Infants' expectations about motion properties of objects:

The role of sequence representations in generalization

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Abstract

Motion cues such as agency and self-propulsion are considered central to infants' developing ability to distinguish animate and inanimate entities. Although infants' ability to encode these properties and attribute them to the appropriate classes of entities has been well-documented, no consensus exists regarding how infants represent these motion properties and generalize between them. The present work sought to address these issues: it expands on prior research on infants' generalization about motion, proposes a new account of generalization, and rigorously evaluates the account using experimental and observational methods.

The first set of studies presented herein examined infants' ability to generalize about stopping, which is a motion property that can distinguish animates from inanimates (only the former can stop abruptly without an external force) and has not been studied previously. In particular, the studies examined infants' ability to form expectations about stopping based on other motion properties typically attributed to animates and inanimates, namely, agency and recipiency. In Experiments 1 and 2, infants were habituated to a causal event and shown test events in which the agent and the recipient stopped gradually or abruptly. The results of Experiment 1 showed that 12- and 16-month-old infants looked longer at an agent that stopped gradually than one that stopped abruptly, indicating the presence of expectations for the manner of stopping of agents but not recipients. The results of Experiment 2 showed that 14-month-old infants did not have expectations about either agents or recipients. This U-shaped developmental trajectory may have been due to the different types of information that 12- and 16-month-olds encoded. When causal role information was removed in Experiment 3, 12-month-olds' behavior remained similar to their behavior in Experiment 1, which implied that they may have attended to something other than causal roles during habituation. Finally, the results of Experiment 4

showed that the addition of a self-propulsion cue that correlated with agency did not induce 14-month-old infants to generalize about stopping. Taken together, these studies demonstrate that the development of expectations about stopping emerges within the second year of life.

The second set of studies was designed to test a new theoretical account of the foundation of infants' generalization. The account posited that infants' generalization about motion is dependent on their ability to learn sequential motion information from their environment. Experiment 5 tested the prediction that infants' experience with motion sequences constrains their learning such that they learn sequences that are consistent with their experience but not those that are inconsistent. The results of the experiment confirmed the prediction and demonstrated a developmental change in the emergence of experience-based constraints: whereas 12-month-olds showed similar learning regardless of sequence type, 16-month-olds only learned sequences consistent with their experience. The Observational Study examined the theoretical account further by quantifying infants' daily experience with motion. Specifically, the study examined which regularities in infants' environments are sufficient to give rise to generalization: regularities in the frequency of individual events, in the frequency of event pairs, or in the transitional probability within event pairs. The results suggested that the frequency of event pairs provides the information that agrees most closely with infants' behavioral patterns.

Taken together, the studies reported herein make significant contributions to the existing research on infants' generalization. Specifically, they provide new evidence regarding the extent of these abilities and they clarify the mechanism that enables infants to form such expectations. Furthermore, the studies demonstrate that the regularities in infants' environments are sufficient to support generalization about animate and inanimate properties, which implies that specialized mechanisms may not be necessary for the emergence of the animate/inanimate distinction.

Infants' expectations about motion properties of objects: The role of sequence representations in generalization

The development of generalization, or the ability to extend previously-learned information to new objects, people, or situations, is critical for infants because it reduces the amount of new information that they need to encode when faced with a context that is unfamiliar in some respect. For example, when faced with a new person, the ability to generalize may help the infant to lower the burden of processing all of the new input by extending previously-learned information to this person, such as the fact that people tend to act in a goal-directed manner. Although there are dozens of studies on early generalization that have demonstrated infants' ability to generalize in a variety of contexts, there is no consensus about the mechanisms and representations that underpin these abilities, particularly in the context of generalization about properties of animates and inanimates. The goal of the present work was to extend the existing research on infants' ability to generalize about motion properties of animates and inanimates, to develop a new theoretical account of this ability that provides a better explanation of the empirical findings than previous accounts, and to evaluate this new theoretical account with empirical and observational work.

Coherent Representations of Complex Information

Young children's early environments are rich with a variety of sensory input. For example, Franchak, Kretch, Soska, and Adolph (2011) found that in unstructured interactions between mother-infant dyads, mothers vocalized at an average rate of 8.1 utterances per minute. These utterances presented diverse pieces of information: 19.6% named specific objects in the child's environment, 15.8% referred to objects without naming them, and the majority of utterances, 64.7%, did not have a referent. Similarly, an analysis of a subset of over 16,000 utterances produced by mothers during interactions with their children from the CHILDES

corpus found that only 15% of the utterances had a subject-verb-object structure, with the rest of the utterances exhibiting diverse structures such as questions (32%) and imperatives (9%) (Cameron-Faulkner, Lieven, & Tomasello, 2003). Children's early visual environments are similarly rich. For example, an analysis of a 12-month-old infant's visual environment from video that was collected by a head-mounted camera worn by the infant has shown that he was experienced over 800 instances of causal agency per hour and over 40 instances of self-propulsion (Cicchino, Aslin, & Rakison, 2011). The content of children's visual input can shift very rapidly: in a simple laboratory task where 21- to 24-month-old children and their parents interacted with just 3 objects, the dominating object in the child's view, as determined from video collected by a head-mounted camera, changed on average 12.8 times per minute (Yu, Smith, Shen, Pereira, & Smith, 2009). In a non-laboratory setting, which may have many more objects, such frequent switching of attention could expose children to a vast variety of objects in a very short period of time.

Despite the volume and complexity of the information to which infants and young children are exposed, they exhibit the ability to form coherent representations of this information at an early age and to extend these representations to new contexts. One categorical distinction that emerges early on in infancy is that of animate and inanimate entities (Rakison & Poulin-Dubois, 2001). This distinction has been referred to by some as foundational (Opfer & Gelman, 2011), particularly due to its presence across languages (Diesendruck, 2003). Infants as young as two days old can distinguish point-light displays of biological motion (a walking hen) from non-biological motion (random dot motion), and prefer the former to the latter (Simion, Regolin, & Bulf, 2008). Furthermore, they are sensitive to directional violations of this motion and look longer at upright rather than inverted biological motion. Three- and four-month-old infants can form a category of mammals that excludes furniture, and a category of furniture that excludes

mammals in a visual habituation procedure (Behl-Chadha, 1996). In the second year of life, infants can form distinct categories of animals and vehicles (Mandler, Bauer, & McDonough, 1991; Rakison & Butterworth, 1998).

A number of static and dynamic properties can help to distinguish between animate and inanimate entities. For example, a reindeer can be distinguished from its sleigh by the presence of legs and eyes, as well as the ability to move without an external influence (Grüner, 1929). Infants are sensitive to such properties within the first two years of life. For example, 18-month-olds' categorization of animals and vehicles has been shown to be dependent on the differential parts that these two categories possess: legs and wheels, respectively (Rakison & Butterworth, 1998). Similarly, this distinction can be supported by dynamic properties (Rakison & Poulin-Dubois, 2001). For example, animates tend to be self-propelled, follow non-linear patterns of motion, and tend to exhibit contingent interaction. In contrast, inanimates tend to be caused to move, tend to exhibit linear motion, and do not engage in contingent interaction. Infants have been shown to be sensitive to how these dynamic properties correlate with animate and inanimate categories. For example, 6- and 9-month-old infants associate human hands but not similarly-structured inanimate objects with goal-directed action (Woodward, 1998). Seven-month-olds show the ability to learn that an entity is self-propelled if the entity has animate features, but fail to do so if the entity has inanimate features (Markson & Spelke, 2006). Within the first year of life infants can also generalize previously-unobserved properties to entities based on their animacy status. Saxe, Tzelnic, and Carey (2007) have shown that 7- and 10-month-old infants expect the motion of an inanimate object to have been caused by a human hand but not a toy train, demonstrating that infants expect animate, but not inanimate objects to cause the motion of inanimate objects.

In addition to demonstrating expectations about dynamic properties of entities based on

observed animate or inanimate featural information, infants can also generalize dynamic properties of animates and inanimates based solely on observed dynamic properties. That is, upon observing an entity display one dynamic property that is associated with either animates or inanimates, infants can form an expectation about another dynamic property that is similarly associated with the same class of entities. For example, Luo, Kaufman, and Baillargeon (2009) found that 5-month-old infants expect a self-propelled box to reverse direction on its own, but they do not expect an inert box to do so. Similarly, Johnson, Shimizu, and Ok (2007) demonstrated that 12-month-old infants expect an ambiguous object to be goal-directed if it interacts contingently with an experimenter by beeping when the experimenter speaks to it; in contrast, 12-month-olds do not expect it to be goal-directed if it remains silent when the experimenter speaks. Finally, Cicchino et al. (2011) showed that 14-month-old infants expect the agent in a causal launch event, but not the recipient, to be self-propelled. Taken together, these studies demonstrate that infants are able to associate static and dynamic properties that are typically attributed to animates and inanimates, as well as the ability to associate pairs of dynamic properties. Furthermore, they show that infants can form expectations about one motion property when given information about another motion property. Numerous theories have been developed to explain the mechanism or mechanisms that underpin these abilities. These are discussed in the following section.

