 1149–1157.

Csibra, G., Gergely, G., Bíró, S., Koós, O., & Brockbank, M. (1999). Goal attribution without agency cues: The perception of 'pure reason' in infancy. *Cognition, 72*, 237–267.

Cummings, E. M., & Bjork, E. L. (1983). Perseveration and search on a five-choice visible displacement hiding task. *The Journal of Genetic Psychology, 142*, 283–291.

Daum, M. M., & Gredebäck, G. (2011). The development of grasping comprehension in infancy: Covert shifts of attention caused by referential actions. *Experimental Brain Research, 208*, 297–307.

Daum, M. M., Prinz, W., & Aschersleben, G. (2011). Perception and production of object-related grasping in 6-month-olds. *Journal of Experimental Child Psychology, 108*, 810–818.

Decety, J., Grezes, J., Costes, N., Perani, D., Jeannerod, M., Procyk, E., et al. (1997). Brain activity during observation of actions: Influence of action content and subject's strategy. *Brain, 120*, 1763–1777.

Decety, J., & Sommerville, J. A. (2004). Shared representations between self and other: A social cognitive neuroscience view. *Trends in Cognitive Sciences, 7*, 527–533.

Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by infants' performance on AB. *Child Development, 56*, 868–883.

Diamond, A. (1990). The development and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkeys. *Annals of the New York Academy of Sciences, 608*, 267–317.

Diedrich, F. J., Thelen, E., Smith, L. B., & Corbetta, D. (2000). Motor memory is a factor in infant perseverative errors. *Developmental Science, 3*, 479–494.

Elsner, B. (2007). Infants' imitation of goal-directed actions: The role of movements and action effects. *Acta Psychologica, 124*, 44–59.

Elsner, B., & Aschersleben, G. (2003). Do I get what you get? Learning about the effects of self-performed and observed actions in infancy. *Consciousness and Cognition, 12*, 732–751.

Elsner, B., Hauf, P., & Aschersleben, G. (2007). Imitating step by step: A detailed analysis of 9- to 15-month-olds' reproduction of a three-step action sequence. *Infant Behavior and Development, 30*, 325–335.

Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Motor facilitation during action observation: A magnetic stimulation study. *Journal of Neurophysiology, 73*, 2608–2611.

Ferrari, P. F., Rozzi, S., & Fogassi, L. (2005). Mirror neurons responding to observation of actions made with tools in monkey ventral premotor cortex. *Journal of Cognitive Neuroscience, 17*, 212–226.

Frith, C., & Frith, U. (2006). How we predict what other people are going to do. *Brain Research, 1079*, 36–46.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain, 119*, 593–609.

Gao, T., Newman, G. E., & Scholl, B. J. (2009). The psychophysics of chasing: A case study in the perception of animacy. *Cognitive Psychology, 59*, 154–179.

Gergely, G., Nádasdy, Z., Csibra, G., & Bíró, S. (1995). Taking the intentional stance at 12 months of age. *Cognition, 56*, 165–193.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77*, 73–99.

Grèzes, J., Frith, C., & Passingham, R. E. (2004). Inferring false beliefs from the actions of oneself and others: An fMRI study. *NeuroImage, 21*, 744–750.

Heider, F., & Simmel, M. (1944). An experimental study of apparent behavior. *American Journal of Psychology, 57*, 243–259.

Hofer, T., Hauf, P., & Aschersleben, G. (2005). Infant's perception of goal-directed actions performed by a mechanical device. *Infant Behavior and Development, 28*, 466–480.

Huang, C-T., & Charman, T. (2005). Gradations of emulation learning in infants' imitation of actions on objects. *Journal of Experimental Child Psychology, 92*, 276–302.

James, W. (1890). *The principles of psychololgy* (Vol. 2). New York, NY, US: Henry Holt & Co..

Kilner, J. M., Paulignan, Y., & Blakemore, S. J. (2003). An interference effect of observed biological movement on actions. *Current Biology, 13*, 522–525.

Király, I., Jovanovic, B., Prinz, W., Aschersleben, G., & Gergely, G. (2003). The early origins of goal attribution in infancy. *Consciousness and Cognition, 12*, 752–769.

Kuhlmeier, V. A., Wynn, K., & Bloom, P. (2003). Attribution of dispositional states by 12-month-olds. *Psychological Science, 14*, 402–408.

Legerstee, M., & Markova, G. (2008). Variations in 10-month-old infant imitation of people and things. *Infant Behavior and Development, 31*, 81–91.

Lockman, J. J. (2000). A perception–action perspective on tool use development. *Child Development, 71*, 137–144.

Longo, M. R., & Bertenthal, B. I. (2006). Common coding of observation and execution of action in 9-month-old infants. *Infancy, 10*, 43–59.

Longo, M. R., Kosobud, A., & Bertenthal, B. I. (2007). Automatic imitation of biomechanically possible and impossible movements: Effects of priming movements vs. goals. *Journal of Experimental Psychology: Human Perception & Performance, 34*, 489–501.

Luo, Y. (2011). Three-month-old infants attribute goals to a non-human agent. *Developmental Science, 14*, 453–460.

