

Published in final edited form as:

Cognition. 2011 February ; 118(2): 171–192. doi:10.1016/j.cognition.2010.11.005.

Correspondences between what infants see and know about causal and self-propelled motion

Jessica B. Cicchino¹, Richard N. Aslin², and David H. Rakison¹

¹ Carnegie Mellon University

² University of Rochester

Abstract

The associative learning account of how infants identify human motion rests on the assumption that this knowledge is derived from statistical regularities seen in the world. Yet, no catalog exists of what visual input infants receive of human motion, and of causal and self-propelled motion in particular. In this manuscript, we demonstrate that the frequency with which causal agency and self-propelled motion appear in the visual environment predicts infants' understanding of these motions. In an observational study, an infant wearing a head-mounted camera saw people act as agents in causal events three times more often than he saw people engaged in self-propelled motion. Subsequent experiments with the habituation paradigm revealed that infants begin to generalize self-propulsion to agents in causal events between 10 and 14 months of age. However, infants cannot generalize causal agency to a self-propelled object at 14 or 18 months unless the object exhibits additional cues to animacy. The results are discussed within a domain-general framework of learning about human action.

Motion is a powerful predictor of what things are. Consider walking in the woods and coming across a slithering object in the grass; even without seeing the coloring, texture, or facial features of the object, most people would identify it as a snake on the basis of its characteristic motion. Indeed, one of the most telling ways that animals and people differ from inanimate objects is the motions in which they engage. For example, people and animals, but not inanimate objects, frequently change directions to reach goals, move along irregular paths, and speed up to reach a target location. Because motion is such a crucial factor that differentiates animates (e.g., animals and people) from inanimate objects, it has been proposed that the ability to link animates with the motions that they produce forms the basis of how infants learn to distinguish these two basic categories of entities (Mandler, 1992; Rakison & Poulin-Dubois, 2001).

Two motion properties that are frequently cited as critical to early concepts of animacy are *causal agency*, or an entity's ability to contact other objects and change their physical states, and *self-propulsion*, or an entity's capacity to begin motion unaided and without the application of external force (e.g., Gelman, 1990; Gelman & Spelke, 1981; Mandler, 1992; Rakison & Poulin-Dubois, 2001; Spelke, Phillips, & Woodward, 1995). These motions are often discussed concurrently because they are complementary to each other in that causal agents typically act upon objects that are not self-propelled (Kotovsky & Baillargeon, 2000; Luo, Kaufman, & Baillargeon, 2009). In support of this view, there is evidence that infants

begin to recognize causal and self-propelled motion in the first year after birth (Cicchino & Rakison, 2008; Leslie & Keeble, 1987; Oakes, 1994). Infants also expect people, but not inanimate objects, to engage in these motions. For example, very young infants anticipate that human hands, but not trains or blocks, cause other objects to move (Leslie, 1984; Saxe, Tenenbaum, & Carey, 2005; Saxe, Tzelnic, & Carey, 2007). At the end of the first year after birth, infants similarly predict that entire human figures, but not balls, robots, or novel inanimate objects will begin to move without prior contact from another entity (Kosugi, Ishida, & Fujita, 2003; Poulin-Dubois, Lepage, & Ferland, 1996; Spelke et al., 1995).

In this manuscript, we evaluated the frequency of visual input that infants receive with respect to causality and self-propulsion. Based on these findings, we then tested predictions of how infants should generalize between self-propulsion and causality. By adopting this approach – that is, examining how infants’ environments predict their knowledge – we could assess whether domain-general or domain-specific mechanisms provide a better account of infants’ learning about objects’ motion properties.

Theoretical Perspectives

A variety of domain-specific theories have sought to explain how infants develop an understanding that people and animals tend to be causal agents and self-propelled. Several theorists have proposed that infants possess an innately specified module responsible for perceiving self-propelled motion and attributing animate properties to self-propelled objects. Specifically, Premack (1990) argued that infants automatically ascribe intentionality to the motion of self-propelled objects (for similar ideas see also Baron-Cohen (1995) and Bassili (1976)). In a comparable but more detailed account, Leslie (1994, 1995) proposed that infants have modular systems that process properties of objects that he calls Agents; such properties include the ability to move from an internal source of energy, act on goals, and understand the minds of others. Note that “Agent” in this case is not equivalent to the term “causal agent” that we use elsewhere in this paper; in fact, Leslie (1995) specifically stated that an object’s role as an agent in a causal event does not provide sufficient information to allow its designation as an Agent. In Leslie’s (1994, 1995) view, a self-propelled object is classified as an Agent through this modular system, and thus infants bestow upon self-propelled objects the animate-typical properties listed above.

Other theorists impart infants with innately specified knowledge or mechanisms that pertain to their understanding of animates and their motions. Spelke (2003; Spelke et al., 1995; Spelke & Kinzler, 2007) proposed that infants have several core knowledge systems, or structures of innate knowledge, in evolutionarily significant domains. One core knowledge system deals with the properties of physical objects, and a second represents agents (e.g., animates and intentional objects) and their actions (see also Kuhlmeier, Bloom, & Wynn, 2004). Because infants possess separate systems of reasoning for animate and inanimate objects, they understand that constraints on motion that apply to physical objects may not hold true for people and animals. In a different vein, Mandler (1992, 2000, 2003) asserted that infants develop knowledge about the motions of animates and inanimates through a process called *perceptual analysis*, which generates *image schemas* or conceptual representations of the spatial structure of motion events. According to this view, then, infants in the first year after birth form rich concepts for animates and inanimates that include information about their appearance as well as their motion capabilities.

In contrast to these domain-specific accounts, theorists that espouse a domain-general view argue that infants learn about identities and properties of the objects that appear in causal and self-propelled events through their experiences with specific kinds of entities that engage in these motions. More explicitly, proponents of the *associative learning* view maintain that infants use learning mechanisms that operate across all domains of knowledge

to encode statistical regularities in their environments, and that infants' concepts encompass representations of these statistical regularities (Jones & Smith, 1993; Madole & Oakes, 1999; Quinn & Eimas, 1997, 2000; Rakison & Lupyan, 2008). The associative learning view provides an account for how infants come to know the identities of both self-propelled objects and causal agents; in contrast, the majority of domain-specific theories presented here only focus on one motion type (Leslie, 1994, 1995; Premack, 1990). Furthermore, because associative learning utilizes one domain-general process, its proponents argue that it encompasses a more parsimonious view of development than do theories in which different domain-specific systems process distinct types of information (Quinn & Eimas, 2000; Rakison & Lupyan, 2008). This account is described in the following section.

Statistical Learning and the Nature of the Input

The associative learning account of conceptual development relies on two assumptions: one, that infants can compute statistical regularities from visual input; two, that the visual input infants receive contains statistical regularities that are consistent with their demonstrated knowledge. Considerable evidence exists in support of this first assumption, as a number of experiments have determined that infants robustly encode visual associations after short training periods in the lab (Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002; Kirkham, Slemmer, Richardson, & Johnson, 2007; Lewkowicz, 2008). Yet, evidence in support of the second assumption is sparse. Baldwin and colleagues (Baldwin, Baird, Saylor, & Clark, 2001; Saylor, Baldwin, Baird & LaBounty, 2007) proposed that infants can learn the structure of human action through associative learning—which would presumably include information about causal and self-propelled motions—and have demonstrated that adults quickly learn statistical information embedded in human action sequences in the lab (Baldwin, Andersson, Saffran, & Meyer, 2008). However, it is unknown if infants can compute such statistics and, more crucially, if they do in fact receive structured visual input about human actions in the world that is reflected in their knowledge of the domain.

The first goal of the studies presented in this manuscript was to determine what visual input infants receive regarding causal agency and self-propulsion in the real world. Because infants associate both causal agency and self-propelled motion with people but not inanimate objects, one obvious prediction compatible with the associative learning view is that infants observe mostly people – but rarely inanimate objects—engaging in these motions. We further hypothesize, however, that infants observe more instances of people acting as agents in causal events than instances of people engaging in self-propelled motion. This is because we assume that infants rarely observe the onset of self-propelled motions—although they may often see people moving across their field of vision—and will far more often observe the moment of contact that defines a causal event. Both of these hypotheses about the distributional properties of visual events in the infant's world predict, according to the associative learning view, that infants' developing representations of the cues that give rise to knowledge of animacy will be graded, or stronger or weaker, depending on the amount of real-world experience an individual has with these cues. The possibility that concepts are graded based on amount of experience has been implemented in a connectionist model pertaining to infants' understanding of occluded objects (Munakata, McClelland, Johnson, & Siegler, 1997). Similarly, individual differences in environmental exposure to male and female faces, as well as to cats, affects representational strength for these concepts in infancy (Kovack-Lesh, Horst, & Oakes, 2008; Quinn, Yahr, Kuhn, Slater, & Pascalis, 2002; Ramsey, Langlois, & Marti, 2005).

The second goal of the present studies was to gather further empirical evidence for infants' ability to use causal agency or self-propulsion in their interpretation of motion events. Based on our hypothesis that self-propulsion is more prevalent in events involving people than inanimate objects, we predicted that infants would infer that self-propulsion is a cue for

animacy in events involving ambiguous objects. Previous studies suggest that infants and children do not expect novel self-propelled objects to possess characteristics indicative of animacy, such as the ability to engage in goal-directed action or biological properties (Csibra, Gergely, Bíró, Brockbank, & Koós, 1999; Mahajan, Woodward, & Ridgeway, 2008; Opfer, 2002; Shimizu & Johnson, 2004). There is also evidence that children and adults do not always judge novel self-propelled objects to be animate (Gelman et al., 1995; Poulin-Dubois & Héroux, 1994; Richards & Siegler, 1986). Moreover, infants learn about causal agents and their features at an earlier age than they do for self-propelled objects and their features. For example, infants are able to recognize causal motion before they can recognize self-propelled motion (Cicchino & Rakison, 2008; Oakes, 1994), and they expect causal agents to have features indicative of animacy (e.g., moving parts) at a younger age than when they expect the same of self-propelled objects (Rakison, 2005a, 2006). Taken together, these findings suggest that infants may have a stronger representation of causal agents, and especially of causal agents as animates, than they do of self-propelled objects primarily because they see more instances of causal agency, and particularly people acting as agents in causal events, than they see instances of self-propulsion.

Generalization

The third goal of the experiments in this manuscript was to elucidate further the nature of how infants represent causal agency and self-propelled motion by examining how they *generalize* between these motions, or infer that an entity has one property (e.g., causal agency) on the basis of another property (e.g., self-propulsion). To address this goal, we assessed the possibility that the manner in which infants generalize between these motions is consistent with the frequency with which causal agency and self-propulsion are seen in the world. The ability to generalize is a fundamental process for making sense of the world because infants and adults alike must do so to identify the properties of novel objects and to keep track of the not readily visible features of familiar ones (Baldwin, Markman, & Melartin, 1993; Gelman & Markman, 1987; Rakison & Cicchino, 2009). The ability to generalize less-obvious properties – such as motion cues—is particularly critical to developing mature concepts for animate entities and inanimate objects because animals and people possess a large number of characteristics that cannot always be perceived directly but that are very strong predictors of what they are (Gelman, 2003; Keil, 1989). Because motion does not require language to be encoded, unlike many other properties of animates that consist of factual knowledge (e.g., the understanding that people and animals have blood inside), motion properties are among the first less-obvious animate properties to which infants can attend and thus use as the basis of generalization (Rakison, 2003).

The predictions consistent with associative learning theory and domain-general mechanisms versus modular and domain-specific mechanisms regarding infants' generalizations between causal agency and self-propulsion are outlined in Table 1. If infants' representations of causal agency and self-propulsion are indeed graded based on their differential levels of experience with these motions, generalization between these properties should be asymmetric. That is, infants should be able to generalize from the property for which they have a stronger representation (i.e., causal agency) to the property for which they have a weaker representation (i.e., self-propulsion) before they can generalize in the inverse direction (i.e., from self-propulsion to causal agency). Asymmetric generalization is predicted because infants and adults generalize from categories with which they have developed expertise to a wider variety of instances than they do from categories with which they have less experience (e.g., Quinn, 2005; Shafto & Coley, 2003). For instance, Quinn and Eimas (1998) found that 3- and 4-month-old infants who were familiarized to pictures of humans generalized this category to non-human animals such as horses, cats, and fish, but

infants familiarized to pictures from a non-human animal category (i.e., cat or horse) did not generalize this category to humans nor non-human animals of a different kind.

Quinn (2004, 2005) suggested that this asymmetry in generalization is the result of the expertise that young infants have with humans relative to non-human animals; when infants develop expertise in a category, they are more readily able to encode relationships among features of category members than they are for categories with which they have less experience. We predicted that infants' generalizations between causal agency and self-propelled motion will exhibit a similar asymmetry, with infants generalizing more widely from causal agency and more narrowly from self-propulsion based on their differing levels of expertise with these motions.

It is important to note that theorists who espouse domain-specific accounts for concept learning would not predict that infants' generalizations between causal agency and self-propulsion would exhibit asymmetry. Premack's (1990) modular theory of how infants learn the identities of self-propelled objects does not include a discussion of other types of motion, and thus Premack (1990) could not make any prediction regarding how infants would generalize between causal and self-propelled motion. Luo et al. (2009; see also Baillargeon, Wu, Yuan, Li, & Luo, 2009; Leslie, 1994, 1995), for example, found that by 5 months of age infants distinguish between inert objects and self-propelled objects and have distinct expectations for physical events with these objects. As a result, they claimed that infants assume an object is not self-propelled unless they are given unambiguous evidence otherwise. Thus, infants should not infer that a self-propelled object should act as an agent or a recipient in a causal event, because infants would consider both of those objects to be inert. Similarly, according to this view infants should not infer that a causal agent is self-propelled, because seeing an object act as an agent alone is insufficient evidence to deem that the object is not inert.