Theories on Infants' Sensitivity to the Distinction between Animates and Inanimates

Theories of early conceptual development, particularly the development of concepts of animates and inanimates, can roughly be grouped into two classes. The first class posits that the development of concepts in infants and young children is supported by domain-specific mechanisms; that is, mechanisms that are specifically targeted to acquire information for a specific area of knowledge. For example, Kinzler and Spelke (2007) have argued that infants'

concepts of objects, people, number, and geometry are supported by four distinct core knowledge systems. Typically, domain-specific mechanisms are thought to be operational at birth or triggered soon after. The second class posits that conceptual development is supported by domain-general mechanisms; that is, the same mechanisms allow infants to acquire information regardless of area of knowledge. For example, Rogers and McClelland (2004) have demonstrated that a mechanism that learns consistent covariation patterns of features in the input can explain infants' ability to learn labels or to form categories of plants and animals.

Domain-specific theoretical approaches. As discussed above, according to domain-specific theories of conceptual development, specialized mechanisms are necessary for the acquisition of particular types of knowledge. Thus, infants need distinct systems to acquire information about animates and inanimates, distinct from other areas of knowledge. These systems have been formulated in a variety of ways by different researchers, with the primary differences stemming from the number of systems proposed and the features of the input that are thought to be processed by each system. For example, Premack (1990) suggested that infants divide the world into entities that change motion states on their own and those that change motion states by external influence. This distinction is made based on an innate module that is activated by the perception of self-propulsion. When self-propulsion is detected in the input, the interpretation of intentionality and animacy for the self-propelled entity is activated. Leslie (1994, 1995) has proposed a similar account in which the perception of the source of an entity's change in motion is central to the interpretation of the entity as possessing characteristics of animates or inanimates. According to this account, infants have three innate hierarchically-arranged modules that are dedicated to the understanding of mechanical properties of events, goal-directedness, and mental states. The first of these modules attributes internal energy to entities that are observed to change motion states on their own and classifies such entities as

agents, or animate beings; conversely, entities that that are observed to change motion states as a result of an external force are judged to lack internal energy. In contrast to Premack and Leslie who have focused on the source of motion as the foundation of the detection of agency and animacy, Gergely (2011; see also Bíró, Csibra, & Gergely, 2007; Csibra, Gergely, Bíró, Koós, and Brockbank, 1999) has argued that it is instead based on the detection of efficient or rational action. According to this account, infants have a specialized *teleological action representation and interpretation system* that applies principles of rationality and efficiency to interpret observed actions. If an entity is judged to be acting in a rational and efficient manner given the constraints of the environment, then it is judged to be an *instrumental agent*, or an entity that can act on the world to bring about desired outcomes, a characteristic typically attributed to animates.

The above accounts have all proposed a single dedicated system that detects a particular kind of information in the environment to support the development of animate and inanimate concepts. Other theorists have proposed even further domain-specificity with separate systems for the detection of information that is relevant for animates and inanimates. For example, Gelman (1990; Gelman, Durgin, & Kaufman, 1995) has suggested that infants possess separate innate skeletal principles for animates and inanimates that draw infants' attention to the relevant properties of those categories. The *innards-principle guides* infants' attention to properties that help to identify animates, which have an internal source of energy that allows them to move on their own. In contrast, the *external-agent principle* guides infants' attention to the relevant properties to identify inanimates, which do not have an internal energy source and rely on external forces to convert potential energy into kinetic energy. Similarly, Kinzler and Spelke (2007; see also Spelke, 2003, Spelke & Kinzler, 2007) have proposed separate innate core systems for the processing of information about objects and agents. These systems manipulate different types of information from the environment: the system that is dedicated to objects

processes information about spatiotemporal principles of motion such as movement along

continuous trajectories, and the system that is dedicated to agents processes a different set of

information such goal-directedness or contingency in interaction. Finally, Baillargeon and

colleagues (Baillargeon, Li, Ng, & Yuan, 2009; Luo et al., 2009; Wang & Baillargeon, 2007)

have suggested that infants possess a specialized *physical reasoning system* that interprets

physical interactions between objects using core knowledge about physical properties of the

world; this system is separate from a system that allows infants to interpret psychological events

involving agents.

Despite the variability in exact specification, the domain-specific theories reviewed

above all share an underlying core that infants' concepts of animates and inanimates are based on

the work of one or several dedicated mechanisms that only operate on the information that is

relevant to the animate/inanimate distinction. What is the foundation for positing the need for

such specialized mechanisms? First, evidence that knowledge of animates and inanimates could

be selectively impaired following brain damage has been used to suggest that distinct neural

mechanisms have evolved to support the processing of these two categories (Caramazza &

Shelton, 1998; Warrington, 1981). Second, proponents of domain-specific mechanisms have

argued that the input available to infants regarding animates and inanimates is ambiguous,

intermittent, and unconstrained, with no clear indication of which properties are relevant for the

animate/inanimate distinction (Baillargeon & Carey, 2012; Gelman et al., 1995; Keil, 1991,

1994). Thus, skeletal structures or core knowledge systems are necessary to constrain this

information and drive infants' attention to the relevant properties of the input. It is only with

such innate constraints that infants would learn the properties associated with animates and

inanimates and display the expectations regarding those properties that have been found in the

empirical work reviewed above.

Domain-general theoretical approaches. Unlike domain-specific approaches, domain-general theories of conceptual development posit that the formation of concepts is underwritten by the same general mechanisms across areas of knowledge and modalities such as habituation, associative learning, and conditioning. Proponents of the domain-general approach have argued that infants gradually develop the ability to form associations between various properties of entities that surround them and it is based on this associative learning that the distinction between animates and inanimates emerges (Eimas, 1994; Madole & Oakes, 1999; Quinn & Eimas, 1996; Rakison & Lupyan, 2008; Rogers & McClelland, 2004). Initially, infants are capable of learning associations between static features, such as the particular parts of an animal (e.g., Younger & Cohen, 1986). As infants' information-processing abilities improve, they develop the ability to form associations between static and dynamic properties, such as the appearance of an object part and its function (Madole & Cohen, 1995), and between pairs of dynamic properties of objects, such as the presence of a moving part on an object and motion properties like causal agency (Rakison, 2005) and self-propulsion (Rakison, 2006). As discussed above, animate and inanimate entities possess distinct clusters of properties, particularly with respect to their motion characteristics. Over time, infants attend to and encode the property correlations that are characteristic of animates and inanimates and thereby develop distinct representations of the two categories. Thus, according to the domain-general perspective, infants' representations of animates and inanimates are the result of a general associative learning mechanism that allows them to learn clusters of features that co-occur for those categories. Infants' differential responses to animates and inanimates in laboratory tasks therefore are not supported by conceptual knowledge of the meaning of animacy (e.g., understanding that animates have a renewable energy source as suggested by Leslie (1994, 1995) and Gelman (1990)), but rather by a representation of perceptual information. Crucially, infants' associative

learning about properties of animate and inanimate entities does not differ from associative learning in other domains such as language or number.

A discussed above, two arguments are commonly presented in support of the domain-specific view of conceptual development: the apparent presence of categorical knowledge in the brain, and the unconstrained nature of the input. How do domain-general theories respond to these arguments? First, with respect to knowledge representation in the brain, more recent arguments have been made for distributed networks of semantic knowledge based on findings that categorical knowledge impairments need not arise from consistent patterns of damage (Humphreys & Forde, 2001). Second, with respect to the need for constraints on the multitude of correlations that are available to infants, these constraints need not be specified innately and can emerge as a result of domain general learning or broad patterns of maturation that are not unique to a particular domain of knowledge (Madole & Oakes, 1999; Rakison & Lupyan, 2008; Rakison & Yermolayeva, 2011; Sloutsky, 2010). Madole and Oakes (1999) and Rakison and colleagues (Rakison & Lupyan, 2008; Rakison & Yermolayeva, 2011) have argued that as young children are exposed to consistent experiences throughout their development, these experiences come to constrain their subsequent learning such that only information that is consistent with prior experience is encoded. Thus, infants do not need innate constraints to assist them in attending to the relevant properties of the input. Such constraints can emerge over time as a result of consistent input. For example, Rakison (2006) has shown that 18-month-old infants associate a moving part of an object with the object's self-propulsion and a static part with its self-propulsion. In contrast, 20-month-olds only encode the association between a moving part and self-propulsion, which may be due to their consistent real-world experience that self-propelled entities tend to have moving rather than static parts. This example demonstrates how attention to the relevant features of animates can emerge as a result of experience. Over time infants see

many correlations between self-propulsion and moving parts and few correlations between self-propulsion and static parts, so they encode the former but not the latter correlation, and begin to attend to this correlation in their input, which happens to be a reliable cue for distinguishing animate and inanimate entities. Importantly, the emergence of such experience-based constraints is not limited to learning about animates and inanimates and has been found in other domains such as speech perception or learning social cues such as gesture (for a review, see Rakison & Yermolayeva, 2011).