Luo, Y., & Baillargeon, R. (2005). Can a self-propelled box have a goal? Psychological reasoning in 5-month-old infants. *Psychological Science, 16*, 601–608.

Luo, Y., Kaufman, L., & Baillargeon, R. (2009). Young infants' reasoning about physical events involving inert and self-propelled objects. *Cognitive Psychology, 58*, 441–486.

Marcovitch, S., & Zelazo, P. D. (1999). The A-not-B error: Results from a logistic meta-analysis. *Child Development, 70*, 1297–1313.

McCarty, M. E., Cliftron, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy, 2*, 233–256.

Meltzoff, A. N. (1995). Understanding the intentions of others: Re-enactment of intended acts by 18-month-old children. *Developmental Psychology, 31*, 838–850.

Munakata, Y., McClelland, J. L., Johnson, M. H., & Siegler, R. S. (1997). Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review, 104*, 686–713.

Nielsen, M. (2009). 12-month-olds produce others' intended but unfulfilled acts. *Infancy, 14*, 377–389.

Piaget, J. (1937/1954). The construction of reality in the child [M. Cook, Trans.]. New York, New York, US: Basic Books.

Press, C., Bird, G., Flach, R., & Heyes, C. (2005). Robotic movement elicits automatic imitation. *Cognitive Brain Research, 25*, 632–640.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9*, 129–154.

Rakison, D. H., & Poulin-Dubois, D. (2001). Developmental origin of the animate–inanimate distinction. *Psychological Bulletin, 127*, 209–228.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience, 27*, 169–192.

Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. *Cognitive Brain Research, 3*, 131–141.

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews Neuroscience, 2*, 661–670.

Rochat, M. J., Caruana, F., Jezzini, A., Escola, L., Intskirveli, I., Grammont, F., et al. (2010). Response of mirror neurons in area F5 to hand and tool grasping observation. *Experimental Brain Research, 204*, 605–616.

Saxe, R., Xiao, D.-K., Kovacs, G., Perrett, D. I., & Kanwisher, N. (2004). A region of right posterior superior temporal sulcus responds to observed intentional actions. *Neuropsychologia, 42*, 1435–1446.

Scholl, B. J., & Tremoulet, P. (2000). Perceptual causality and animacy. *Trends in Cognitive Sciences, 4*, 299–309.

Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review, 106*, 235–260.

Sommerville, J. A., Hildebrand, E. A., & Crane, C. C. (2008). Experience matters: The impact of doing versus watching on infants' subsequent perception of tool-use events. *Developmental Psychology, 44*, 1249–1256.

Sommerville, J. A., & Woodward, A. L. (2005). Pulling out the intentional structure of action: The relation between action processing and action production in infancy. *Cognition, 95*, 1–30.

Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition, 96*, B1–B11.

Spencer, J. P., Dineva, E., & Smith, L. B. (2009). Comment on "Infants' perseverative search errors are induced by pragmatic misinterpretation". *Science, 325*, 1624-a.

Spencer, J. P., & Schutte, A. R. (2004). Unifying representations and responses: Perseverative biases arise from a single behavioral system. *Psychological Science, 15*, 187–193.

Tennie, C., Call, J., & Tomasello, M. (2006). Push or pull: Imitation vs. emulation in great apes and human children. *Ethology, 112*, 1159–1169.

Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences, 24*, 1–86.

Topál, J., Gergely, G., Miklósi, A., Erdőhegyi, A., & Csibra, G. (2008). Infants' perseverative search errors are induced by pragmatic misinterpretation. *Science, 321*, 1831–1834.

Tremoulet, P. D., & Feldman, J. (2000). Perception of animacy from the motion of a single object. *Perception, 29*, 943–951.

Tsai, C-C., & Brass, M. (2007). Does the human motor system simulate Pinocchio's actions? Coacting with a human hand versus a wooden hand in a dyadic interaction. *Psychological Science, 18*, 1058–1062.

van Hof, P., van der Kamp, J., & Savelsbergh, G. J. P. (2002). The relation of unimanual and bimanual reaching to crossing the midline. *Child Development, 73*, 1353–1362.

Wellman, H. M., Cross, D., & Bartsch, K. (1986). Infant search and object permanence: A meta-analysis of the A-not-B error. *Monographs of the Society for Research in Child Development, 51*, 1–51.

Woodward, A. L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition, 69*, 1–34.

Woodward, A. L. (1999). Infants' ability to distinguish between purposeful and non-purposeful behaviors. *Infant Behavior and Development, 22*, 145–160.

Woodward, A. L., & Sommerville, J. A. (2000). Twelve-month-old infants interpret action in context. *Psychological Science, 11*, 73–76.

Woodward, A. L., Sommerville, J. A., & Guajardo, J. J. (2001). How infants make sense of intentional action. In B. F. Malle, L. J. Moses, & D. A. Baldwin (Eds.), *Intentions and intentionality* (pp. 149–169). Cambridge, MA: MIT Press.

Zelazo, P. D., Reznick, J. S., & Spinazzola, J. (1998). Representational flexibility and response control in a multistep multilocation search task. *Developmental Psychology, 34*, 203–214.