Gelman et al. (1995) also proposed that infants have an innate ability to identify self-propelled motion through a bias to attend to the source of an object's motion, which is similar to Leslie's (1994, 1995) theoretical perspective. According to Gelman et al.'s (1995) account, however, motion is not meaningful unless it is presented in an informative context. Consequently, although infants attend to objects' locus of motion, they would not make inferences about its other properties based on its motion alone; that is, infants should not be able to infer that an entity is animate (and correspondingly that it acts as an agent in causal events) by seeing it engage in self-propelled motion.

Lastly, Mandler's (1992) and Spelke's (2003, Spelke & Kinzler, 2007) views imply that infants are able to generalize at a young age both that causal agents are self-propelled and that self-propelled objects are causal agents. In Spelke's (2003) account, infants reason about animates and their actions through a core system dedicated to this domain. Thus, there should be no difference in the age at which infants can generalize between different motion properties because this process involves the same innate system and innately specified concepts. Similarly, Mandler (1992) maintains that early in life infants have a rich conceptual understanding of animacy that includes information about the motions in which animates partake. Because all animate motions activate the same conceptual representation of animacy, infants should be able simultaneously to generalize that causal agents are self-propelled and that self-propelled objects are causal agents.

The Current Studies

In this manuscript, we report observational and experimental work that will provide evidence in support of the associative learning view of how infants learn the identities of causal agents and self-propelled objects. Specifically, we demonstrate that statistical

regularities in the visual input correspond with infants' pattern of generalization between causal agency and self-propulsion. To illuminate the visual input infants receive regarding causal and self-propelled motion, dynamic images recorded from a head-mounted camera worn by an infant at 3, 8, and 12 months were analyzed to assess how often the infant saw people and inanimate objects act as agents in causal events, serve as recipients in causal events, and engage in self-propelled motion. Infants' ability to generalize between causal agency and self-propelled motion was in turn measured in a series of four experiments using the habituation procedure. Infants between 10 and 18 months of age first saw an object engage in a target motion (e.g., causal agency) and then were tested with events in which the same object engaged in a novel motion (e.g., self-propulsion). Combining these two methodologies made it possible to perform one of the first investigations of whether infants' demonstrated knowledge in a controlled lab setting is consistent with their real-world visual experiences.

Observational Study

In this observation study, video footage from a small camera mounted on an infant's head was analyzed to develop a preliminary catalog of the frequency with which causal and self-propelled motion appear in an infant's view, and of what kinds of objects and entities appear in these motion events. This relatively new methodology has been used by several researchers, primarily in the lab, to assess the content of infants' visual input in common situations (e.g., playing with toys) without the mobility constraints inherent to using an eye-tracker (Aslin, 2009; Fiser, Aslin, Lathrop, Rothkopf, & Markant, 2006; Pereira, James, Jones, & Smith, 2008; Schmitow, Stenberg, von Hofsten, & Grönqvist, 2008; Smith, Yu, & Pereira, in press; Yoshida & Smith, 2008).

Method

Apparatus and recording procedure—One male infant wore a small SONY model 480TVL CCD “bullet” camera embedded in a headband on his forehead at 3 months, 8 months, and 12 months of age. The camera was positioned so that the central gaze of the infant was recorded. This involved minor adjustments of the angle (horizontal and vertical) and rotation of the video camera so that the resultant video was directed to a series of objects located slightly out of the infant's reach when the infant was clearly attending to the object. Video from the camera was sent wirelessly to a Sony digital video recorder. The sample of video analyzed in this manuscript was 218.61 min total in length and consisted of 69.15 min of footage at 3 months, 70.04 min at 8 months, and 79.42 min at 12 months; this final sample was culled from a larger set of recordings that totaled 469.50 min (3 months: 138.82 min, 8 months: 189.90 min, 12 months: 140.78 min). The footage was recorded by the Baby Lab at the University of Rochester (see Aslin, 2009, for other analyses of this video).

Recordings at each age were made while the infant was in two to four different locations inside and outside the home. Included in the final sample was footage taken at 3 months in the home (39.84 min, 57.62% of sample for that age) and on a shopping trip (29.31 min, 42.38%); at 8 months during a playgroup (21.30 min, 30.41%), at home while the infant played with toys (29.80 min, 42.55%), and during a walk to pick up a sibling at school (18.94 min, 27.05%); and at 12 months at home while the infant played with toys (39.42 min, 49.64%), at home while the infant ate (10.34 min, 13.02%), during a trip to the library (20.19 min, 25.42%), and during a walk outdoors (9.47 min, 11.92%). The sample of footage analyzed was chosen semi-randomly from the total available sample so that the percentage of video coded from each location at each age was similar to what was originally recorded.

The number of people other than the infants that appeared in each location ranged from 2 to 86. At 3 months, when the infant was in the home the infant's mother and one lab assistant were with the infant; at 8 and 12 months, the infant's mother and two lab assistants were present. In the majority of the analyzed footage (133.41 min, 61.03% of sample) only the mother, infant, and lab assistant(s) appeared. The percentage of analyzed footage in which only the mother and lab assistant(s) were present varied slightly by age (3 months: 50.22 min, 72.72% of sample for that age; 8 months: 40.24 min, 57.45%; 12 months: 53.40 min, 67.23%).

Coding

Videos were analyzed using the program MacSHAPA (Sanderson et al., 1994), which allowed coding of frequency and duration of motions.

Agent-contact relations—Action in the footage was coded as an agent-contact relation when a first entity came into contact with a second entity and appeared to cause its motion. The beginning of the motion was recorded at the moment when both the agent and recipient, whether human or object, were visible onscreen and engaging in a causal interaction (e.g., not when only the agent or only the recipient was visible). The end of a motion was noted either when the causal motion ceased or when the agent and/or recipient moved out of the view of the camera. The entirety of the human or object did not need to be visible in the frame for the event to be coded as causal. A frame from the beginning of an agent-recipient relation event with an infant acting as an agent is pictured in Figure 1a; A frame from an agent-recipient relation event with someone other than the infant acting as an agent is pictured in Figure 1b;

Self-propelled motion—A frame from the start of a self-propelled event is illustrated in Figure 2. A motion was coded as self-propelled when an entity began moving on its own (i.e., without an observable external force propelling it), and the onset of its autonomous motion was unambiguous (i.e. an entity was visible and proceeded from a stationary to moving state). The beginning of the event was marked when the self-propelled motion began, and the end was recorded when the entity ceased moving or exited the view of the camera. Only movement with a visible autonomous onset was classified under this category because motion onset is the defining feature of self-propulsion. To be sure, an entity that appears to move independently but that does not have a visible motion onset is not necessarily self-propelled; for example, a ball that is thrown into view would look as if it moved autonomously when it was in fact the recipient of an obscured causal action. It is likely that infants would learn that all independent human motion is self-propelled if most of the autonomous motion they view is produced by humans. Yet, ambiguously starting motion does not in and of itself provide information regarding motion onset. The entirety of the object did not need to be in the field of view for its motion to be self-propelled, as long as its motion onset was unambiguous; for example, in the self-propelled event pictured in Figure 2, the person's motion was coded as self-propelled even though only her legs were visible to the infant.

Only global motion, and not that of parts (e.g., a moving arm), was classified as self-propelled. It is unclear to a naïve viewer if the local motion of the parts of an entity constitutes self-propulsion because parts are attached to the body of the entity, which could conceivably cause their movement. Self-propelled motion has been described theoretically as a global motion property that is distinct from the local motion of parts (Rakison, 2006), and infants' and children's understanding of self-propulsion has almost always been tested empirically using figures that are globally self-propelled or by asking children questions that imply global self-propulsion, such as, "Do you think it could go up the hill all by itself?"

(Massey & Gelman, 1988, p. 311; also Cicchino & Rakison, 2008; Csibra et al., 1999; Gelman & Gottfried, 1996; Kosugi et al., 2003; Luo & Baillargeon, 2005; Luo et al., 2009; Mahajan et al., 2008; Newman, Hermann, Wynn, & Keil, 2008; Opfer, 2002; Poulin-Dubois et al., 1996; Rakison, 2006; Spelke et al., 1995). Note also that we did not code as self-propelled those movements that imply an internal source of energy, such as spontaneous accelerations or changes in direction. Although some theorists (e.g., Luo et al., 2009; Gelman et al., 1995; Leslie, 1995) have proposed that these cues are important in identifying self-propelled motion, we focused instead on spontaneous onsets of motion because they, unlike for example changes in direction, are unambiguous with regard to how an object starts to move. We further chose to concentrate on simple instances of motion because infants' information processing skills improve over developmental time and allow them to process more complex motion with age. Thus, simple real-life instances of self-propulsion and causal agency may be the first ones to which infants can attend and learn (e.g., Oakes & Cohen, 1990).

Entities in the motion events—The identities of the objects in the motion events – that is, the causal agent and recipient in the agent-contact relation events and the moving object in the self-propelled events – were recorded. Specifically, it was noted if these objects were people, animals, or inanimate objects. The baby's own agency was only recorded if both the baby and his recipient were visible on the camera. We did not code if the baby engaged in self-propelled motion or was acted upon as a recipient because in these situations the baby did not actually see self-propulsion or an agent-contact relation.

Reliability—A second judge who was blind to the hypotheses of the experiment coded two videos for each age group (6 total), which equaled 48.88 minutes of reliability coding (22.36% of the total footage coded by the main experimenter). The second coder judged the frequency and duration of animate and inanimate motions in the agent contact, recipient, and self-propelled categories. Overall coder reliability was high for both frequency, $r = .93$, and duration of motion, $r = .91$. In addition, the mean difference between the two coders' scoring was not reliably different, all p 's $> .83$.

Results

The main set of analyses examined the frequency with which the infant viewed people and inanimate objects acting as causal agents, recipients, and self-propelled objects while wearing the head-mounted camera. (Note that the infant did not have a pet in the home and did not view any non-human animals in the coded video footage.) Throughout this manuscript, frequency will be presented as instances of motion seen per hour; also, in these analyses, the number of motions and not the participant formed the basic unit of analysis (for similar analysis approaches see Corrigan (1994) and Sobel, Li, & Corriveau (2007)). Frequency data and corresponding duration data across the age points are reported in Table 2.

The key finding from the head-camera videos is that the frequency with which the infant viewed people engaged in agent-contact events was greater than the frequency with which he saw people engaged in self-propulsion, $\chi^2(1) = 50.1$, $p < .0001$ (ratio of 2.79 human agent-contact events to every human self-propelled event). Because duration and frequency data closely mirrored one another, statistics are only reported for frequency.

The infant viewed people act as agents in causal events 27.7 times more often than inanimate objects act as causal agents, $\chi^2(1) = 512.74$, $p < .0001$. This same dominance of people over inanimate objects was present for self-propelled motions, $\chi^2(1) = 37.06$, $p < .0001$, but the ratio was considerably less than for agent-contacts (9.0 vs. 27.7). Moreover,

the denominator in these ratios (the frequency of agent-contacts or self-propulsion events for inanimate objects) did not differ.

The frequency of agentive and self-propulsion events performed by a person that the infant observed increased with age, $\chi^2(2) = 186.93, p < .0001$. The infant viewed more people in self-propelled events at 8 months than during the other two age points, $\chi^2(2) = 18.8, p < .0001$. However, an inconsistent amount of footage for each age group was taken outside of the home, and during this footage there was also a discrepancy in the maximum number of people viewed (3 months: 56 people, 8 months: 86 people, 12 months: 14 people). Thus, the infant's viewing of people in self-propelled events was re-analyzed to include only footage recorded in the home and when the mother and lab assistant(s) were the only others present. This new analysis revealed that the frequency with which the infant viewed self-propulsion in the home increased with age, $\chi^2(2) = 9.67, p < .01$, especially between 8 and 12 months. Data separated by age can be viewed in Table 3.

Discussion

This study provides a preliminary catalog of the visual input infants receive in the real world of causal and self-propelled motion. The infant wearing the head camera saw more than 3 times as many instances of people acting as agents in causal events as of people engaged in self-propelled motion; additionally, the ratio of motions that the infant saw performed by people as compared to inanimate objects was also three times as high for agentive motions than it was for self-propelled motions. This finding is compatible with the associative learning account of conceptual development because these frequencies align with infants' knowledge of causality and self-propulsion. Indeed, empirical evidence indicates that infants do not associate self-propulsion strongly with animacy (e.g., Csibra et al., 1999; Shimizu & Johnson, 2004), and the current study demonstrates that people are not often viewed engaging in self-propelled motion. Baldwin (Baldwin et al., 2001) and Woodward (Woodward, Sommerville, & Guajardo, 2001) have suggested that infants view regularities in human action that cohere with patterns in early motion knowledge, and this is the first study that supports empirically this claim.

It has been demonstrated that infants can learn the relative frequencies with which objects appear in their environments (e.g., Kirkham et al., 2002). Taken a step further, an associative learning account for early learning about motion properties is consistent with the notion that the relative frequency with which people and inanimate objects are seen engaged in agentive and self-propelled motion influences infants' knowledge of these motions. That is, if a higher proportion of agentive motions than of self-propelled motions are performed by people, regardless of the absolute number of times infants view these motions, infants should have a stronger representation that agency is a human motion than that self-propulsion is a human motion. We suggest that the absolute and relative frequencies with which infants see people engaged in these motions play a role in infants' understanding of them; indeed, probability and frequency have both been implicated in human learning (Fiser & Aslin, 2002; Howard, Howard, Dennis, & Kelly, 2008; Monaghan & Rowson, 2008). In this study, both the relative and absolute frequencies with which agentive and self-propelled motions were performed by humans indicated that infants' representations of animate agents should be stronger than their representations of animate self-propelled objects.