In addition to experience-based constraints, the acquisition of relevant information for conceptual development can be influenced by general maturation-based constraints. Infants' developing perceptual and motor skills alter their perception of the world and the information that is available to them (Madole & Oakes, 1999). For example, the emergence of the ability to manipulate objects is related to infants' perception of goal-directedness (Sommerville, Woodward, & Needham, 2005) and causal agency (Rakison & Krogh, 2012), both properties of animates. Interventions that allow infants to manipulate objects at an earlier age cause earlier perception of goal-directedness and causal agency. Similarly, the commencement of crawling has been related to the recognition of self-propulsion in visual events (Cicchino & Rakison, 2008). Neural development can also function to constrain available input and alter children's ability to attend to relevant features (Sloutsky, 2010). Specifically, the maturation of the prefrontal cortex, which undergoes a protracted development relative to other areas of the brain (Casey, Tottenham, Liston, & Durston, 2005; Huttenlocher & Dabholkar, 1997), allows for the emergence of executive control, enabling children to focus on features that may be relevant for distinguishing different classes of objects. Thus, as children mature, their physical development may change their experience and their neural development may change the information to which they are able to attend; these forces can operate jointly to allow children to learn the relevant

features for the distinction between animates and inanimates, without the need for the specification of innate guiding principles. As with experience-based constraints on learning, maturation-based constraints are similarly domain-general. For example, the emergence of coordinated object manipulation not only changes infants' perception of goal-directedness and causal agency, but also their 3D object completion, or the perception that objects that are only seen from the front have a back side (Soska, Adolph, & Johnson, 2010). Similarly, the development of the prefrontal cortex allows for the direction of attention to the relevant features of categories regardless of category domain (Sloutsky, 2010).

A recent series of studies by Cicchino et al. (2011) pitted the domain-general account against the domain-specific account and provided strong evidence for the former. Specifically, Cicchino et al. hypothesized that according to the domain-general account, infants' experience in the world should govern their generalization of properties attributed to animates and inanimates. In contrast, according to the domain-specific account, infants' experience in the world should be less related or unrelated to their generalization abilities as those are supported by innate mechanisms or skeletal principles. In the experimental portion of the work, the authors showed that infants display an asymmetry in their generalization between causal agency and self-propulsion: at 14 months, infants expect causal agents but not causal recipients to be self-propelled, but they do not have expectations about the causal roles of self-propelled objects. In the observational portion of the work, the authors collected data on infants' visual experience through a camera worn by an infant during a range of daily activities. These data showed that infants receive much more experience with causal agency than self-propulsion. From the domain-general perspective, the observational data on infants' experience provide an explanatory clue for the asymmetry in generalization that is found in the behavioral data. Infants' greater experience with causal agency than with self-propulsion allows them to form a stronger

representation of the former than the latter. The authors argued that a stronger representation can support expectations about a weaker representation, but not vice versa. From the domain-specific perspective, however, the experimental data are difficult to explain. Visual input regarding agency and self-propulsion should be equally likely to activate skeletal principles, modules, or core knowledge systems of animacy, which would, in turn, activate other properties of animates. Thus, it is unlikely that an asymmetry would be observed. Cicchino et al.'s behavioral and observational findings suggest that the domain-general approach to explaining theoretical development may be more appropriate than the domain-specific approach. The present work seeks to expand on these findings and to examine further the domain-general account of conceptual development.

Present Experimental and Observational Work

The experimental and observation studies reported below sought to probe infants' generalization abilities further with respect to another motion property that can distinguish animates and inanimates, to provide a mechanistic account of infants' generalization abilities from the domain-general perspective that revises and extends that of Cicchino et al., and to evaluate this account with empirical and observational data.

Further assessment of infants' generalization abilities. Previous work on infants' generalization about dynamic properties of animates or inanimates has primarily focused on causal agency (e.g., Cicchino et al., 2011; Saxe et al., 2007), self-propulsion (e.g., Luo et al., 2009; Cicchino et al., 2011), and goal-directedness (e.g., Johnson et al., 2007). The present set of experiments expands on this work by studying infants' generalization about stopping properties of animates and inanimates. Animate entities are considered to have an internal renewable source of energy, whereas inanimate entities lack such a source (Gelman, 1990; Leslie, 1994). Based on this energy, animates can sustain their motion and stop abruptly at will without an external

influence, whereas inanimates stop abruptly only when physically contacted by another entity and otherwise gradually reduce their speed with a constant deceleration. The experiments discussed herein assess whether infants associate different stopping properties of animates and inanimates with their different causal roles. Specifically, Experiment 1 addressed this question with 12- and 16-month-old infants using a design similar to that of Cicchino et al. (2011). Infants were habituated to a casual event in which one ball, the agent, contacted another ball, the recipient, and caused it to move. Subsequently, infants viewed test events in which the agent or the recipient stopped abruptly or gradually, which provided information regarding infants' expectation of stopping properties of agents and recipients. Experiment 2 used the same procedure as Experiment 1 but with 14-month-old infants to plot the developmental trajectory in infants' expectations between 12 and 16 months. Experiment 3 was conducted to control for a perceptual confound found in Experiments 1 and 2. Finally, Experiment 4 was conducted to assess if the presence of an additional cue to animacy, self-propulsion, along with causal agency assists infants in forming expectations about stopping. Taken together, Experiments 1 through 4 add to the existing literature on infants' developing abilities to form expectations about dynamic properties typically attributed to animates and inanimates based on observed dynamic information.

Revised domain-general theoretical account of generalization. The empirical work presented in Experiments 1 through 4, as well as a reanalysis of the theoretical account proposed by Cicchino et al. (2011) raises an alternative theoretical explanation of infants' behavior that provides a mechanism by which generalization between two dynamic properties may occur. Cicchino et al.'s account focuses on infants' ability to form separate representations of agency, recipiency, and self-propulsion based on their experience, and it suggests that the apparent asymmetry in generalization is due to the unequal representation strengths of these concepts.

However, the account does not specify a mechanism by which the observation of one dynamic property allows the infant to form expectations about another dynamic property. To explain this mechanism, a new theoretical account is presented below that suggests that infants attend to sequential information regarding motion properties and form representations of the next likely motion properties given information about the current motion property. As a result, when one motion property is presented, infants form expectations about the motion properties that tend to follow. Note that this account is domain-general like that of Cicchino et al. and capitalizes on infants' ability to learn the distributional statistics of the input, which has been demonstrated for other domains such as language (e.g. Saffran, Aslin, & Newport, 1996). Crucially, previous work has shown that when frequency information is pitted against information about likelihood of sequential input, infants encode information about likelihood rather than frequency (Aslin, Saffran, and Newport, 1998). Thus, the proposed theoretical account not only aims to dig deeper with respect to a mechanistic analysis of infants' generalization about motion properties, it is also more consistent with prior findings on the types of statistical regularities that infants extract from their input.

Evaluation of the revised theoretical account. The final component of the work presented below is an evaluation of the proposed theoretical account. This is accomplished in two ways: with a behavioral experiment and an observational study. The behavioral experiment, Experiment 5, was conducted to assess if infants at 12 and 16 months are able to learn sequences of motion events studied by Cicchino et al. (2011), causal agency and self-propulsion, and if infants are more likely to learn a particular order of the two events. Specifically, if infants generalize from causal agency to self-propulsion but not the reverse, then infants in Experiment 5 were expected to learn a sequence of causal agency followed by self-propulsion but not self-propulsion followed by causal agency. Additionally, the theoretical account was evaluated using

an observational study to determine if infants do, in fact, see consistent sequences of motion events. In particular, based on infants' behavior in Cicchino et al.'s experiments, it was predicted that infants should be more likely to experience causal agency followed by self-propulsion than self-propulsion followed by causal agency. Taken together, the observational study and the behavioral experiment provide a two-pronged approach to evaluating the new theoretical account of infants' generalization: they measure the information that is available to infants and assess whether or not infants are capable of learning that information.

<div align="center">

Experiment 1

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Animate entities possess a renewable source of internal energy that inanimates lack (Gelman, 1990; Leslie, 1994). This renewable energy source governs many of their motion properties such as the ability to cause the motion of other entities and to stop at will without an external influence. In contrast, inanimates require external action to start and to stop without gradual deceleration. The first experiment reported here was designed to establish if 12- and 16-month-old infants are sensitive to these differences in motion typically associated with animates and inanimates, and if they can generalize stopping properties to objects based on their causal roles. To address this, infants were habituated to a causal launch event in which one ball contacted another ball and set it in motion. Infants were tested with test events in which each ball seen during habituation bounced to an abrupt or a gradual stop on screen. It was predicted that if infants can generalize from causal roles to stopping, then they should display elevated looking when the typical stopping pattern for agents and recipients is violated in the test phase.