That the infant's viewing of causal agency increased most sharply between 3–8 months is consistent with the developmental trajectory of infants' developing knowledge because they begin to identify causal events and understand that hands act on goals in this age range (Oakes, 1994; Woodward, 1998). This finding is similarly in accord with the course of infants' motor skill development, as they begin to produce coordinated reaches towards objects at this time (Bertenthal & Clifton, 1998). Indeed, it has been proposed that infants'

reaching experience brings about the ability to recognize the causal and goal-directed motions of others (Rakison, 2009; Sommerville, Woodward, & Needham, 2005). It is likely both that infants attend to more agentive events because they understand their structure due to their own action experience, and that infants' increased visual experience bi-directionally improves their understanding of such events. An analogous point can be made about the increase in the infant's viewing of self-propelled events between 8 and 12 months, as the majority of infants begin to produce self-propelled motion by crawling and walking between these ages (Bayley, 1969).

Some limitations of this study should be noted. Because only one infant was tested, it is impossible to generalize his visual experiences to all infants. Additionally, at times multiple people, objects, and events appeared simultaneously in the view of the head-mounted camera, and thus it is difficult to know to what exactly the infant attended in such scenes. However, this coarse grain of analysis and the limitations intrinsic to a single-subject design were suitable for obtaining a preliminary measure of what kinds of events appear in an infant's view. Finally, it is worth noting that one potential criticism of our observational study is that it involved only one infant and is therefore unrepresentative of the typical viewing experience of infants more broadly. However, in our view the size of the effects found in the observational study were so large – and the settings in multiple contexts so natural – that it is difficult to envisage that the infant's experiences were an anomaly. In other words, we propose that given the size of the effects garnered from one infant, that our data are representative of infants' typical input about agency and self-propulsion.

Experiment 1

The following four experiments investigated if the differential frequency with which infants see people engaged in causal agency and self-propulsion accounts for the disparity in their ability to generalize between these motions. These experiments examined infants' responses to the motions of geometric shapes, and not to the motion of people or animates, in order to examine infants' representation of motion without the additional influences of perceptual animacy cues. In Experiment 1, we examined if, and at what age, infants understand that an agent in a causal event should also engage in self-propelled motion. Ten- and 14-month-old infants were tested. By 10 months of age infants can recognize causal motion in simple and complex events (Oakes, 1994; Oakes & Cohen, 1990), and they can also identify self-propelled motion (Cicchino & Rakison, 2008); thus, the youngest infants tested in this study had developed the motion recognition abilities that are a necessary precursor to motion generalization. Infants were first habituated to a Michotte-like causal launching display (Michotte, 1963) in which the agent and recipient were a different color and shape. In the test trials of the experiment, infants viewed events that depicted the self-propelled motion of either the agent or the recipient from the habituation events. If infants infer that agents in causal events, and not recipients, are self-propelled, they should look longer at the test event in which the recipient is self-propelled than at the event in which the agent is self-propelled, because the recipient event will run counter to their expectations. However, if infants cannot generalize that a causal agent also engages in self-propelled motion, they should look equally to both types of test events.

Method

Participants—Participants were twelve 10-month-old (mean age 10 months 3 days, range = 9 months 5 days to 10 months 15 days) and twelve 14-month-old (mean age 14 months 4 days, range = 13 months 24 days to 14 months 14 days) healthy full-term infants. There were 5 males and 7 females at both 10 and 14 months. Data from 11 additional infants were collected but excluded from the final sample, due to failure to habituate (three 10-month-olds and two 14-month-olds), fussiness (four 14-month-olds), experimenter error (one 10-

month-old) or fatigue indicated by looking at a post-test trial presented at the end of the experiment for less than 2 s (one 14-month-old). In all studies reported in this paper the participants were mostly Caucasian and from middle-class backgrounds. Infants were recruited through birth lists obtained from a private company and were given a small gift for their participation.

Stimuli—The pre-test, habituation and test stimuli were computer-animated movies created with Macromedia Director 8.0 and shown on a 14 × 24 inch LCD screen at a viewing distance of 24 inches. To acclimatize infants to the task, before the main experiment began participants were shown a pre-test event in which an animated mouse bounced across a stage depicted on the LCD display. This pre-test event lasted for 8 s. During the habituation phase of the study, infants viewed simple Michottian causal launching events in which either an orange square or green octagon entered from off-screen and hit a different simple geometric shape (also either an orange square or green octagon, whichever was not the first object onscreen), setting it immediately into motion. Note that the onset of motion of the first object onscreen was ambiguous; that is, since it entered from off-screen it could conceivably be either caused-to-move or self-propelled. Each causal launching event lasted 6 s. A schematic of this event is illustrated in Figure 3a.

The moving objects in this study were depicted as geometric shapes so that infants would not be given cues to the identities of the objects other than their motion (e.g., no perceptual identity cues such as eyes). To maximize infants' attention to the screen, the orange square had a blue heart in its center and the green octagon had a yellow sun in its center. These extra features made the objects more interesting but did not signal that the objects were animate or inanimate. Objects were 4.5 in. tall and 3.75 in. wide, and they moved at a speed of 6 inches per second across a brown stage and against a light purple background.

In the test phase, infants viewed two different types of events that depicted the self-propelled motion of a single object that was previously seen during habituation. In the *consistent* test event, the agent in the causal launching seen during habituation (e.g., the first object moving onscreen in the causal launching event) was motionless in the center of the screen. After a pause of 1.5 s, the orange square or green octagon moved off-screen to either the right or the left as during habituation. This event type is referred to as the *consistent* test event because if infants generalize that an agent in a causal event should also be self-propelled, they should expect that the object in these test events (the causal agent from habituation) would be self-propelled.

In the *inconsistent* test trial, infants saw an event that was identical to the consistent test event except that the recipient from the causal launching event shown during habituation was shown in motion. This event was called *inconsistent* because it should violate infants' expectations if they generalize that an agent in a causal event, but not a recipient, is self-propelled. The test events are illustrated in Figures 3b and 3c.

The total length of each test event was 6 s, which is identical to the length of each habituation event. Note that the self-propelled object in the test event began movement from the center of the stage, which was the starting point for the recipient in the causal launching events shown in habituation. In addition, the distance traveled by the self-propelled object was identical to the distance traveled by both the causal agent and recipient in the habituation events.

Procedure and Design—Each infant sat on their parent's lap facing the computer monitor. Parents were instructed not to interact with infants verbally or otherwise, to not fixate on the computer screen, and to otherwise remain neutral. A habituation procedure

with a subject-controlled criterion was used. In the habituation phase of the experiment, infants were presented with the stimulus set described in the *Stimuli* section. During the habituation phase of the experiment, a trial ended if the infant looked away from the screen for 1 s or if 30 s had passed (five presentations of the habituation event, or three presentations of the pre-test event).

Infants were first shown the pre-test event and then the habituation events. Different presentations of the causal launching events shown in habituation began on the left side of the screen or on the right side of the screen, in a semi-random order for each infant. The identities of the objects in the habituation event (e.g., if the agent was an orange square or a green octagon), and the direction of motion in the first habituation event, were counterbalanced across infants. Each participant viewed only one type of object act as an agent and a different object act as a recipient throughout the habituation phase, so that if an infant saw the orange square act upon the green octagon in the first habituation event, the infant saw this same agent-recipient pairing throughout habituation.

The habituation phase ended, and the test phase began, after 16 trials had passed or after infants' looking times reached a specified criterion. To reach criterion, an infant's looking times on a block of three consecutive trials had to be less than 50% of their total looking times on the first four trials. Infants who did not reach criterion within 16 trials were not included in the final analysis. Infants viewed each type of test event twice in block form, so that they first saw a pair of consistent-inconsistent test events before viewing each event type for a second time.

The test trials continued until the infant looked away for 1 s or for a maximum of 60 s (10 presentations of the events). The test trials were longer than the habituation trials because pilot testing indicated that many infants looked at the test events for the maximum duration when they were shorter in length. Type of test trial presented first (consistent or inconsistent) and direction of motion in the test trials were counterbalanced across infants. The order of the test trial type was identical in both blocks.

Apparatus—Infants were tested individually in a quiet laboratory room. Events were presented on a 14 in. x 24 in. computer monitor that was approximately 24 in. from the infant's face. A full-length black curtain hung behind the computer monitor and surrounded the testing area. An experimenter observed the infants' looking patterns through a closed-circuit video camera that was placed behind the monitor and hidden from the infant's view by the curtain. Infants' looking behaviors were recorded for later reliability coding. An Apple G5 computer running Habit X software (Cohen, Atkinson, & Chaput, 2004) was used to control the experiment.

An experimenter hidden from infant's view observed the infant's gaze on a television monitor connected to the video camera. The length of a gaze was recorded by pressing a key on a computer keyboard when the infant looked at the computer monitor. When the infant looked away from the monitor, the experimenter released the key. A green circle was flashed against a black background on the screen, and a chiming noise was played, in order to capture the infant's attention prior to the beginning of the experiment and before each trial. The experimenter started a trial by pressing a preset key on the computer keyboard as soon as the infant's gazes focused on the computer monitor. The computer automatically established when the habituation phase ended and the test phase began.

Coding—The length of infants' visual fixations during the study was coded by the experimenter's key press and recorded by the computer. Coders were blind to when the habituation phase ended and the test phase began, and to the order of presentation of the test

events. A second judge recoded data from 25% of the infants to establish reliability. Across the experiments presented here using the habituation methodology, looking times were highly correlated between coders, $r > .92$.

Results

Habituation Phase—Ten-month-old infants required a mean of 8.58 trials ($SD = 3.12$) to reach the habituation criterion, which was greater than the mean of 6.17 trials ($SD = 1.64$) required by 14-month-olds, $F(1, 22) = 5.64$, $p < .05$, $\eta^2_p = .20$. This difference in the number of trials needed to habituate between age groups is unsurprising because older infants have greater information processing capacity than do younger infants and thus tend to decrease their looking to stimuli more quickly (Hunter & Ames, 1988). Infants' looking to the last three habituation trials did not vary by age, $p > .4$, which suggests that 10-month-olds ($M = 6.61$, $SD = 3.35$) and 14-month-olds ($M = 7.49$, $SD = 2.72$) were equally as attentive before the start of the test events.

Test Phase—The main analysis measured infants' looking patterns to the two consistent and inconsistent test events. Looking times to these events were entered into a 2 (Age: 10 months vs. 14 months) \times 2 (Block: first vs. second) \times 2 (Trial Type: consistent vs. inconsistent) mixed-design ANOVA, with repeated measures on the block and trial type variables. This analysis resulted in a main effect of block, $F(1, 22) = 7.25$, $p < .025$, $\eta^2_p = .25$. Infants looked at test events that occurred during the first block of two events ($M = 11.49$, $SD = 7.31$) longer than at the test events that were shown during the second block of two events ($M = 6.97$, $SD = 5.56$). Block did not interact with any variable, p 's $> .5$, which suggests that infants' looking patterns to the two categories of test events were similar within each block. There was also a marginally significant main effect of trial type, $F(1, 22) = 3.37$, $p < .08$, $\eta^2_p = .13$, which was mediated by an interaction between trial type and age, $F(1, 22) = 6.22$, $p < .025$, $\eta^2_p = .22$. Planned comparisons indicated that 10-month-olds looked equally as long at the consistent and inconsistent test events, $F(1, 11) = .20$, $p > .66$, $\eta^2_p = .02$, but that 14-month-olds looked longer during the inconsistent test trials than during the consistent test trials, $F(1, 11) = 10.17$, $p < .01$, $\eta^2_p = .48$. Infants' looking times are illustrated in Figure 4.

Discussion

The results of Experiment 1 indicated that infants between the ages of 10 and 14 months develop the ability to infer that an agent in a causal event, but not a recipient, is self-propelled, because only 14-month-olds looked longer at the inconsistent test events than at the consistent test events. This finding is one of the first to establish that infants can generalize from one motion property of an object to another. Indeed, because motion is not constantly available in the perceptual array, generalizing between two motion properties requires infants to perform the challenging task of remembering a less-obvious feature and mapping it to an entity in the absence of visual feedback. Previous work demonstrated that in an action task children are unable to generalize between two less-obvious properties of animates until 5 years of age (Sheya & Smith, 2006).

Infants' ability to generalize from causal to self-propelled motion is consistent with the associative learning view presented in the introduction of this paper. The Observational Study indicated that infants see many instances of humans acting as agents in their daily lives, which would suggest that infants develop a strong representation that animates are agents. In turn, infants should be able to generalize from agency to other actions in which agents engage.

Why, then, were 10-month-olds unable to perform this generalization task? By 10 months, infants have a great deal of experience seeing animates act as agents; the infant examined in the Observational Study saw nearly 350 instances an hour of humans engaging in agentive actions as early as 3 months of age. Although correlations between animates and their motions exist abundantly in a 10-month-old's world, we suggest that the improvements in information processing skills that occur between 10 and 14 months enabled the older infants tested, and not the younger, to process correlations between objects and their motions in this experimental context. This explanation is consistent with several other studies that have demonstrated that infants' ability to form correlations involving moving objects improve greatly between 10 and 14 months of age. For example, 14-month olds, but not 10-month-olds, form correlations between an object's moving parts and its global motion pattern (Rakison & Poulin-Dubois, 2002), identify the originating agent in a causal chain (Cohen, Rundell, Spellman, & Cashon, 1999), and form associations between novel words and moving objects (Werker, Cohen, Lloyd, Casasola, & Stager, 1998).