Method

Participants. Twenty-eight 12-month-old infants and twenty-eight 16-month-old infants were recruited to participate in the study. All infants were healthy and full-term. Four infants were excluded from the 12-month-old group: 2 for fussiness and 2 for failure to habituate. Four
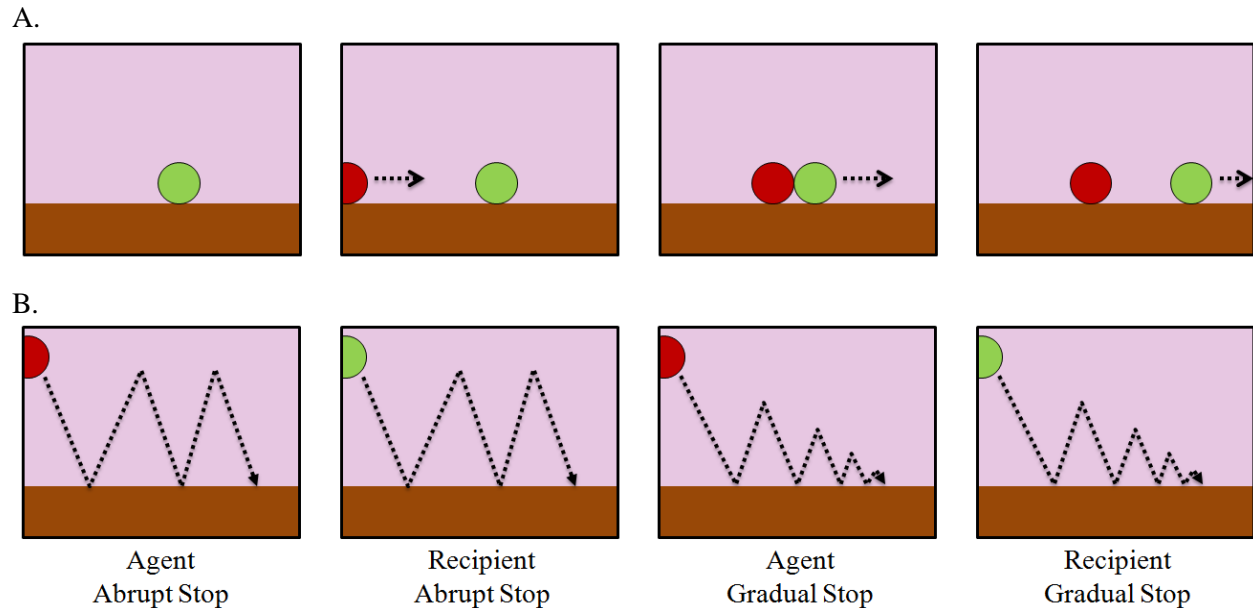
A.

B.

| Agent | Recipient | Agent | Recipient |
| Abrupt Stop | Abrupt Stop | Gradual Stop | Gradual Stop |

Figure 1. Panel A displays the habituation event in Experiment 1 in which a red ball (agent) caused a green ball (recipient) to move. Panel B displays the four test events that were used in Experiment 1. Dotted lines indicate trajectories of motion.

infants were excluded from the 16-month-old group: 3 for fussiness and 1 for failure to habituate. The final sample for each age group consisted of 24 infants. For the 12-month-olds, the mean age was 12.10 months ($SD = 0.31$ months; range: 11.57 months to 12.59 months); there were 16 males and 8 females. For the 16-month-olds, the mean age was 15.98 months ($SD = 0.34$ months; range: 15.29 months to 16.57 months); there were 11 males and 13 females. Infants were recruited using lists from a private company and received a small gift for their participation.

Stimuli. Six animations of motion events were created using Macromedia Director. The first animation showed a wind-up toy mouse that moved across the screen; the event lasted for 7.5 seconds. This animation was used as the pretest and the posttest. The second animation was used as the habituation stimulus and is shown in Figure 1A. It depicted a causal launch event (Michotte, 1963) in which a red ball, the agent, rolled onto the screen from the left, contacted a stationary green ball, the recipient, at the center of the screen, and set it in motion such that it

rolled off-screen to the right; the event lasted for 7.5 seconds. The third, fourth, fifth, and sixth

animations were used as test stimuli and were of equal length of 7.5 seconds each; these are

depicted in Figure 1B. The third animation depicted the red agent ball come onto the screen from

the top left, bounce off the ground twice to the same height, and come to an abrupt stop on-

screen. The fourth animation depicted the green recipient ball come onto the screen from the top

left, bounce to the same height twice, and then come to an abrupt stop on-screen. The fifth

animation depicted the red agent ball come onto the screen from the top left, bounce four times

off the ground to a progressively lower height eventually coming to a gradual stop on-screen.

The sixth animation depicted the green recipient ball come onto the screen from the left, bounce

four times to a progressively lower height, and come to a gradual stop on-screen. Note that the

discrepancy in number of bounces between the abrupt stop and the gradual stop events was

necessary to keep the overall amount of motion equal between the two of test events. In the

gradual stop test events the ball traveled less distance and took less time on each successive

bounce than in the abrupt stop test events; therefore, it was necessary for the ball to make more

bounces in the gradual test events to equate the time and distance of motion to the those of the

abrupt test events. However, as is described in more detail below, infants' looking times are not

predicted to be systematically higher or lower for one type of stop; rather, it was predicted that

looking time would depend on both the stop and the causal role of the object. Thus, although a

perceptual difference in the number of bounces does exist between the two conditions, attending

solely to this difference would not generate the predicted pattern of results.

        Materials. An Apple G5 computer was used to administer the stimuli and code looking

times using HabitX software (Cohen, Atkinson, & Chaput, 2004). A 14-inch by 24-inch LCD

monitor was used to present the stimuli, which was placed 48 inches away from the infant. Two

speakers were placed next to the monitor to play the attention-getting sound. A camera was

placed above the monitor to record infants' looking behavior. A second monitor was placed within view of the experimenter; the monitor was connected to the camera to allow the experimenter to code infants' looking. A curtain was used to obscure the infant and the stimulus-presentation monitor from the experimenter.

Design. A mixed design was used with three independent variables: (1) age, 12 or 16 months; (2) test trial condition, abrupt stop or gradual stop; (3) causal role of the tested object, agent or recipient. Age and test trial condition were between-subjects variables and causal role was a within-subjects variable. Looking time, in seconds, was the dependent variable. Within each age group, half of the infants ($N = 12$) were randomly assigned to a test trial condition that determined the two stopping events that they saw in the test phase. Infants in the abrupt stop condition saw one event in which the agent stopped abruptly and one event in which the recipient stopped abruptly. Infants in the gradual stop condition saw one event in which the agent stopped gradually and one event in which the recipient stopped gradually. In both conditions, the order of the two test events was counterbalanced across infants.

If infants can generalize different stopping properties to agents and recipients, then an interaction between the object's causal role and the test trial condition should be observed. This interaction can be broken down into four specific predictions. First, infants should look longer when an agent displays gradual stopping than when an agent displays abrupt stopping. Second, infants should look longer when a recipient displays abrupt stopping than when a recipient displays gradual stopping. Third, infants should look longer when an agent displays gradual stopping than when a recipient displays gradual stopping. Fourth, infants should look longer when a recipient displays abrupt stopping than when an agent displays abrupt stopping. These predictions were generated based on expected correlations of motion properties in infants' environments: entities that are agents tend to be entities that stop abruptly, and entities that are

recipients tend to be entities that stop gradually.

Procedure. Infants were tested one at a time in a quiet room. Each infant sat on his or her caregiver's lap and faced a monitor on which the stimuli were displayed. The infant and the parent were occluded from the experimenter by a curtain to ensure that the infant's behavior was not affected by the experimenter, and to prevent the experimenter from knowing which stimulus was being shown to the infant. Prior to the start of the experiment, caregivers were instructed to remain neutral and refrain from interacting with their infants during the study.

An infant-controlled habituation procedure was used. The experiment consisted of a pretest trial, up to 16 habituation trials, two test trials, and one posttest trial. Each trial lasted until the infant looked away for at least one second, or the maximum trial length was reached. Between trials an attention-getter played until the infant looked back at the screen; the attention getter depicted a looming green circle on a black background that was accompanied by a dinging sound. The pretest trial displayed the pretest stimulus, discussed above, for a maximum of 4 repetitions or 30 seconds. Following the pretest, the habituation phase began. Each habituation trial displayed a maximum of 4 repetitions of the habituation stimulus described above and or a total of 30 seconds. In the habituation phase, the total looking over the first three trials was calculated, and the habituation criterion was established as a 50% decline in total looking over any three consecutive trials after the first trial. Thus, the minimum number of trials an infant could receive was 4. When infants reached the habituation criterion or when infants viewed 16 trials, the habituation phase ended. Infants who did not habituate within the maximum 16 trials were not included in the final analysis. After the habituation phase, infants viewed the two test trials as determined by the condition to which they were assigned (abrupt stop or gradual stop) and the trial order. Each test trial displayed a maximum of 4 repetitions of the test stimulus and lasted up to 30 seconds. After the second test trial, infants were exposed to the posttest trial,

which displayed an identical stimulus to the pretest for the same number of repetitions.

Coding. Looking was coded online during the course of the experiment. The experimenter, blind to what the infant was seeing, watched the infant's looking behavior on a monitor. A key was pressed when the infant looked at the screen and depressed when the infant looked away. A second coder coded a random sample of 25% of the infants in each age group offline from video recordings. Reliability was assessed in two ways. First, the mean difference between the original coder's times and the reliability coder's times was computed; this difference was 0.38 seconds. Second, a Pearson product-moment correlation between the original coder's scores and the reliability coder's scores was calculated. The results indicated a strong association between the scores, $r = 0.91$.

Results

Preliminary analyses indicated that sex of the infant and test trial order did not produce significant main effects or interactions. Therefore, these factors were not included in the analyses reported below.

Habituation Phase. On average, infants required 73.90 seconds to habituate ($SD = 35.38$). The mean decrement in their looking, defined as one minus the ratio of total looking on the last three trials to total looking on the first three trials, was 0.62 ($SD = 0.09$). The effects of age and test trial condition on the total amount of time it took infants to habituate were analyzed using a 2(age: 12 months, 16 months) x 2(test trial condition: abrupt stop, gradual stop) between-groups ANOVA. The analysis yielded no significant main effect of age, $F(1,44) = 0.97, p = 0.33, \eta_p^2 = 0.02$, no significant main effect of condition, $F(1,44) = 1.32, p = 0.26, \eta_p^2 = 0.03$, and no significant interaction between age and condition, $F(1,44) = 0.29, p = 0.59, \eta_p^2 = 0.01$. The results suggest that habituation times were equal for both age groups. Crucially, the results also demonstrate that the two test trial conditions were equivalent after the habituation phase, which

Table 1.

Mean looking times, in seconds, during the Experiment 1 test trials as a function of infants' age, assigned test trial condition, and the causal role of the ball seen in the test trial. Standard deviations are given in parentheses.

Causal Role	12-month-olds (N=24)		16-month-olds (N=24)	
	Abrupt Stop (N=12)	Gradual Stop (N=12)	Abrupt Stop (N=12)	Gradual Stop (N=12)
Agent	6.22 (4.98)	13.04 (9.25)	9.81 (5.60)	15.74 (9.58)
Recipient	11.50 (8.62)	10.94 (8.46)	9.48 (8.86)	10.22 (5.02)

suggests that differences in test trial looking could not be attributed to unequal rates of habituation between the two groups.

The effects of age and test trial condition on the decrement in looking at the end of habituation were analyzed using a 2(age: 12 months, 16 months) x 2(test trial condition: abrupt stop, gradual stop) between-groups ANOVA. The analysis yielded a significant main effect of age, $F(1,44) = 4.31$, $p = 0.04$, $\eta_p^2 = 0.09$. Sixteen-month-olds showed a larger decrement in looking that 12-month-olds ($M = 0.64$, $SD = 0.09$ and $M = 0.59$, $SD = 0.08$, respectively). There was no significant main effect of condition, $F(1,44) = 0.001$, $p = 0.97$, $\eta_p^2 < 0.0005$, and no significant interaction between age and condition, $F(1,44) = 0.70$, $p = 0.41$, $\eta_p^2 = 0.02$. Once again, the results demonstrate that the two conditions were equivalent prior to the test phase as was expected because both conditions received the same habituation event.

Test Phase. The effects of age, test trial condition, and causal role on infants' looking during the test phase were analyzed using a 2(age: 12 months, 16 months) x 2(test trial condition: abrupt stop, gradual stop) x 2(causal role: agent, recipient) mixed design ANOVA, with age and condition as between-subjects factors and causal role as a within-subjects factor. Table 1 presents
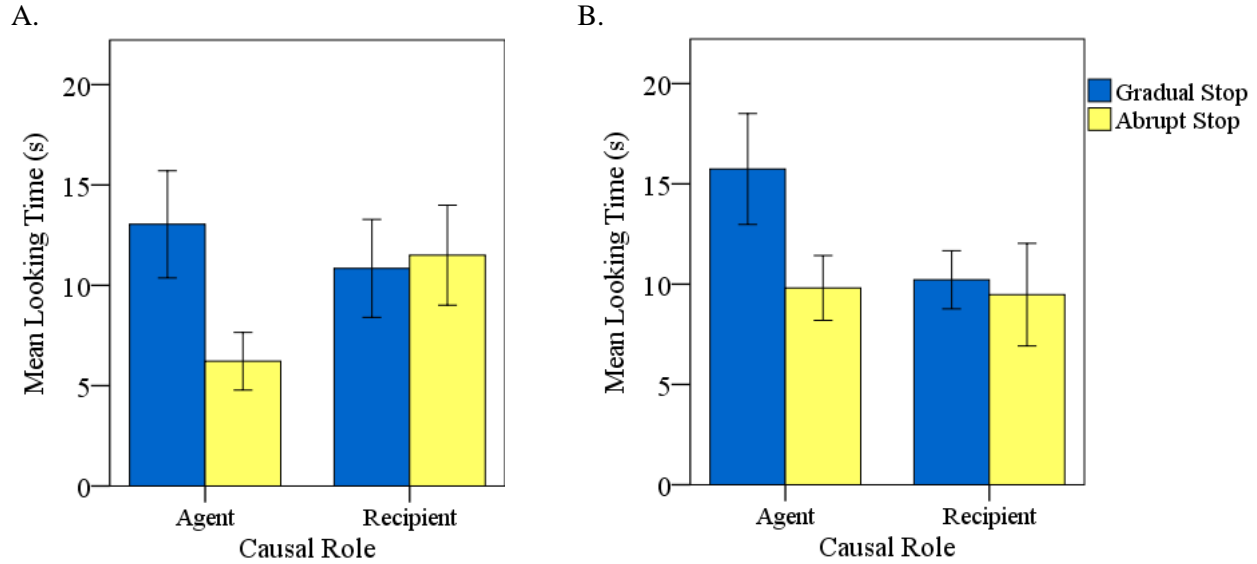
A.   B.

Figure 2. Panel A displays the looking-time data for 12-month-olds in Experiment 1. Panel B displays the data for 16-month-olds. Error bars indicate one standard error. Both age groups display a pattern consistent with expectations about abrupt stopping of agents and no expectations about recipients.

the descriptive statistics split by the three factors. The analysis yielded no main effect of causal role, $F(1,44) = 0.33$, $p = 0.57$, $\eta_p^2 = 0.01$ or age, $F(1, 44) = 0.23$, $p = 0.63$, $\eta_p^2 = 0.01$. There was a marginal main effect of condition, $F(1,44) = 2.88$, $p = 0.10$, $\eta_p^2 = 0.06$; infants looked longer at gradual stops than abrupt stops. There was a significant interaction between causal role and condition, $F(1,44) = 6.93$, $p = 0.01$, $\eta_p^2 = 0.14$, and a marginally significant interaction between causal role and age $F(1,44) = 3.45$, $p = 0.07$, $\eta_p^2 = 0.07$. The results for 12- and 16-month-olds are shown in Figures 2A and 2B, respectively.

The significant interaction between causal role and condition was examined further using independent-samples t-tests. There was a significant effect of condition on looking at the agent ball's stopping in the test phase, $t(46) = 2.89$, $p = 0.01$: infants looked longer when the agent stopped gradually ($M = 14.39$, $SD = 9.31$) than when it stopped abruptly ($M = 8.01$, $SD = 5.50$). In contrast, there was no significant effect of condition on looking at the recipient ball's stopping in the test phase, $t(46) = 0.02$, $p = 0.99$: infants looked equally long at a recipient that stopped

gradually ($M = 10.53$, $SD = 6.81$) and one that stopped abruptly ($M = 10.49$, $SD = 8.61$). These results are consistent with the looking-time predictions for the agent but not the recipient.

Additionally, the interaction was examined using paired-samples t-tests. There was a significant effect of causal role on looking in the gradual stop condition, $t(23) = 2.75$, $p = 0.01$: infants looked longer at the agent that stopped gradually than at the recipient that stopped gradually. There was no significant effect of causal role on looking in the abrupt stop condition, $t(35) = 1.23$, $p = 0.23$: infants looked equally long at the agent that stopped abruptly and the recipient that stopped abruptly. These results are consistent with the looking-time predictions for the gradual stopping but not the abrupt stopping.

The marginal interaction between causal role and age was examined using independent-samples t-tests as well. There was no significant effect of age on infants' looking at the agent's stopping behavior, $t(46) = 1.34$, $p = 0.19$: 12- and 16-month-old infants looked equally long during the agent test events ($M = 9.63$, $SD = 8.06$ and $M = 12.78$, $SD = 8.25$, respectively). Likewise, there was no significant effect of age on infants' looking at the recipient's stopping behavior, $t(46) = 0.59$, $p = 0.56$: 12- and 16-month-old infants looked equally long during the recipient test events ($M = 11.17$, $SD = 8.36$ and $M = 9.85$, $SD = 7.05$, respectively). The interaction was explored further using paired-samples t-tests. There was no significant effect of causal role for the 12-month-olds, $t(23) = 0.81$, $p = 0.43$: infants looked equally long at the agent and the recipient in the test phase. There was a marginally-significant effect of causal role for the 16-month-olds, $t(23) = 1.74$, $p = 0.10$: infants looked longer at the agent than the recipient in the test phase.

Discussion

Experiment 1 examined infants' ability to generalize about objects' stopping properties based on their causal roles at 12 and 16 months of age. Specifically, the experiment tested if

infants expect causal agents to stop abruptly and causal recipients to stop gradually after observing a causal launch event. The results yielded a significant interaction between causal role and test trial condition, in accordance with the initial prediction. Infants looked longer when an agent stopped abruptly than when it stopped gradually. Furthermore, they looked longer when an agent stopped gradually than when a recipient stopped gradually. These results suggest that after infants observe an entity act as an agent and cause the motion of a recipient, they expect the agent to stop abruptly rather than gradually. Similarly, they expect the recipient, rather than the agent, to stop gradually.