An alternative explanation for 14-month-olds' behavior in this study is that they responded to which object first moved on-screen rather than to motion properties of the objects. That is, the causal agent was the first object to move in the habituation events, but the recipient was the first object in motion in the inconsistent test events. It is possible that infants attended primarily to the causal agent in the habituation events only because it was the first object in motion, and for that reason dishabituated when they saw a different object (the recipient) move in test. This possibility was addressed in Experiment 2.

Experiment 2

Experiment 2 sought to control for the possibility that 14-month-olds' visual attention in Experiment 1 was the result of infants' attention to which object moved first in the scene rather than to the motion properties (causal agent, recipient, or self-propelled) of the objects. This experiment was identical to Experiment 1 with one exception: during the habituation phase, infants viewed a non-causal event with a gap and delay, in which the two objects onscreen do not contact each other, rather than a causal launching. Previous studies have demonstrated that infants perceive as non-causal such a gap and delay in an event (e.g., Oakes & Cohen, 1990; Leslie, 1984; Rakison, 2006).

Although the two test events are no longer consistent or inconsistent in comparison with the habituation events, they will retain their labels for ease of comparison with Experiment 1. If 14-month-olds tested in this experiment respond on the basis of which object moves first on the screen, they should look longer at the inconsistent test events than at the consistent test events, as they did in Experiment 1. However, if infants respond on the basis of the motion properties exhibited by the objects, they should look equally long at both events. Although the second object onscreen in this experiment was visibly self-propelled, the motion of the first object was ambiguous; that is, it could or could not be self-propelled. Thus, because the first object onscreen does not exhibit any cues that would suggest it is not self-propelled, seeing it move in a self-propelled manner in the test trials would not violate infants' expectations.

Method

Participants—Twelve fourteen-month-old (mean age 14 months 4 days, range 13 months 19 days to 14 months 22 days) healthy full-term infants participated in this study. Five were males and seven were females. Four additional infants were tested but not included in the final sample due to failure to habituate (1), fussiness (2), or equipment malfunction (1). Infants were recruited by the same means as in Experiment 1.

Stimuli—The stimuli used in this study were identical to those of Experiment 1, with the exception of the one difference previously outlined. Namely, in the habituation trials of Experiment 2 infants viewed a non-causal launching event with a gap and delay. One object, either an orange square or green octagon as in Experiment 1, entered the screen from off-stage and stopped moving at a distance of 4 in. from a second object that differed in shape and color. After a pause of 666 ms, the second object then moved off-screen without contact from the first. This event is illustrated in Figure 5a. The objects moved at the same speed as those in Experiment 1, and trial length was also the same as in Experiment 1. The test, pre-test, and post-test events were identical to those used in Experiment 1, and the test events are again illustrated in Figures 5b and 5c.

Procedure, Design, Apparatus, and Coding—The procedure, design, apparatus, and coding for Experiment 2 were identical to that of Experiment 1.

Results

Habituation Phase—Infants in Experiment 2 required a mean of 8.83 trials ($SD = 3.35$) to reach the habituation criterion, which was significantly more trials than 14-month-olds needed to reach the criterion in Experiment 1, $F(1, 22) = 6.12, p < .025, \eta^2_p = .22$. This finding suggests that infants do find a non-causal event with a gap and delay to be harder to process than a similar causal launching scenario. However, previous work has indicated that infants do not consider events with a gap and delay, such as those infants viewed during habituation in Experiment 2, to be inherently more interesting than causal launching events (Oakes & Cohen, 1990); infants tested in Experiment 2 likewise did not look longer during the first three habituation trials, $M = 20.61, SD = 6.44$, than did 14-month-olds tested in Experiment 1, $M = 19.53, SD = 7.49, p > .7$. Experiment 2's participants looked at the last three habituation events for a mean of 7.17 s ($SD = 2.16$), which did not differ from the time that 14-month-olds in Experiment 1 attended to the last three habituation events, $p > .4$.

Test Phase—As in Experiment 1, infants' looking times to the four test trials were entered into a 2 (Block: first vs. second) \times 2 (Trial Type: consistent vs. inconsistent) repeated-measures ANOVA. This analysis resulted in only a significant main effect of block, $F(1, 11) = 4.88, p < .05, \eta^2_p = .31$. As in Experiment 1, infants looked longer during the first block of test trials, $M = 19.05, SD = 14.20$, than during the second block of test trials, $M = 12.42, SD = 8.11$. There was no significant interaction between trial type and block, $p > .5$. Most pertinently, there was also no significant main effect of trial type, $F(1, 11) = .00, p = .97, \eta^2_p = .00$. The null trial type effect is illustrated in Figure 4.

Discussion

After habituation to a non-causal event with a gap and delay, 14-month-olds looked equally as long at test events in which the first and second moving objects from the habituation trials engaged in self-propelled motion. This finding suggests that infants in this experiment, as well as those in Experiment 1, did not respond to the events on the basis of which object moved first. Instead, these data indicate that the performance of 14-month-olds in Experiment 1 reflected their ability to generalize self-propulsion to a causal agent. Note that it is difficult to infer too much from null results; however, these data in conjunction with those from Experiment 1 suggest that infants expect that self-propelled objects also act as agents in a causal scene.

Interestingly, infants in this experiment looked equally long at both test events even though the second object in the habituation event (e.g., the object in the inconsistent test event) was clearly self-propelled during habituation, while the onset of motion of the first object in the habituation event (e.g., the object in the consistent test event) was ambiguous. This result

runs counter to the hypothesis of Luo et al. (2009; see also Kotovsky & Baillargeon, 2000), who proposed that infants assume that an object is not self-propelled unless they are given unambiguous evidence to the contrary. If this were the case, infants would have looked longest at the consistent test event that depicted the self-propelled motion of an object that they should have categorized as inert. Instead, it could be that infants make no assumptions about the motion properties of objects that have ambiguous motion onsets, or that infants generalized that the first object in the habituation event was self-propelled because it stopped moving independently (e.g., without hitting a barrier).

Experiment 3a

The results of Experiments 1 and 2 suggest that by 14 months infants generalize self-propulsion to causal agents. Experiment 3a was designed to assess the possibility that 14-month-olds can make the inverse inference, or generalize causal agency to self-propelled objects. In conjunction with Experiments 1 and 2, this study tested the hypotheses that infants' generalizations between causal agency and self-propulsion are asymmetric or more specifically, that infants will be unable to infer that self-propelled objects act as agents in causal events at the same age at which they infer the inverse.

Method

Participants—Twelve 14-month-old (mean age 13 months 28 days, range 13 months 9 days to 14 months 13 days) healthy full-term infants participated in this experiment, 8 male and 4 female. An additional 7 infants were not included in the final sample for failure to habituate (1), fussiness (2), infant's eyes not being visible to the experimenter for the entire study (2), fatigue as indicated by looking less than 2 s at the post-test event (1), or experimenter error (1). Infants were recruited by similar means as in previous experiments.

Stimuli—Infants viewed the same events as in Experiment 1, except that the movies that portrayed the self-propelled motion of a single object were shown during the habituation phase, and causal launching events were shown during the test phase. Because infants only saw the self-propelled motion of one object during habituation (e.g., either a green octagon or orange square, but not both), each type of test event contained a novel object. In the consistent test event, the object from habituation served as the agent in the causal launching event and the novel object served as the recipient (e.g., if the orange square was self-propelled during habituation, the orange square would be the agent and the green octagon would be the recipient in this test causal launching event). In the inconsistent test event, the object from habituation served as the recipient in the causal launching and the novel object served as the agent (e.g., if the orange square was seen in habituation, in this test event the green octagon would be the agent and the orange square would be the recipient). These events are illustrated in Figure 6.

Procedure, Design, Apparatus, and Coding—The procedure, design, apparatus, and coding for this study were identical to that of Experiment 1 with the exception that infants saw self-propelled events during habituation and causal launching events in test. Different presentations of the self-propelled events in habituation moved towards different sides of the screen (either to the left or right), in a semi-random order for each infant. The identities of the object in the habituation events (e.g., if the object was an orange square or a green octagon), and the direction of motion in the first habituation event, were counterbalanced across infants. Each participant viewed only one object in the habituation phase, so that if an infant was habituated to the self-propelled motion of an orange square, that infant did not see a green octagon until the test phase.

As in previous experiments, infants viewed each test event type twice in a blocked manner, so that each type of test event (consistent and inconsistent) was seen once before moving on to the second block. The type of test trial presented first and the order of motion in the test trials were counterbalanced across infants. Finally, the order of test trials was duplicated in both blocks shown to an individual infant (so that if the consistent test event was the first test trial, it was also the third test trial).

Results

Habituation Phase—Infants required 7.08 trials ($SD = 1.83$) to reach habituation, which did not differ from the number of trials required for 14-month-olds tested in Experiment 1, $p > .2$. Looking time to the first three habituation events, $M = 18.75$, $SD = 7.93$, did not differ from that for 14-month-olds in Experiment 1, $p > .8$, nor did looking time to the last three habituation events, $M = 6.83$, $SD = 4.08$, $p > .6$. Thus, it can be concluded that 14-month-olds did not find the self-propelled events to be inherently more interesting or harder to process than the causal launching events.

Test Phase—As in previous experiments, for the principal analysis infants' looking times to the consistent and inconsistent test events were entered into a 2 (Block: first vs. second) \times 2 (Trial Type: consistent vs. inconsistent) repeated-measures ANOVA. This test resulted in only a significant main effect of block, $F(1, 11) = 11.54$, $p < .01$, $\eta^2_p = .51$, as infants looked longer during the first block of test trials, $M = 17.34$, $SD = 12.81$, than during the second block of test trials, $M = 11.99$, $SD = 10.00$. There was no significant main effect of trial type, $F(1, 11) = 1.10$, $p = .32$, $\eta^2_p = .09$, nor a significant interaction between trial type and block, $p > .2$. This null effect of trial type is displayed in Figure 7.

Discussion

The results of this experiment revealed that 14-month-old infants do not generalize causal agency to a self-propelled object; that is, infants did not increase their looking time to an event in which a formerly self-propelled object served as a recipient in a causal launching event. These data diverge from the findings of Experiment 1 in which 14-month-olds generalized self-propulsion to an agent in a causal event. Yet, these findings are consistent with the hypothesis that infants' generalizations between causal agency and self-propulsion are asymmetric due to their differential amount of experience with, and thus different representational strengths for, people engaged in agentive and self-propelled motions. The infant in the Observational Study did not see many instances of self-propulsion, but saw many of causal agency; if infants' exposure to agency and self-propulsion are asymmetric, then the associative learning view would predict that their representations for these motions would reflect the same asymmetry.

That infants did not generalize causal agency to a self-propelled object contradicts previous research that revealed that 5- and 12-month-olds do not expect self-propelled objects, but do expect inanimate objects that have not demonstrated self-propelled motion, to serve as recipients in causal events (Luo et al., 2009; Saxe et al., 2005). However, the self-propelled objects in these experiments exhibited additional cues to animacy as well as self-propulsion. In Saxe et al.'s (2005) study the self-propelled object had fur, eyes, and legs, and was described to "jump" across a stage (presumably non-linearly). Similarly, the self-propelled box that Luo et al. (2009) showed to infants changed directions independently. Considering the results of the current experiment, it is likely that infants tested by Saxe et al. (2005) and Luo et al. (2009) responded to these additional animate features as opposed to or in conjunction with the autonomous onset of the object's motion.

Experiment 3b

It is unknown from Experiment 3a if infants develop the ability to generalize from causal agency to self-propulsion shortly after 14 months, or if this ability either does not develop until considerably later in development. To examine if infants can perform this generalization later in infancy, 18-month-olds were tested in the same paradigm as were 14-month-old infants in Experiment 3a. Eighteen-month-olds were chosen for the experiment because previous work has shown that infants associate the animate feature of moving parts with self-propelled objects four months later than they do with causal agents (Rakison, 2005a, 2006). Thus, it is plausible that infants are also able to generalize from self-propulsion to causal agency four months after they can perform the inverse generalization.

Method

Participants—Participants in this experiment were twelve healthy 18-month-old infants (mean age 18 months 3 days, range 17 months 19 days to 18 months 17 days). Four infants were male and 8 were female. Ten additional infants participated but were removed from the final sample for failure to habituate (3), fussiness (4), equipment malfunction (2), and prematurity (1).

Stimuli, Procedure, Design, Apparatus, and Coding—The experimental protocol was identical to Experiment 3a.

Results

Habituation Phase—Infants tested in Experiment 3b needed 7.08 trials ($SD = 2.27$) to habituate, which did not differ from 14-month-olds tested in Experiment 1, $p > .2$. Looking time to the first three habituation trials ($M = 19.91$, $SD = 5.84$) also did not diverge from Experiment 1's 14-month-olds, $p > .8$, nor did looking time to the last three habituation trials, $M = 7.36$, $SD = 2.51$, $p > .9$.

Test Phase—For the primary analysis infants' looking times to the test events were entered in a 2 (Block: first vs. second) \times 2 (Trial Type: consistent vs. inconsistent) repeated-measures ANOVA. This analysis only revealed a marginally significant main effect of block, $F(1, 11) = 4.81$, $p = .051$, $\eta^2_p = .30$, in which infants looked longer during the first block of test trials, $M = 23.75$, $SD = 15.77$, than during the second block of test trials, $M = 12.76$, $SD = 8.95$. As in Experiment 3A, neither was the effect for trial type significant, $F(1, 11) = 0$, $p = .99$, $\eta^2_p = .00$, nor was the interaction between trial type and block, $p > .7$. The comparison of test trials can be seen in Figure 7.

Discussion

Experiment 3b revealed that like 14-month-olds, infants at 18 months also do not generalize from seeing an object as self-propelled to judging that object as a causal agent. It is thus unclear from these results when this ability emerges, if it does at all; however, the fact that increasingly older infants did not make the generalization is in accord with evidence that suggests that children and adults do not view self-propulsion as a strong cue to animacy (Gelman et al., 1995; Opfer, 2002).