However, it should be noted that two follow-up comparisons did not yield the predicted pattern of results. First, infants looked equally long at a recipient that stopped abruptly and at a recipient that stopped gradually. Second, infants looked equally long at a recipient that stopped abruptly and at an agent that stopped abruptly. These results highlight the possibility that infants' expectations are primarily formed about agents' stopping properties but not about recipients' stopping properties. That is, after they observe a causal event, infants have expectations about how the agent will stop, but they have no expectations about how the recipient will stop, which leads to equal looking for both types of recipient stopping test trials. This possibility is consistent with previous research showing that infants tend to encode less information about the recipient of the causal event than about the agent (Cohen & Oakes, 1993). Furthermore, Experiment 1 yielded a marginal interaction between causal role and age such that at 16 months, infants tended to look longer at agents than recipients overall, which suggests that infants may pay less attention to the latter than the former. Alternatively, it is possible that infants' experience in the world is such that agents are more likely to demonstrate abrupt stopping than gradual stopping, whereas recipients demonstrate both types of stopping. For example, recipients may stop abruptly upon contact with another entity (e.g., a ball that is rolled by a parent may stop when it hits a wall).

The results of Experiment 1 extend the findings of Cicchino et al. (2011) on infants' ability to generalize about motion properties of objects based on those objects' observed causal roles. Specifically, the work of Cicchino et al. demonstrated that by 14 months, infants generalize self-propulsion to objects that are agents but not to those that are recipients. The present study suggests that infants also generalize abrupt stopping, but not gradual stopping, to agents. However, infants' expectations about recipients' stopping properties are less clear. The timetable for the emergence of this generalization ability is slightly earlier than that found by Cicchino et al.: infants in the present study showed behavior consistent with generalization about agents' stopping by 12 months. However, a marginal interaction between causal role and age was found, which suggests that a developmental change in generalization about the target properties may occur between 12- and 16-months. Accordingly, Experiment 2 was conducted to test an intermediate age group, 14-month-olds, to examine that change in more detail.

Experiment 2

The results of Experiment 1 imply that 12- and 16-month-olds have expectations about how an object's motion ceases based on that object's role as a causal agent, but they have no such expectations for the recipient. Furthermore, the results suggest that a developmental shift may occur between 12 and 16 months, particularly with respect to attention to agents and recipients. To examine this developmental shift in more detail, Experiment 2 was conducted with 14-month-old infants – an intermediate age group to those studied in Experiment 1 – using an identical procedure to that in Experiment 1.

Method

Participants. Twenty-nine 14-month-old infants were recruited to participate in the experiment. All infants were healthy and full term. Of these, one infant was excluded for failure to habituate, and four were excluded for extreme fussiness that prevented them from completing

the experiment or caused them to go off-camera such that looking could not be coded. This

resulted in a final sample of 24 infants with a mean age of 13.80 months ($SD = 0.32$ months;

range: 13.25 months to 14.43 months). There were 15 males and 9 females. Twelve infants were

randomly assigned to each of the two conditions, abrupt stop and gradual stop. Infants were

recruited using records from a private company and received a small gift for their participation.

Stimuli and Materials. The same stimuli and materials that were used in Experiment 1

were used in Experiment 2.

Design. The experiment employed a mixed design with two independent variables: (1)

test trial condition, abrupt stop or gradual stop; (2) causal role, agent or recipient. Test trial

condition was between-subjects and causal role was within-subjects. All other aspects of the

design were identical to Experiment 1. Additionally, the same predictions were made as in

Experiment 1: if infants generalize abrupt stopping to agents and gradual stopping to recipients,

then longer looking should occur for test events that display gradual stopping of agents and

abrupt stopping of recipients, as compared to test events that display abrupt stopping of agents

and gradual stopping of recipients.

Procedure. The procedure was identical to Experiment 1.

Coding. Looking-time data were collected in the same manner as those in Experiment 1.

To assess coder reliability, a second experimenter coded looking time for a randomly-selected

sample of 25% of the infants. This coding was completed off-line using video recordings.

Reliability of the primary coder was assessed in two ways: by calculating the mean difference

and the Pearson product-moment correlation between the two coders. The mean difference was

0.14 seconds. The correlation between the scores was 0.76.

Results

Preliminary analyses indicated that sex of the infant and test trial order did not produce

any significant main effects or interactions. Therefore, these factors were not included in the

analyses reported below.

Habituation Phase. On average, infants required 86.17 seconds to habituate (SD =

43.37). The mean decrement in their looking, defined as one minus the ratio of total looking on

the last three trials to total looking on the first three trials, was 0.61 (SD = 0.08). Independent-

samples t-tests were used to compare the total habituation time and the decrement between the

two test trial conditions. With respect to total habituation time, infants in the abrupt stop

condition required the same amount of time to habituate as infants in the gradual stop condition,

$t(22) = 0.08$, $p = 0.94$ (M = 86.92, SD = 42.46 and M = 85.42, SD = 46.15, respectively). With

respect to the decrement, there was also no difference between the abrupt stop and the gradual

stop condition, $t(22) = 0.63$, $p = 0.54$ (M = 0.62, SD = 0.08 and M = 0.60, SD = 0.08,

respectively). These results demonstrate that the infants in the two conditions were equivalent in

their habituation: they required the same amount of time to habituate and decreased their looking

by the same proportion by the end of the habituation phase. Equivalent results during habituation

were expected because both conditions received the same habituation event.

Test Phase. The means and standard deviations for infants' looking times during the test

phase as a function of the stopping condition and causal role of the entity in the test event are

displayed in Table 2. A 2(test trial condition: abrupt stop, gradual stop) x 2(causal role: agent,

recipient) mixed ANOVA was conducted to examine the effects of condition and causal role on

looking time during the test phase. Condition was a between-subjects factor and causal role was

a within-subjects factor. The results indicated no main effect of condition, $F(1,22) = 0.69$, p =

0.41, $\eta_p^2 = 0.02$, no main effect of causal role, $F(1,22) = 0.34$, $p = 0.57$, $\eta_p^2 = 0.03$, and no

interaction between condition and causal role, $F(1,22) = 0.45$, $p = 0.51$, $\eta_p^2 = 0.02$. Infants

looked equally long in both test trial conditions and for both agents and recipients. These results

Table 2.

Fourteen-month-old infants' mean looking times, in seconds, during the Experiment 2 test trials as a function of the test trial condition and the causal role of the ball seen in the event. Standard deviations are given in parentheses.

	Test Trial Condition	
Causal Role	Abrupt Stop (N = 12)	Gradual Stop (N = 12)
Agent	11.72 (9.78)	11.03 (8.06)
Recipient	11.91 (7.99)	8.19 (8.18)

are not consistent with the pattern of results that would be expected if infants can generalize different stopping properties to agents and recipients.

Discussion

Experiment 2 was designed to examine 14-month-olds' expectations about objects' stopping based on their causal roles as agents or recipients. The infants in the study displayed uniform looking to all test events regardless of stopping manner or causal role. This suggests that at 14 months, infants do not have expectations about the stopping manner of agents or recipients.

The above finding is somewhat surprising given the results of Experiment 1, which showed that 12- and 16-month-olds displayed looking patterns consistent with the generalization of abrupt stopping, but not gradual stopping, to agents. The combination of these results with those of the present experiment suggests a U-shaped trajectory in generalization about agents' stopping such that generalization is present in the youngest age group, deteriorates in the intermediate age group, and is present again in the oldest age group. Naturally, the observation of such an unexpected pattern poses a question regarding the basis for its emergence. One possibility is that similar observed behaviors from the youngest and the oldest age groups occur for different reasons.

In the case of the present study, longer looking at a gradually-stopping agent than an abruptly-stopping agent can occur for two reasons that were confounded in the design. First, as already discussed, this pattern of looking can occur if infants attend to the causal roles of the object during the habituation event and form expectations about stopping based on those causal roles. Specifically, infants may look longer at a gradual stop by the agent as compared to an abrupt stop by the agent in the test phase because the latter violates the expectation that agents stop abruptly. Second, this pattern of looking can occur if infants attend to how the balls stop during the habituation event and generalize stopping in the test phase based on stopping during habituation rather than based on causal roles. In the habituation event, the agent ball stops abruptly when it comes in contact with the recipient ball and causes it to move; the recipient ball rolls off-screen and there is no information about how it stops, abruptly or gradually. Based only on this stopping information, infants may display the same pattern of longer looking at a gradually-stopping agent rather than an abruptly-stopping agent because the former pattern of stopping was not seen during the habituation phase; thus, the causal role information may not be necessary for infants to display the observed behavior. Similarly, infants' equal looking at an abrupt and a gradual stop by the recipient may be due to the fact that no stop was observed for the recipient during habituation; the fact that the ball was a recipient may be irrelevant.

Thus, there are two distinct possibilities that may explain infants' behavior: (1) infants generalize stopping properties based on previously-observed causal role information; (2) infants generalize stopping properties based on previously-observed stopping properties. It is possible that the U-shaped curve in generalization performance occurs because infants shift from using one type of information to using another type of information. The former generalization is more complex than the latter because it involves matching across motion types (physical causality and stopping) rather than within motion types (stopping horizontally and stopping via a bouncing

motion), so if a shift in generalization occurs between 12 and 16 months of age it is likely to result from a shift from the less complex to the more complex processing of the event. Accordingly, it is possible that 12-month-old infants generalize based on stopping properties and that 16-month-old infants generalize based on causal roles. The 14-month-old infants tested in Experiment 2 are in the middle of the transition and cannot use either type of information to generalize. Thus, the transition between two different forms of generalization may result in a complete failure to generalize due to a combination of processes. Infants may attend less to stopping and more to causal roles during habituation as they become older. However, by 14 months infants may not have learned which causal roles are associated with which stopping properties, which prevents them from generalizing in the test phase. Experiment 3 was designed to address these issues by disentangling causal roles from stopping properties. Specifically, it tested whether 12-month-old infants display the same pattern of looking when only stopping information is present and there are no causal agents or recipients in the habituation phase.

The results of Experiment 2 demonstrate that although infants can generalize self-propulsion based on causal roles at 14 months (Cicchino et al., 2011), they are unable to generalize stopping based on causal roles. This finding is somewhat inconsistent with the theory presented by Cicchino et al., which relies on representation strength to explain generalization abilities. It is unclear why the representation of causal agency is sufficiently strong to support generalization about self-propulsion at 14 months, but is not strong enough to support generalization about stopping. This point will be addressed in more detail below in relation to the revised theoretical account of generalization. Additionally, there is a question regarding infants' generalization abilities at this age with respect to stopping: can infants generalize stopping properties to objects when more motion cues are present? Prior work by Cicchino et al. suggests that additional motion cues can aid in generalization. It is possible that 14-month-olds may be

able to generalize stopping properties to agents and recipients when supplementary motion information that is thought to correlate with agency or recipiency is provided during habituation. Experiment 4 was designed to test this hypothesis by administering a habituation event which depicted a causal launch in which the agent was seen to be self-propelled on screen.

<div align="center">**Experiment 3**</div>

Experiments 1 and 2 demonstrated an apparent U-shaped curve in infants' generalization about the stopping properties of agents: 12- and 16-month-olds expect agents to stop abruptly but not gradually and 14-month-olds have no expectations. However, as discussed in Experiment 2, this U-shaped pattern may be due to a change in the information to which infants attend during habituation: younger infants may attend to stopping properties and older infants may attend to causal roles. Experiment 3 was designed to test this hypothesis by removing the confound between stopping and causal roles during habituation. Twelve-month-old infants were habituated to a non-causal event in which one ball stopped abruptly and one ball rolled off-screen such that its stop was not visible. Subsequently, all infants were shown the same test events used in Experiments 1 and 2 that showed each ball stopping abruptly or gradually. If stopping properties during habituation are sufficient for generalization, then infants should display the same pattern of looking as in Experiment 1. However, if infants' looking during Experiment 1 was based on causal roles then the same pattern of looking should not be observed in the present study.

Method

Participants. Thirty-one infants were recruited for the study using records provided by a private company. All infants were healthy and full-term. Of these, 5 infants were excluded because they did not habituate, 1 infant was excluded because she was very active and went off-camera, and 1 infant was excluded because he could not complete the experiment due to fussiness. Thus, there were 24 infants in the final sample (mean age of 12.00 months; $SD = 0.28$
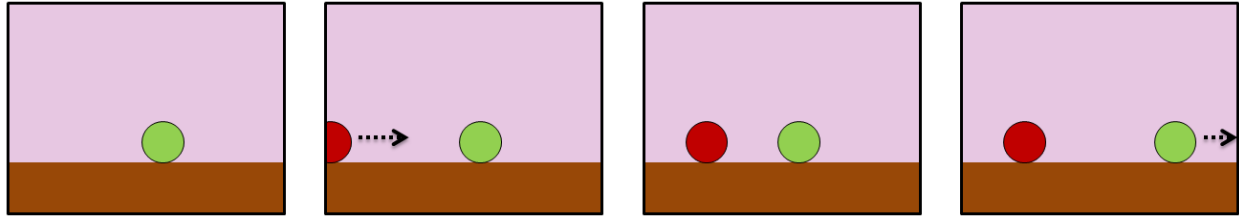
Figure 3. The habituation event used in Experiment 3. The event depicted a red ball that rolled onto the screen and stopped short of the green ball. The green ball rolled off-screen after a delay. Dotted lines indicate trajectories of motion.

months; range: 11.51 months to 12.36 months); there were 14 males and 10 females. Infants received a small gift for their participation.

Stimuli. A new habituation event was created for this experiment (see Figure 3). The event depicted the same red and green ball as in Experiments 1 and 2, but the balls did not interact in a causal manner. At the beginning of the trial, the green ball was seen stationary on the screen as in the previous experiments. Then, the red ball rolled onto the screen but stopped short of the green ball. The two balls remained stationary for 1 second. After the delay, the green ball began to move and rolled to off-screen. Thus, the habituation event was a non-causal event: the red ball was no longer an agent and the green ball was no longer a recipient. However, the two balls maintained the same stopping properties as in Experiments 1 and 2: the red ball stopped abruptly on the screen, and the green ball did not stop. The same four test events that were used Experiments 1 and 2 were used in the present study, which depicted the red ball and the green ball stopping abruptly and stopping gradually. Because there are no causal roles to assign to the balls based on the habituation event, the red ball, previously the agent, will be referred to as the *prior-agent ball*, and the green ball, previously the recipient, will be referred to as the *prior-recipient ball*.

Materials. With the exception of the habituation event, the same materials were used in

Experiment 3 as in Experiments 1 and 2.

Design. The present experiment used a mixed design with two independent variables: (1) habituation ball: prior-agent and prior-recipient; (2) test trial condition: abrupt stop, gradual stop. The former was a within-subjects variable and the latter was a between-subjects variable. The dependent variable was looking time during the test phase, in seconds. Infants were assigned randomly to either the abrupt stop or the gradual stop test trial condition ($N = 12$, per condition). In the abrupt stop condition, infants saw one test trial in which the prior-agent displayed an abrupt stop, and one test trial in which the prior-recipient displayed an abrupt stop. In the gradual stop condition, infants saw one test trial in which the prior-agent displayed a gradual stop, and one test trial in which the prior-recipient displayed a gradual stop. The order of the two test events was counterbalanced across infants.

Two sets of predictions could be made, which depend on whether infants generalize stopping properties based on the causal roles seen during habituation or based on stopping properties seen during habituation. No differences in looking times would be expected if infants generalize based on causal roles because no causal information was available in the habituation events. Specifically, infants should look equally long at the prior-agent that stops abruptly and at the prior-agent that stops gradually. Similarly, they should look equally long at the prior-recipient that stops abruptly and at the prior-recipient that stops gradually.

A different set of predictions can be generated if infants generalize stopping in the test trials based on stopping during habituation. The two balls in the present experiment maintain the same stopping properties during habituation as they did in Experiments 1 and 2. Thus, if 12-month-old infants' generalization in Experiment 1 was based on that information, infants should display the same pattern of looking in the present study. Specifically, it is expected that no differences in looking will be found for the prior-recipient when it stops abruptly and when it

stops gradually because no stop was observed for that ball during habituation. In contrast, looking should be greater when the prior-agent stops gradually than when it stops abruptly because that ball was seen to stop abruptly during the habituation phase. In sum, if the looking patterns found here are the same as those found for 12-month-olds in Experiment 1, then it is likely that stopping properties, rather than causal roles, underpinned infants' looking in that previous experiment.

Procedure. The procedure was the same as in Experiments 1 and 2 with the exception of the habituation event, as described above.

Coding. Infants' looking time was measured on-line as in Experiments 1 and 2. A second coder provided reliability coding for a randomly-selected subset of 25% of the infants. The reliability coding was done off-line using videos recorded during the testing sessions. Reliability was assessed by computing the mean difference between the original coder's values and the reliability coder's values, as well as by computing the Pearson product-moment correlation coefficient between them. The mean difference between the scores was 0.39. There was a strong correlation between them, $r = 0.97$

Results

Habituation Phase. Infants' mean habituation time was 88.10 seconds ($SD = 48.94$ seconds). The mean decrement in looking, defined as one minus the ratio of total looking over the last three trials to total looking over the first three trials was 0.60 ($SD = 0.08$). Independent samples t-tests were conducted to check that infants in both test trial conditions performed the same in the habituation phase. There was no difference observed in their total habituation time, $t(22) = 0.20$, $p = 0.85$ (abrupt stop: $M = 90.12$, $SD = 53.53$; gradual stop: $M = 86.08$, $SD = 46.20$) or in the decrement in their looking, $t(22) = 1.31$, $p = 0.21$ (abrupt stop: $M = 0.57$, $SD = 0.06$; gradual stop: $M = 0.62$, $SD = 0.09$). Thus, any differences observed between the two conditions

Table 3.

Twelve-month-old infants' mean looking times, in seconds, during the Experiment 3 test trials as a function of the test trial condition and the habituation ball seen in the event. Standard deviations are given in parentheses.