An alternative explanation of the null results found in Experiments 3a and 3b could be that infants were overwhelmed, from an information-processing perspective, with the addition of a second, novel object in the test trials. According to this argument, infants did not respond to the test events in terms of the motion properties of the objects because they allocated their cognitive processing to this second novel object. This possibility was explored in Experiment 4.

Experiment 4

As a control for Experiment 3, this experiment investigated if 14-month-old infants generalize causal agency to a self-propelled object that also displays additional cues to animacy. Infants tested in Experiment 4 viewed during habituation a self-propelled object that also changed direction independently and accelerated, and then were presented with the same test events as infants in Experiment 3. The goal of this experiment was to demonstrate that infants can generalize from the motion of a single object to causal agency, and thus that the null performance in Experiment 3 was not due to the addition of an extra object during the test phase.

The additional cues of an independent direction change and acceleration were chosen because they have been shown to be highly associated with animacy or animate properties by infants and adults (Gelman et al., 1995; Johnson, Shimizu, & Ok, 2007; Luo et al., 2009; Luo & Baillargeon, 2005; Tremoulet & Feldman, 2000). Thus, it can be inferred that infants have a strong representation that these cues are associated with animacy. Based on the hypothesis that infants can generalize on the basis of motions that they strongly associate with animates to other strongly animate motions (such as causal agency), we predicted that the combination of these cues would lead infants to generalize from the motion of a single self-propelled object to causal agency.

Method

Participants—Participants were twelve 14-month-old (mean age 14 months 5 days, range 13 months 20 days to 14 months 17 days) healthy full-term infants, 10 males and 2 females. Four further infants were tested but not included in the final sample due to failure to habituate (1), equipment failure (1), fussiness (1), and looking to all four test trials for the maximum possible duration (1). Infants were recruited by way of the same methods as in previous experiments.

Stimuli—The stimuli duplicated those used in Experiment 3 with the exception of those shown during the habituation phase (Figure 8). As previously noted, during the habituation phase infants viewed the self-propelled motion of a single object (either an orange square or green octagon, as in prior studies) that also changed direction autonomously and accelerated. As in Experiment 3, the object originated in the middle of the screen and remained motionless for 1.5 s. After this period of motionlessness, the object moved in one direction for a distance of 6 in at the same speed that it traveled in all other experiments (6 in/s). The object then paused for 0.5 s, and next traveled 10 inches in the opposite direction at a constant speed before pausing again for 0.5 s. Finally, after this ultimate pause, the object changed direction for a second time and accelerated off-screen, reaching a final speed of 27 in/s. The length of each individual habituation animation event was 7.7 s. The test stimuli used in this experiment were the same as those employed in Experiment 3.

Procedure, Design, Apparatus, and Coding—The procedure, design, apparatus, and coding for this experiment were identical to those for Experiment 3.

Results

Habituation Phase—Infants in Experiment 4 required a mean of 7.08 trials ($SD = 2.57$) to reach the habituation criterion, which did not differ from the number of trials needed by 14-month-olds tested in Experiment 3A, $p = 1.00$. Looking times to the first three habituation trials, $M = 15.28$, $SD = 8.38$, and to the last three habituation trials, $M = 6.01$, $SD = 3.75$, did not deviate from Experiment 3A, p 's $> .1$.

Test Phase—Infants' looking times to the test events were entered into a 2 (Block: first vs. second) \times 2 (Trial Type: consistent vs. inconsistent) repeated measures ANOVA. This analysis revealed a significant main effect of block, $F(1, 11) = 9.59, p < .01, \eta^2_p = .47$; infants looked longer during the first block of test trials ($M = 22.40, SD = 15.11$) than during the second block ($M = 11.73, SD = 7.29$). Critically, there was also a main effect of trial type, $F(1, 11) = 5.91, p < .05, \eta^2_p = .35$, which indicated that infants looked longer at the inconsistent test trial than the consistent test trial. There was no significant interaction between the two variables, $p > .6$. These values can be seen in Figure 7.

Discussion

Experiment 4 was designed to test if 14-month-olds can generalize from the motion of a single object to causal agency. Results revealed that infants did so when the single object was self-propelled, changed direction independently, and accelerated. This finding suggests that the null results of Experiment 3 were not a consequence of cognitive overload due to the addition of a novel object in the test trials.

The current study additionally extends the findings of Luo et al. (2009) and Saxe et al. (2005). Both of these previous studies discovered that infants do not expect a self-propelled object with additional agency cues to serve as a recipient in a causal event, but provided no evidence concerning infants' expectation that such an object would serve as an agent in a causal event. The present study establishes that 14-month-old infants expect this kind of moving object to act as an agent in a causal event. Furthermore, these findings are in accord with other research that has shown that infants attribute goal-directedness and other animate properties to objects that change direction independently (Baillargeon et al., 2009; Johnson et al., 2007; Luo et al., 2009; Luo & Baillargeon, 2005) but not to those that are self-propelled and simply move along a linear path (Csibra et al., 1999; Mahajan et al., 2008; Shimizu & Johnson, 2004).

The results of Experiments 3 and 4 raise the question of how self-propulsion should be defined. Although infants only associate an independent direction change with animacy, and not just autonomous motion onset, studies that tested infants' knowledge of both kinds of motion interchangeably refer to them as "self-propelled." To get a clearer understanding of how infants process motion, these two types of motion need to be differentiated in the literature. It is uncertain how infants come to associate so strongly an independent direction change with animacy; if they do not observe linear self-propelled motion often, it is likely that they also do not see people frequently changing direction. One possibility is that infants' representation of such motion is strengthened because it inherently contains multiple cues to animacy. That is, infants can draw on multiple types of experience when interpreting motion that is both autonomous and that is non-linear. A second possibility is that infants learn more from instances of motion that has a direction change than from linear motion, as the change in direction is attention-grabbing.

Another type of motion that must be distinguished from global self-propulsion is the movement of an object's parts. The infant tested in the Observational Study did not observe many instances of global self-propulsion, but he did see many instances of hands moving; presumably, at times when these hands moved they appeared to do so on their own. We suggest that infants readily learn that people have moving parts, but that they do not (at least initially) transfer this understanding to global motion; that is, infants' experience viewing moving parts does not seem to increase their knowledge of global self-propelled motion. This idea is supported by empirical evidence that has indicated that infants attend to the local motion of an object's parts before they attend to its global motion path (Rakison & Poulin-Dubois, 2002), and that infants respond to an object's moving parts before they

recognize its self-propelled global motion specifically (Markson & Spelke, 2006; Shutts, Markson, & Spelke, 2009).

General Discussion

The associative learning view of concept formation rests upon the assumption that infants encounter statistical regularities in their environments and exploit these regularities to make sense of their world. The current work tested this assumption in the domains of infants' understanding of causality and self-propulsion. Through a case study in which an infant's visual experience was evaluated as he wore a head-mounted camera, it was determined that causal agency is much more frequently viewed than self-propulsion. Subsequent experiments using the infant habituation procedure revealed that infants begin to generalize that causal agents are self-propelled between 10 and 14 months of age, but cannot perform the inverse generalization (e.g., that self-propelled objects are causal agents) at the same age unless the self-propelled object exhibits additional cues to animacy.

Taken together, these data suggest that the strength of infants' representations for causal agency and self-propulsion, and in turn their ability to generalize between these motion properties, are shaped by their differential amounts of experience with them. It has been previously established that the language input infants receive in the real world predicts their understanding of concepts such as number (e.g., Sarnecka, Kamenskaya, Yamana, Orgura, & Yudovina, 2007); however, the current experiments are among the first to demonstrate an analogous correspondence between input and knowledge in the visual domain.

The Cause of Asymmetric Generalizations

That infants generalized from the category in which they have more experience to the category in which they have less experience, but did not generalize in the opposite direction, is consistent with Quinn and Eimas's (1998) finding that very young infants can form a category for humans that includes non-human animals but cannot form a category for non-human animals that includes humans. Quinn (2002, 2004, 2005) suggested that this asymmetry is due to differences between the representations that infants hold for objects and events in which they do and do not have expertise. With increasing expertise, infants have been shown to progress from a piecemeal manner of representing objects and events, in which individual features are represented but not necessarily integrated, to a more holistic approach, in which global properties are represented. This progression to holistic representations is seen in infants' processing of novel static and dynamic categories, in which they represent individual features of objects before relations among features (Cohen & Younger, 1984; Rakison, 2004; Rakison & Poulin-Dubois, 2002; Younger & Cohen, 1986; Younger & Furrer, 2003) and in infants' representation of parts of objects before attending to overall shape (Pereira & Smith, 2009; Rakison & Butterworth, 1998).

Indeed, Quinn (2004; Quinn, Lee, Pascalis, & Slater, 2007) discovered that infants of the same age tested in the Quinn and Eimas (1998) generalization study represent humans by their overall shape, and represent non-human animals as a collection of smaller parts. Quinn (2004, 2005) argued that such holistic representations account for asymmetries in infants' generalizations because they give infants a broader base from which to generalize than do representations based on a non-integrated subset of features. Quinn (2004, 2005) furthermore suggested that strong representations might serve as "attractors" that pull weaker concepts towards them in representational space (in which more similar concepts are closer together and more dissimilar concepts are farther apart; see Kuhl, 1991; Thelen & Smith, 1994). Consistent with this proposal, infants have also exhibited asymmetric generalization in perceptual categorization tasks in which the properties of one category's members were more widely dispersed than those of a second category (French, Mareschal,

Mermillod, & Quinn, 2004; Mareschal, French, & Quinn, 2000; Mareschal, Quinn, & French, 2002; Quinn, Eimas, & Rosenkrantz, 1993).

We propose that infants' asymmetric generalization between causal agency and self-propulsion is similarly a product of their varying levels of expertise with these human motions. Infants can more easily generalize from the robust representations that they form from their extensive visual experience with causal agency than they can from weaker representations they form for self-propelled motion. If infants are agency "experts" they should be able to more easily represent relations between agentive motions and the features of the animates that produce these motions, which is essential for generalizing the motion property to novel entities, than they can for self-propelled motions.

It is noteworthy that this proposal is in accord with the domain-general view of learning because it presumes that infants' concepts of causal agency and self-propulsion are graded with regard to the amount of visual experience they have with each motion property. However, the results of the experiments presented in this paper would not be predicted by theorists who espouse a principle-based account of infants' understanding of causality and self-propulsion. In particular, that 14-month-olds in Experiment 4 generalized self-propulsion to causal agents contradicts the theories of Gelman et al. (1995), Leslie (1994, 1995), and Luo et al. (2009), as all of these theorists would predict that infants should not be able to generalize between these two motions. That 14-month-olds in Experiment 1 did not generalize causal agency to self-propelled objects likewise conflicts with the views of Mandler (1992) and Spelke (2003), who would expect infants to be able to generalize between causal agency and self-propulsion without asymmetry. Note that we cannot, at this point, eliminate the possibility that the findings reported here were generated by domain-general mechanisms that are constrained by lower-level biases, for example, toward certain ranges of speed and acceleration. Further research on young infants' expectations about speed and acceleration is necessary, however, before it is possible to determine whether this is the case. Moreover, it must be recognized that a domain-general statistical learning mechanism, when confronted with the incredible complexity of the visual environment, must solve a computational explosion problem – namely, that the number of *possible* statistical relations is enormous. As a result, there must be some constraints on which of these relations is attended to and encoded for learning to take place in a reasonable amount of time (see Aslin & Fiser, 2005). Again, future research will be needed to determine precisely what these constraints are on statistical learning and how they may change over development.

Domain-General Mechanisms for Learning About Causality and Self-Propulsion

To be clear, we do not claim on the basis of the results presented here that frequency of visual experience is the only means by which infants learn about their environments and, in particular, about causality and self-propulsion. Infants' information processing capacities, which continually develop, as well as their prior knowledge, constrain what they learn from the input they receive (Rakison, 2005a, 2006; Rakison & Lupyan, 2008). With regard to causal agency and self-propulsion, the structure of the motions themselves likely makes it easier for infants to learn about agency than to learn about self-propulsion. Agentive motions tend to be informative for extended periods of time, as many such actions that infants see involve a person grasping an object and then continuing to act upon it (e.g., by holding it). It is far less frequent that the agent and recipient are only briefly in contact, such as what would happen when a ball is kicked. In contrast, the autonomous onset of motion of a self-propelled event is always brief. These aspects of the structures of the motions make it probable that infants would learn more about the identity of things involved in causal agency than in self-propulsion even if infants were presented with the same number of exemplars of both motions.

Furthermore, it has been shown that adults' object-directed actions tend to be more exaggerated when playing with an infant than they are when interacting with another adult. This may facilitate infants' learning about agentive actions in a manner similar to how the exaggerated features of infant-directed speech assist in early language learning (Brand, Baldwin, & Ashburn, 2002; Brand & Shallcross, 2008; Brand, Shallcross, Sabatos, & Massie, 2007). It is difficult to envisage, however, how adults' self-propelled motions around infants could be similarly exaggerated. The distributional variability of infants' visual experiences similarly can affect what they learn about what they see. In the present study, the infant wearing the head-mounted camera saw a larger proportion of self-propelled events performed by inanimate objects (10%) than he saw of agentive events performed by inanimate objects (3.5%). Because the features of inanimate objects are more variable than those of animates (McRae, Cree, Seidenberg, & McNorgan, 2005; McRae, de Sa, & Seidenberg, 1997), it can be inferred that the variability of the self-propelled objects he saw was greater than the variability of the agentive objects. It could be that initially infants can more easily learn that people act as agents because of the relatively invariant visual evidence they receive, and they have more difficulty learning that people are self-propelled because of the higher amount of variation in the input. To be sure, the variability of category members in visual categorization tasks have been shown to greatly influence the nature of the subsequent categories that infants form (e.g., Kovack-Lesh, & Oakes, 2007; Mareschal et al., 2000; Quinn et al., 1993).

Infants' action experiences in the world certainly also influence what they know. In particular, it has been suggested that infants' experiences acting on objects serve as the main catalyst of their ability to recognize causal motion (Piaget, 1955; Sommerville, 2007; White, 1995). This proposal is supported by evidence from Sommerville, Hildebrand, and Crane (2008) that revealed that infants learn to recognize the causal structure of tool-use events when trained to produce the action, but not after matched visual training (see also Gerson & Woodward, 2008; Rakison, 2009). Similarly, Cicchino and Rakison (2008) found that crawling experience facilitates infants' recognition of self-propulsion. It is not yet clear, however, how infants' action experiences contribute to their motion understanding. One proposed mechanism for this ability is the bidirectional nature of the action-perception relationship (e.g., Sommerville & Woodward, 2005). Specifically, as action experience enhances infants' motion knowledge, infants' attention may become directed to the relevant aspects of the actions of others in their environment, which would allow them to learn more readily from the actions of others. For example, infants with reaching experience may be more likely to direct their attention to the grasps of others because they know that such actions convey important information (e.g., Campos et al., 2000). According to this hypothesis, infants' action experiences serve as a starting point that allow them to extract meaningful input from the actions of others.

It was not possible to analyze the infant's action production in the head camera videos, since the video was taken from the infant's point of view and thus did not always record the actions that he produced as a third-person video view would. However, the inference that infants' action experience directs their attention to action produced by others is corroborated by data from the Observational Study that indicate that the infant saw an increased number of agentive actions with age, which also corresponds to a developmental time period during which infants' action production increases. Similarly, in an eye-tracking experiment, 12-month-olds—who presumably have extensive reaching experience—were shown to look at the goal of a person's reach before contact occurred, while 6-month-olds—who presumably are novice reachers—did not (Falk-Ytter, Gredebäck, & von Hofsten, 2006). This study demonstrates that infants with considerable reaching experience visually selected the most informative aspects of another person's reach. Indeed, infants may not know to which aspects of the display to attend during short visual training with causal events in the lab in

experiments such as Sommerville et al. (2008), but after action experience may be able to engage in active visual experiences in the real world in which selection leads to learning from the visual environment (e.g., Amso & Johnson, 2006; see also Johnson, Slemmer, & Amso, 2004, for evidence that infants' object perception skills correspond with how they scan objects).

Conclusion

In sum, in this manuscript we presented observational data from a head-mounted camera and four experiments that established a relationship between infants' visual experience with causal and self-propelled motion and how they represent these motions in making generalizations about causality and animacy. An infant wearing a head-mounted camera viewed far more instances of causal agency than of self-propelled motion at 3, 8, and 12 months of age. In turn, controlled experiments indicated that infants begin to generalize that causal agents are self-propelled between 10 and 14 months of age, and cannot generalize that self-propelled objects are causal agents at 14 or 18 months. However, 14-month-old infants can generalize that a self-propelled object that exhibits additional cues to animacy is a causal agent. This combination of methodologies provides one of the first demonstrations of how the visual input that infants receive from their environments predicts their understanding of the world. In so doing, this set of studies provided support for the associative learning view of how infants come to understand causal and self-propelled motion. Finally, this work illuminated the mechanisms by which generalization is performed in infancy, and shed light upon how early concepts of animates are formed by elucidating how infants learn relations between features that are thought to be essential to such concepts.

References

- Amso D, Johnson SP. Learning by selection: Visual search and object perception in young infants. *Developmental Psychology* 2006;42:1236–1245. [PubMed: 17087555]
- Aslin RN. How infants view natural scenes gathered from a head-mounted camera. *Optometry and Vision Science* 2009;86:561–565. [PubMed: 19417702]
- Aslin RN, Fiser J. Methodological challenges for understanding cognitive development in infants. *Trends in Cognitive Sciences* 2005;9:92–98. [PubMed: 15737816]
- Baillargeon, R.; Wu, D.; Yuan, S.; Li, J.; Luo, Y. Young infants' expectations about self-propelled objects. In: Hood, B.; Santos, L., editors. *The origins of object knowledge*. Oxford, UK: Oxford University Press; 2009. p. 285-352.
- Baldwin D, Andersson A, Saffran J, Meyer M. Segmenting dynamic human action via statistical structure. *Cognition* 2008;106:1382–1407. [PubMed: 18035346]
- Baldwin DA, Baird JA, Saylor MM, Clark MA. Infants parse dynamic action. *Child Development* 2001;72:708–717. [PubMed: 11405577]
- Baldwin DA, Markman EM, Melartin RL. Infants' ability to draw inferences about nonobvious object properties: Evidence from exploratory play. *Child Development* 1993;64:711–728. [PubMed: 8339691]
- Baron-Cohen, S. *Mindblindness: An essay on autism and theory of mind*. Cambridge, MA: MIT Press; 1995.
- Bassili JN. Temporal and spatial contingencies in the perception of social events. *Journal of Personality and Social Psychology* 1976;33:680–685.
- Bayley, N. *Bayley scales of infant development*. New York: Psychological Corp; 1969.
- Bertenthal, BI.; Clifton, RK. Perception and action. In: Damon, W.; Kuhn, D.; Siegler, R., editors. *Handbook of child psychology: Cognition, perception, and language*. Vol. 2. New York: Wiley; 1998. p. 51-102.
- Brand RJ, Baldwin DA, Ashburn LA. Evidence for “motionese”: Modifications in mothers' infant-directed action. *Developmental Science* 2002;5:72–83.

- Brand RJ, Shallcross WL. Infants prefer motionese to adult-directed action. *Developmental Science* 2008;11:853–861. [PubMed: 19046154]
- Brand RJ, Shallcross WL, Sabatos MG, Massie KP. Fine-grained analysis of motionese: Eye gaze, object exchanges, and action units in infant- versus adult-directed action. *Infancy* 2007;11:203–214.
- Campos JJ, Anderson DI, Barbu-Roth MA, Hubbard EM, Hertenstein MJ, Witherington D. Travel broadens the mind. *Infancy* 2000;1:149–219.
- Cicchino JB, Rakison DH. Producing and processing self-propelled motion in infancy. *Developmental Psychology* 2008;44:1232–1241. [PubMed: 18793057]
- Cicchino, JB.; Rakison, DH. Infants' attribution of object-directed action to non-human animals. 2009. Manuscript submitted for publication
- Cohen, LB.; Atkinson, DJ.; Chaput, HH. Habit X: A new program for obtaining and organizing data in infant perception and cognition studies (Version 1.0). Austin: University of Texas; 2004.
- Cohen LB, Rundell LJ, Spellman BA, Cashion CA. Infants' perception of causal chains. *Psychological Science* 1999;10:412–418.
- Cohen LB, Younger BA. Infant perception of angular relations. *Infant Behavior and Development* 1984;7:37–47.
- Corrigan R. The acquisition of word connotations: Asking "What happened? *Journal of Child Language* 1994;31:381–398. [PubMed: 15495845]
- Csibra G, Gergely G, Bíró S, Koós O, Brockbank M. Goal attribution without agency cues: the perception of 'pure reason' in infancy. *Cognition* 1999;72:237–267. [PubMed: 10519924]
- Falck-Ytter T, Gredebäck G, von Hofsten C. Infants predict other people's action goals. *Nature Neuroscience* 2006;9:878–879.
- Fiser J, Aslin RN. Statistical learning of new visual feature combinations by infants. *Proceedings of the National Academy of Sciences of the United States of America* 2002;99:15822–15826. [PubMed: 12429858]
- Fiser, J.; Aslin, R.; Lathrop, A.; Rothkopf, C.; Markant, J. An infants' eye view of the world: Implications for learning in natural contexts. Paper presented at the Biennial International Conference on Infant Studies; Kyoto, Japan. 2006 Jul.
- French RM, Mareschal D, Mermillod M, Quinn PC. The role of bottom-up processing in perceptual categorization by 3- to 4-month-old infants: Simulations and data. *Journal of Experimental Psychology: General* 2004;133:382–397. [PubMed: 15355145]
- Gelman R. First principles to organize attention to and learning about relevant data: Number and the animate-inanimate distinction as examples. *Cognitive Science* 1990;14:79–106.
- Gelman, R.; Durgin, F.; Kaufman, L. Distinguishing between animates and inanimates: Not by motion alone. In: Sperber, D.; Premack, D.; Premack, AJ., editors. *Causal cognition: A multidisciplinary debate*. New York: Clarendon; 1995. p. 150-184.
- Gelman, R.; Spelke, ES. The development of thoughts about animate and inanimate objects: Implications for research on social cognition. In: Flavell, JH.; Ross, L., editors. *Social cognition*. New York: Academic Press; 1981. p. 43-66.
- Gelman, SA. *The essential child*. New York: Oxford University Press; 2003.
- Gelman SA, Gottfried G. Causal explanations of animate and inanimate motion. *Child Development* 1996;67:1970–1987.
- Gelman SA, Markman EM. Young children's inductions from natural kinds: The role of categories and appearances. *Child Development* 1987;58:1532–1541. [PubMed: 3691200]
- Gerson, S.; Woodward, AL. The effects of active vs. passive experience on infants' action understanding. Poster presented at the International Conference on Infant Studies; Vancouver, BC. 2008 Mar.
- Howard JH, Howard DV, Dennis NA, Kelly AJ. Implicit learning of predictive relationships in three-element visual sequences by young and old adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 2008;34:1139–1157.
- Hunter MA, Ames EW. A multifactor model of infant preferences for novel and familiar stimuli. *Advances in Infancy Research* 1988;5:69–95.

- Johnson SC, Shimizu YA, Ok SJ. Actors and actions: The role of agent behavior in infants' attribution of goals. *Cognitive Development* 2007;22:310–322. [PubMed: 18591991]
- Johnson SP, Slemmer JA, Amso D. Where infants look determines how they see: Eye movements and object perception performance in 3-month-olds. *Infancy* 2004;6:185–201.
- Jones SS, Smith LB. The place of perception in children's concepts. *Cognitive Development* 1993;8:113–139.
- Keil, FC. Concepts, kinds, and cognitive development. Cambridge, MA: MIT Press; 1989.
- Kirkham NZ, Slemmer JA, Johnson SP. Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition* 2002;83:B35–B42. [PubMed: 11869728]
- Kirkham NZ, Slemmer JA, Richardson DC, Johnson SP. Location, location, location: Development of spatiotemporal sequence learning in infancy. *Child Development* 2007;78:1559–1571. [PubMed: 17883448]
- Kosugi D, Ishida H, Fujita K. 10-month-old infants' inference of invisible agent: Distinction in causality between object motion and human action. *Japanese Psychological Research* 2003;45:15–24.
- Kotovskiy L, Baillargeon R. Reasoning about collisions involving inert objects in 7.5-month-old infants. *Developmental Science* 2000;3:344–359.
- Kovack-Lesh KA, Horst JS, Oakes LM. The cat is out of the bag: The joint influence of previous experience and looking behavior on infant categorization. *Infancy* 2008;13:285–307.
- Kovack-Lesh KA, Oakes LM. Hold your horses: How exposure to different items influences infant categorization. *Journal of Experimental Child Psychology* 2007;98:69–93. [PubMed: 17604048]
- Kuhl PK. Human adults and human infants show a “perceptual magnet effect” for the prototypes of speech categories, monkeys do not. *Perception & Psychophysics* 1991;50:93–107. [PubMed: 1945741]
- Kuhlmeier VA, Bloom P, Wynn K. Do 5-month-old infants see humans as material objects? *Cognition* 2004;94:95–103. [PubMed: 15302330]
- Lekowicz DJ. Perception of dynamic and static audiovisual sequences in 3- and 4-month-old infants. *Child Development* 2008;79:1538–1554. [PubMed: 18826541]
- Leslie AM. Infant perception of a manual pick-up event. *British Journal of Developmental Psychology* 1984;2:19–32.
- Leslie, AM. ToMM, ToBy, and Agency: Core architecture and domain specificity. In: Hirschfield, LA.; Gelman, SA., editors. *Mapping the mind: Domain specificity in cognition and culture*. New York: Cambridge University Press; 1994. p. 119–148.
- Leslie, AM. A theory of Agency. In: Sperber, D.; Premack, D.; Premack, AJ., editors. *Causal cognition: A multidisciplinary debate*. New York: Clarendon; 1995. p. 121–149.
- Leslie AM, Keeble S. Do 6-month-old infants perceive causality? *Cognition* 1987;25:265–288. [PubMed: 3581732]
- Luo Y, Kaufman L, Baillargeon R. Young infants' reasoning about physical events involving inert and self-propelled objects. *Cognitive Psychology* 2009;58:441–486. [PubMed: 19232579]
- Luo Y, Baillargeon R. Can a self-propelled box have a goal? Psychological reasoning in 5-month-old infants. *Psychological Science* 2005;16:601–608. [PubMed: 16102062]
- Madole KL, Oakes LM. Making sense of infant categorization: Stable processes and changing representations. *Developmental Review* 1999;19:263–296.
- Mahajan, N.; Woodward, AL.; Ridgeway, LE. Seven-month-old infants imitate animate but not inanimate agents. Poster presented at the International Conference on Infant Studies; Vancouver, BC. 2008 Mar.
- Mandler JM. How to build a baby II: Conceptual primitives. *Psychological Review* 1992;99:587–604. [PubMed: 1454900]
- Mandler JM. Perceptual and conceptual processes in infancy. *Journal of Cognition and Development* 2000;1:3–36.
- Mandler, JM. Conceptual categorization. In: Rakison, DH.; Oakes, LM., editors. *Early category and concept development: Making sense of the blooming, buzzing confusion*. London: Oxford University Press; 2003. p. 103–131.

- Mareschal D, French RM, Quinn PC. A connectionist account of asymmetric category learning in infancy. *Developmental Psychology* 2000;36:635–645. [PubMed: 10976603]
- Mareschal D, Quinn PC, French RM. Asymmetric interference in 3- to 4-month-olds' sequential category learning. *Cognitive Science* 2002;26:377–389.
- Markson L, Spelke ES. Infants' rapid learning about self-propelled objects. *Infancy* 2006;9:45–71.
- Massey CM, Gelman R. Preschoolers' ability to decide whether a photographed unfamiliar object can move itself. *Developmental Psychology* 1988;24:307–317.
- McRae K, Cree GS, Seidenberg MS, McNorgan C. Semantic feature production norms for a large set of living and nonliving things. *Behavioral Research Methods, Instrumentation, and Computers* 2005;37:547–559.
- McRae K, de Sa VR, Seidenberg MS. On the nature and scope of featural representations of word meaning. *Journal of Experimental Psychology: General* 1997;126:99–130. [PubMed: 9163932]
- Michotte, A. The perception of causality. London: Methuen; 1963.
- Monaghan P, Rowson C. The effect of repetition and similarity on sequence learning. *Memory & Cognition* 2008;36:1509–1514.
- Munakata Y, McClelland JL, Johnson MH, Siegler RS. Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review* 1997;104:686–713. [PubMed: 9337629]
- Newman GE, Hermann P, Wynn K, Keil FC. Biases towards internal features in infants' reasoning about objects. *Cognition* 2008;107:420–432. [PubMed: 18068151]
- Oakes LM. Development of infants' use of continuity cues in their perception of causality. *Developmental Psychology* 1994;30:869–879.
- Oakes LM, Cohen LB. Infant perception of a causal event. *Cognitive Development* 1990;5:193–207.
- Opfer JE. Identifying living and sentient kinds from dynamic information: The case of goal-directed versus aimless autonomous movement in conceptual change. *Cognition* 2002;86:97–122. [PubMed: 12435533]
- Pereira, AF.; James, KH.; Jones, SS.; Smith, LB. Active object exploration in toddlers and its role in visual object recognition. In: Love, BC.; McRae, K.; Sloutsky, VM., editors. *Proceedings of the 30th Annual Cognitive Science Society*. Austin, TX: Cognitive Science Society; 2008. p. 2410-2415.
- Pereira AF, Smith LB. Developmental changes in visual object recognition between 18 and 24 months of age. *Developmental Science* 2009;12:67–80. [PubMed: 19120414]
- Piaget, J. The child's construction of reality. London: Routledge & Kegan Paul; 1955.
- Poulin-Dubois D, Héroux G. Movement and children's attributions of life properties. *International Journal of Behavioral Development* 1994;17:329–347.
- Poulin-Dubois D, Lepage A, Ferland D. Infants' concept of animacy. *Cognitive Development* 1996;11:19–36.
- Premack D. The infants' theory of self-propelled objects. *Cognition* 1990;36:1–16. [PubMed: 2383967]
- Quinn, PC. Beyond prototypes: Asymmetries in infant categorization and what they teach us about the mechanisms guiding early knowledge acquisition. In: Kail, R.; Reese, H., editors. *Advances in child development and behavior*. Vol. 29. San Diego: Academic Press; 2002. p. 161-193.
- Quinn PC. Is the asymmetry in young infants' categorization of humans versus nonhuman animals based on head, body, or gestalt information? *Psychonomic Bulletin & Review* 2004;11:92–97. [PubMed: 15116992]
- Quinn, PC. Young infants' categorization of humans versus nonhuman animals: Roles for knowledge access and perceptual process. In: Gershkoff-Stowe, L.; Rakison, D., editors. *Building object categories in developmental time: 32nd Carnegie Mellon symposium on cognition*. Vol. 32. Mahwah, NJ: Erlbaum; 2005. p. 107-130.
- Quinn PC, Eimas PD. A reexamination of the perceptual-to-conceptual shift in mental representations. *Review of General Psychology* 1997;1:271–287.
- Quinn PC, Eimas PD. Evidence for a global categorical representation of humans by young infants. *Journal of Experimental Child Psychology* 1998;69:151–174. [PubMed: 9654437]

- Quinn PC, Eimas PD. The emergence of category representations during infancy: Are separate perceptual and conceptual processes required? *Journal of Cognition and Development* 2000;1:55–61.
- Quinn PC, Eimas PD, Rosenkrantz SL. Evidence for representations of perceptually similar natural categories by 3- and 4-month-old infants. *Perception* 1993;22:463–475. [PubMed: 8378134]
- Quinn PC, Lee K, Pascalis O, Slater AM. In support of an expert-novice difference in the representation of humans versus non-human animals by infants: Generalization from persons to cats occurs only with upright whole images. *Cognition, Brain, & Behavior* 2007;11:679–694.
- Quinn PC, Yahr J, Kuhn A, Slater AM, Pascalis O. Representation of the gender of human faces by infants: A preference for female. *Perception* 2002;31:1109–1121. [PubMed: 12375875]
- Rakison, DH. Parts, motion, and the development of the animate-inanimate distinction. In: Rakison, DH.; Oakes, LM., editors. *Early category and concept development: Making sense of the blooming, buzzing confusion*. London: Oxford University Press; 2003. p. 159-192.
- Rakison DH. Infants' sensitivity to correlations among static and dynamic features in a category context. *Journal of Experimental Child Psychology* 2004;89:1–30. [PubMed: 15336916]
- Rakison DH. A secret agent? How infants learn about the identity of objects in a causal scene. *Journal of Experimental Child Psychology* 2005a;91:271–296. [PubMed: 15869760]
- Rakison DH. Developing knowledge of objects' motion properties in infancy. *Cognition* 2005b; 96:183–214. [PubMed: 15996558]
- Rakison DH. Make the first move: How infants learn the identity of self-propelled objects. *Developmental Psychology* 2006;42:900–912. [PubMed: 16953695]
- Rakison, DH. Action facilitates causal perception in 4 -month-old infants. 2009. Manuscript under review
- Rakison DH, Butterworth GE. Infants' use of object parts in early categorization. *Developmental Psychology* 1998;34:1310–1325. [PubMed: 9823514]
- Rakison, DH.; Cicchino, JB. Induction in infancy. In: Johnson, SP., editor. *Neoconstructivism: A new science of cognitive development*. New York: Oxford University Press; 2009. p. 233-251.
- Rakison DH, Cohen LB. Infants' use of functional parts in basic-like categorization. *Developmental Science* 1999;2:423–431.
- Rakison DH, Lupyan G. Developing object concepts in infancy: An associative learning perspective. *Monographs of the Society for Research in Child Development* 2008;73:1–110.
- Rakison DH, Poulin-Dubois D. Developmental origin of the animate-inanimate distinction. *Psychological Bulletin* 2001;127:209–228. [PubMed: 11316011]
- Rakison DH, Poulin-Dubois D. You go this way and I'll go that way: Developmental changes in infants' detection of correlations among static and dynamic features in motion events. *Child Development* 2002;73:682–699. [PubMed: 12038545]
- Ramsey JL, Langlois JH, Marti NC. Infant categories of faces: Ladies first. *Developmental Review* 2005;25:212–246.
- Richards D, Siegler RS. Children's understandings of the attributes of life. *Journal of Experimental Child Psychology* 1986;42:1–22. [PubMed: 3772292]
- Sanderson PM, Scott JJP, Johnston T, Mainzer J, Wantabe LM, James JM. MacSHAPA and the enterprise of Exploratory Sequential Data Analysis (ESDA). *International Journal of Human-Computer Studies* 1994;41:633–681.
- Sarnecka BW, Kamenskaya VG, Yamana Y, Ogura T, Yudovina YB. From grammatical number to exact numbers: Early meanings of “one”, “two”, and “three” in English, Russian, and Japanese. *Cognitive Psychology* 2007;55:136–168. [PubMed: 17070794]
- Saxe R, Carey S. The perception of causality in infancy. *Acta Psychologica* 2006;123:144–165. [PubMed: 16905110]
- Saxe R, Tenenbaum JB, Carey S. Secret agents: Inferences about hidden causes by 10- and 12-month-old infants. *Psychological Science* 2005;16:995–1001. [PubMed: 16313665]
- Saxe R, Tzelnic T, Carey S. Knowing who dunnit: Infants identify the causal agent in an unseen causal interaction. *Developmental Psychology* 2007;43:149–158. [PubMed: 17201515]

- Saylor MM, Baldwin DA, Baird JA, LaBounty J. Infants' on-line segmentation of dynamic human action. *Journal of Cognition and Development* 2007;8:113–128.
- Schmitow, C.; Stenberg, G.; von Hofsten, C.; Grönqvist, H. Testing the wear-cam: A new tool for infant social studies. Poster presented at the Biennial International Conference on Infant Studies; Vancouver, BC. 2008 Mar.
- Shafro P, Coley JD. Development of categorization and reasoning in the natural world: Novices to experts, naïve similarity to ecological knowledge. *Journal of Experimental Psychology: Learning, Memory, & Cognition* 2003;29:641–649.
- Sheya A, Smith LB. Perceptual features and the development of conceptual knowledge. *Journal of Cognition and Development* 2006;7:455–476.
- Shimizu YA, Johnson SC. Infants' attribution of a goal to a morphologically unfamiliar agent. *Developmental Science* 2004;7:425–430. [PubMed: 15484590]
- Shutts, K.; Markson, L.; Spelke, ES. The developmental origins of animal and artifact concepts. In: Hood, B.; Santos, L., editors. *The origins of object knowledge*. Oxford: Oxford University Press; 2009. p. 189-210.
- Smith LB, Yu C, Pereira AF. Not your mother's view: The dynamics of toddler visual experience. *Developmental Science*. (in press).
- Sobel DM, Li J, Corriveau KH. They danced around my head and then I learned them": Children's developing conceptions of learning. *Journal of Cognition and Development* 2007;8:345–369.
- Sommerville, JA. Detecting causal structure: The role of interventions in infants' understanding of psychological and physical causal relations. In: Gopnik, A.; Schulz, LE., editors. *Causal learning: Psychology, philosophy and computation*. New York: Oxford University Press; 2007. p. 48-57.
- Sommerville JA, Hildebrand EA, Crane CC. Experience matters: The impact of doing versus watching on infants' subsequent perception of tool-use events. *Developmental Psychology* 2008;44:1249–1256. [PubMed: 18793059]
- Sommerville JA, Woodward AL. Pulling out the intentional structure of action: The relation between action processing and action production in infancy. *Cognition* 2005;95:1–30. [PubMed: 15629472]
- Sommerville JA, Woodward AL, Needham A. Action experience alters 3-month-olds' perception of others' actions. *Cognition* 2005;96:B1–B11. [PubMed: 15833301]
- Spelke, ES. Core knowledge. In: Kanwisher, N.; Duncan, J., editors. *Attention and Performance*, vol. 20: *Functional neuroimaging of visual cognition*. Oxford University Press; 2003.
- Spelke ES, Kinzler KD. Core knowledge. *Developmental Science* 2007;10:89–96. [PubMed: 17181705]
- Spelke, ES.; Phillips, A.; Woodward, AL. Infants' knowledge of object motion and human action. In: Sperber, D.; Premack, D.; Premack, A., editors. *Causal cognition: A multidisciplinary debate*. Oxford: Clarendon Press; 1995. p. 44-78.
- Thelen, E.; Smith, LB. *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press; 1994.
- Tremoulet PD, Feldman J. Perception of animacy from the motion of a single object. *Perception* 2000;29:943–951. [PubMed: 11145086]
- Werker JF, Cohen LB, Lloyd VL, Casasola M, Stager CL. Acquisition of word-object associations by 14-month-old infants. *Developmental Psychology* 1998;34:1289–1309. [PubMed: 9823513]
- White, PA. *The understanding of causation and the production of action: From infancy to adulthood*. Hove, Sussex: Lawrence Erlbaum Associates; 1995.
- Woodward AL. Infants selectively encode the goal object of an actor's reach. *Cognition* 1998;69:1–34. [PubMed: 9871370]
- Woodward, AL.; Sommerville, JA.; Guajardo, JJ. How infants make sense of intentional action. In: Malle, BF.; Moses, LJ.; Baldwin, DA., editors. *Intentions and intentionality: Foundations of social cognition*. Cambridge, MA: MIT Press; 2001. p. 149-169.
- Yoshida H, Smith LB. What's in view for toddlers? Using a head camera to study visual experience. *Infancy* 2008;13:229–248. [PubMed: 20585411]

- Younger BA, Cohen LB. Developmental change in infants' perception of correlations among attributes. *Child Development* 1986;57:803–815. [PubMed: 3720405]
- Younger BA, Furrer SD. A comparison of visual familiarization and object-examining measures of categorization in 9-month-old infants. *Infancy* 2003;4:327–348.

Figure 1a



Figure 1b

**Figure 1.**

Figure 1a. Frame from the beginning of an agent-recipient relation event in which the infant reaches for a toy.

Figure 1b. Frame from an agent-recipient relation event in which an adult reaches for a toy.

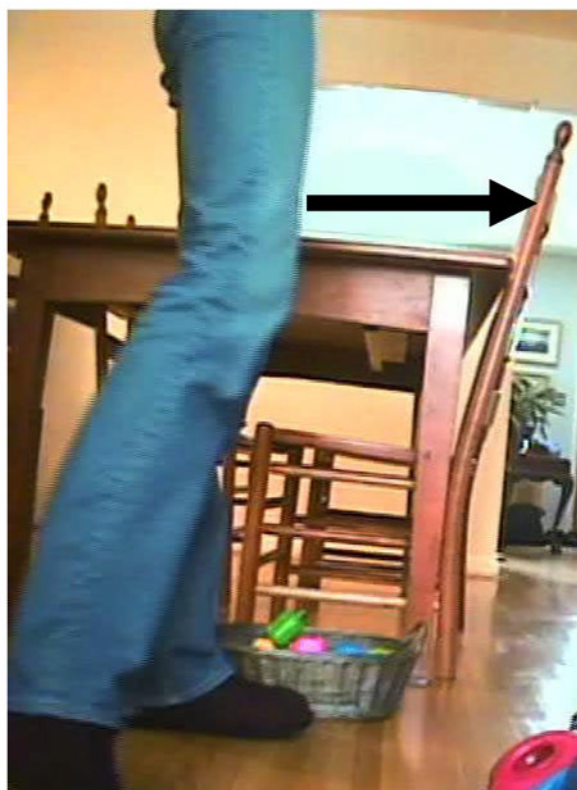


Figure 2.
Frame from the beginning of a self-propelled event. The arrow denotes direction of motion

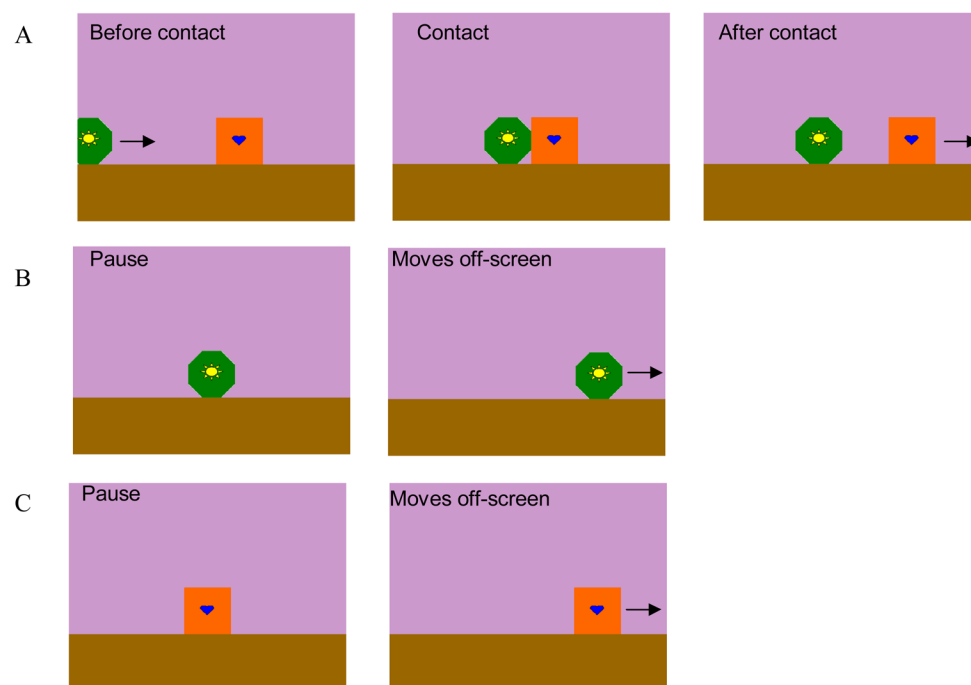


Figure 3. Schematic of habituation event (A), *consistent* test event (B), and *inconsistent* test event (C) shown to infants in Experiment 1.

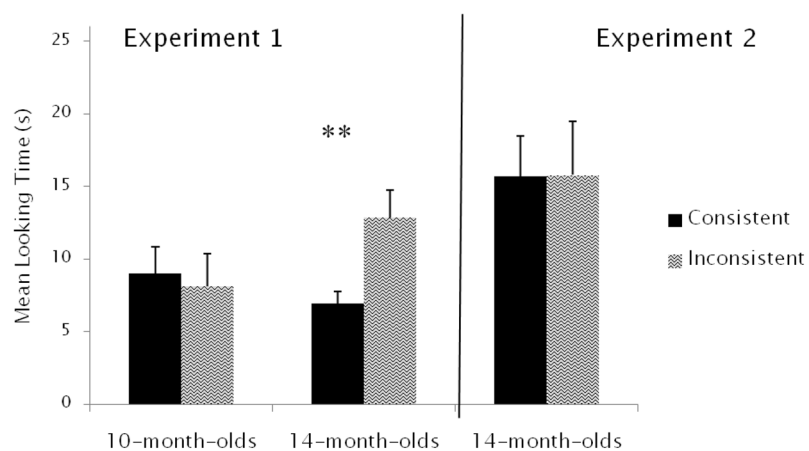


Figure 4. Looking times and standard errors to the test events in Experiments 1 and 2, averaged across test trial pairs. ** $p < .01$

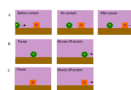


Figure 5. Schematic of habituation event (A), *consistent* test events (B), and *inconsistent* test events (C) shown to infants in Experiment 2.

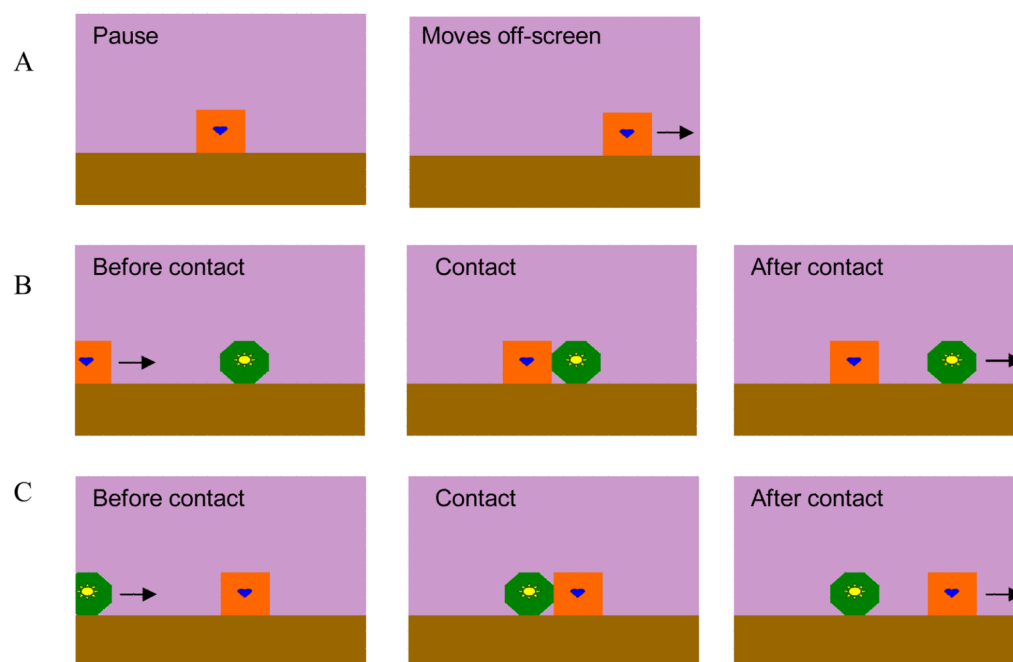


Figure 6. Schematic of habituation event (A), *consistent* test event (B), and *inconsistent* test event (C) shown to infants in Experiment 3.

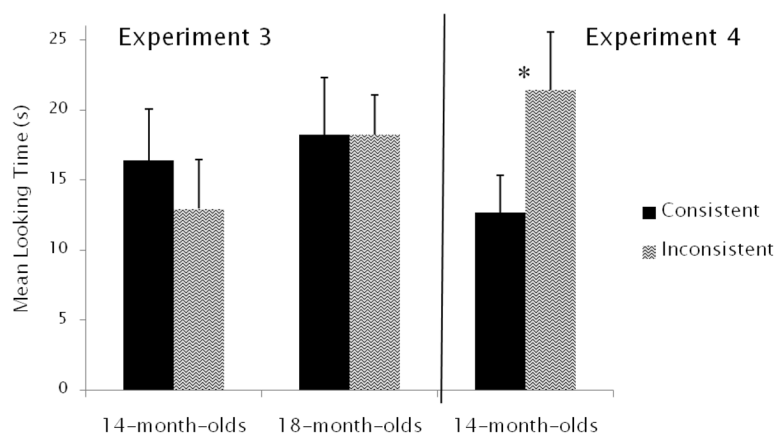


Figure 7. Looking times and standard errors to the test events in Experiments 3 and 4, averaged across test trial pairs.

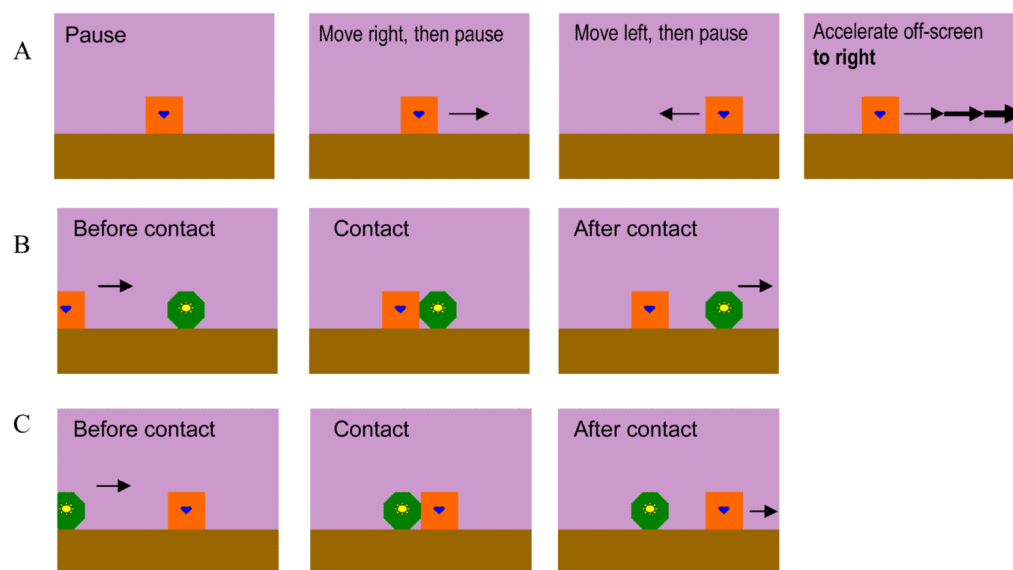


Figure 8. Schematic of habituation event (A), *consistent* test event (B), and *inconsistent* test event (C) shown to infants in Experiment 4.

Table 1

Summary of theoretical views regarding infants' generalizations between causal agency and self-propulsion.

<i>Theorist</i>	<i>View</i>	What Does It Say That Would Affect How Infants Generalize?	Prediction for Generalization
Leslie (1994, 1995)	Modular view of causal perception; Objects with own source of energy are Agents	Agents in causal events are not "Agents" because they do not exhibit own source of energy; Self-propelled objects are Agents	No generalization; neither an agent nor recipient is more likely to be self-propelled
Premack (1990)	Innate attribution of intentionality to self-propelled objects	Says nothing about causal agents	No prediction
Gelman et al., 1995	Skeletal causal principles guide early learning about objects' internal or external energy sources	Autonomous motion alone is not enough to attribute animacy	No generalization if self-propelled motion is not presented in an informative context
Baillargeon et al. (2009), Luo et al. (2009)	Same as Gelman: Skeletal causal principles guide early learning about objects' internal or external energy sources	Infants expect that objects are inert unless given unambiguous evidence that they are self-propelled	No generalization; infants expect agents to be inert
Spelke (2003)	Core knowledge of agents and their actions	Infants have innate knowledge of the ways in which animates move	Generalization in both directions; knowledge that animates are agents in causal events and are self-propelled is embedded in the same core knowledge system
Mandler (1992)	Specialized process called perceptual analysis leads infants to form conceptual representations of animate motion	Infants have rich, conceptual knowledge of animates and their motion properties	Generalization in both directions; knowledge that animates are agents in causal events and are self-propelled is embedded in same conceptual representation of animacy
Madole & Oakes (1999), Quinn & Eimas (1997), Rakison & Lupyan (2008)	Associative learning	Strength of representation for causal agency and self-propulsion is based on the amount of experience infants have viewing these events	Generalization is asymmetric; if infants have stronger representation for causal events than for self-propelled events, they will generalize that agents are self-propelled before they generalize that self-propelled objects are agents

Table 2

Frequency (reported as instances per hour) and duration (reported as percent of total footage) of the infant's viewing of people and inanimate objects engaged in different motion events, aggregated across the three age points. Note that the infant could have more than one action in his visual field at once (e.g., two hands reaching for objects concurrently) and that the sum of the durations of all of these events is included in the above percentages.

	<u>Frequency (instances/hr)</u>		<u>Duration (% of total footage coded)</u>	
	<i>People</i>	<i>Inanimate Objects</i>	<i>People</i>	<i>Inanimate Objects</i>
Agent-Contact	158.64	5.73	9.29	0.16
Self-Propelled	54.34	6.03	3.68	0.23

Table 3

Frequency (reported as instances per hour) and duration (reported as percent of total footage) of the infant's viewing of people engaged in different motion events, separated by age.

Agent	<i>3 months</i>	348.79	16.84
	<i>8 months</i>	620.19	32.80
	<i>12 months</i>	818.96	36.32
Self-Propelled (all)	<i>3 months</i>	38.18	1.92
	<i>8 months</i>	80.52	6.14
	<i>12 months</i>	45.33	3.03
Self-Propelled (in home only)	<i>3 months</i>	20.61	0.91
	<i>8 months</i>	28.19	2.04
	<i>12 months</i>	44.61	3.11