	Test Trial Condition	
Habituation Ball	Abrupt Stop (N = 12)	Gradual Stop (N = 12)
Prior-Agent	9.77 (6.37)	13.73 (9.55)
Prior-Recipient	11.72 (7.73)	11.58 (8.89)

could not be a result of a priori differences generated by the habituation phase.

Test Phase. Means and standard deviations of infants' looking times during for the four test trials are provided in Table 3. Preliminary analyses indicated that participants' sex did not affect the results but that the test trial order did affect the results. Accordingly, the latter variable was included in the main analysis along with the two main variables of interest, habituation ball and test trial condition. Figure 4 shows the results of the experiment split by order: Panel A presents the data for children who were tested on the prior-agent first, and Panel B presents the data for children who were tested on the prior-recipient first. A 2 (habituation ball: prior-agent, prior-recipient) x 2 (test trial condition: abrupt stop, gradual stop) x 2 (order: prior-agent first, prior-recipient first) mixed ANOVA was performed with habituation ball as a within-subjects variable and test trial condition and order as between-subjects variables. The ANOVA yielded a significant interaction between order and habituation ball, $F(1,20) = 10.38$, $p = 0.004$, $\eta_p^2 = 0.34$. No other interactions were significant. No significant main effects were found for habituation ball, $F(1,20) = 0.003$, $p = 0.96$, $\eta_p^2 < 0.0005$, test trial condition, $F(1,20) = 0.52$, $p = 0.48$, $\eta_p^2 = 0.03$, or order, $F(1,20) = 0.09$, $p = 0.77$, $\eta_p^2 = 0.004$.

Additional tests were conducted to examine the significant interaction between order and
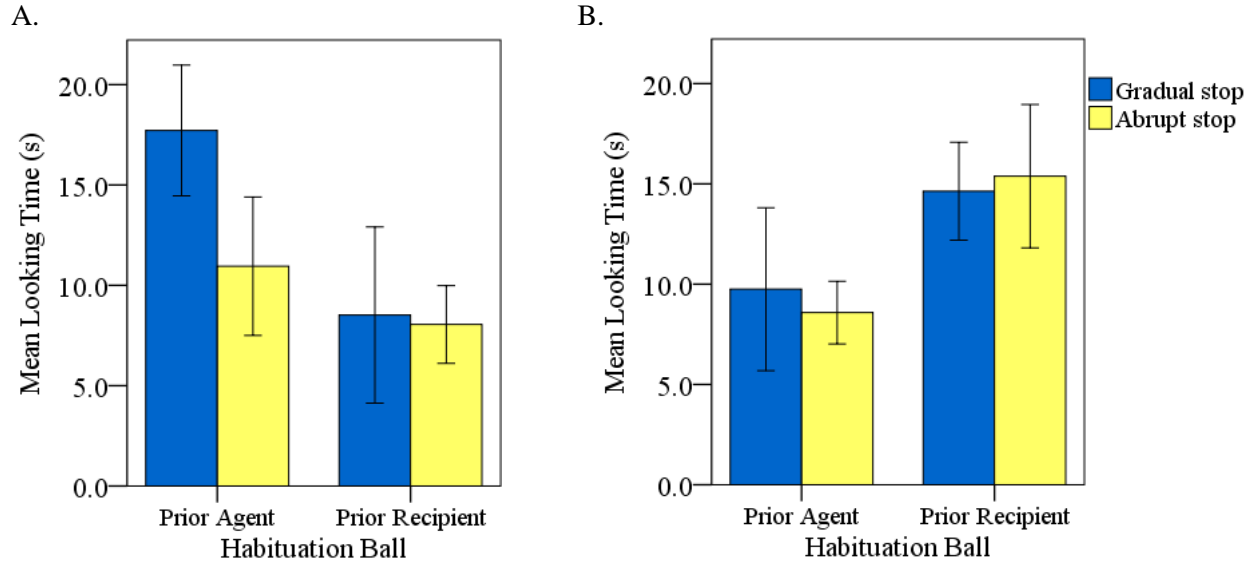
A.
B.

Figure 3. Infants' looking times in Experiment 3 as a function of the order in which they experienced the test trials. Panel A shows infants who were shown the agent trial first and the recipient trial second (N=12) and Panel B shows infants who were shown the recipient trial first and the agent trial second.

habituation ball. Paired-samples t-tests were used to compare looking at the prior-agent to looking at the prior-recipient separately for each order. Infants whose first test trial displayed the prior-agent looked significantly longer at the prior-agent ($M = 14.33$, $SD = 8.59$) than the prior-recipient ($M = 8.28$, $SD = 7.92$), $t(11) = 2.48$, $p = 0.03$. Infants whose first test trial displayed the prior-recipient looking marginally longer at the prior-recipient ($M = 9.17$, $SD = 7.21$) than the prior-agent ($M = 15.01$, $SD = 7.16$), $t(11) = 2.14$, $p = 0.06$. These results suggest that infants consistently looked longer at the first test trial, regardless of their test trial condition or the identity of the habituation ball displayed in that test trial. However, they provide no evidence for differential looking at abrupt and gradual stopping in the test phase.

Discussion

The goal of Experiment 3 was to determine the basis of 12-month-olds' generalization about stopping in Experiment 1. Specifically, the present experiment tested two alternatives:

either infants generalize based on the causal roles or the stopping properties observed during

habituation. To eliminate the confound between these alternatives, the present experiment used

the same balls as Experiment 1, but it removed their causal roles and preserved their stopping

properties during habituation. Recall that in Experiment 1, the agent stopped abruptly during

habituation and the recipient did not stop. In the test phase, infants looked longer when the agent

stopped gradually in the test phase than when it stopped abruptly in the test phase; in contrast,

looking times were equal for both stops displayed by the recipient. Accordingly, it was predicted

that in the present experiment, generalization would not occur in the test phase if it was based on

causal roles because that information was no longer available. However, generalization would

still occur if it was based on stopping because both balls still displayed the same stopping

properties during habituation as in Experiment 1. In the former case, no differences were

expected between any of the test trials. In the latter case, the same pattern of results as in

Experiment 1 was expected.

The results of the present experiment show no differences in looking at the test trial as a

function of the identity of the ball or the stopping property displayed by the ball. Specifically,

when infants are shown that an object displays an abrupt horizontal stop during habituation, they

look equally long when the same object displays an abrupt bouncing stop as when it displays a

gradual bouncing stop in the test phase. The only significant finding is infants' propensity to look

longer at the first test trial with which they are presented. These results suggest that the stopping

properties that objects display during habituation are not sufficient to support expectations about

stopping in the test phase, and therefore it is unlikely that 12-month-old infants' generalization

behavior in Experiment 1 was due simply to how the agent and the recipient stopped during

habituation.

The finding that stopping properties are not sufficient to support generalization at 12

months presents a challenge in interpreting the U-shaped trajectory in generalization observed across Experiments 1 and 2. Recall that in those experiments 12- and 16-month-olds looked longer at an agent that stopped gradually as compared to one that stopped abruptly, and 14-month-olds look equally at the two events. The proposed explanation for this trajectory was that 12- and 16-month-olds generalize based on different aspects of the habituation event, and the 14-month-olds are in transition between the two. Specifically, it was suggested that 12-month-olds rely on perceptual information of how the balls stop during habituation, and 16-month-olds rely on the causal roles of the balls. The results of Experiment 3 do not support this proposal: the data suggest that 12-month-olds cannot generalize when only stopping information is presented during habituation, which suggests that their generalization in Experiment 1 was based on causal roles. If infants can generalize based on causal roles at 12 months, why would they fail to do so at 14 months and then succeed again at 16 months? There are several ways to interpret these results, which are addressed below.

One possibility is that the proposed direction of change is incorrect: it may be that 12-month-olds relied on causal properties in Experiment 1 and 16-month-olds relied on stopping. Generalization based on causal properties involves the formation of expectations about a completely different class of motion—namely, stopping —based on observed agency. In contrast, generalization based on how an object stops moving involves the formation of expectations about the same class of motion that is displayed in a different manner. According to this explanation, 12-month-olds generalize between different motion types, whereas 16-month-olds generalize within the same motion type. This apparent progression from more advanced generalization that spans motion types to less advanced generalization within a motion type is inconsistent with previous findings that showed that infants' generalization abilities increase with age (e.g. Caron, Caron, & Myers, 1982; Cicchino et al., 2011; Learmonth, Lamberth, &

Rovee-Collier, 2004; Wu, Mareschal, & Rakison, 2011). Thus, based on previous findings, it appears unlikely that infants would generalize based on causal roles at a younger but not at an older age. However, this possibility will require further investigation by testing 16-month-olds in the same design as the current experiment.

Another possibility is that the design of the habituation stimulus caused infants to focus on a different type of motion information and ignore stopping properties. To remove causal roles from the habituation display while preserving stopping properties, it was necessary to turn the event into one that displayed self-propulsion of the second ball, the prior-recipient. It is possible that infants attended primarily to self-propulsion during habituation and did not attend to how the prior-agent and the prior-recipient stopped. Subsequently, in the test phase, they did not generalize based on stopping information and did not display the same pattern of behavior as in Experiment 1. Infants attend to self-propulsion and can form expectations about self-propelled objects within the first year of life (Cicchino & Rakison, 2008; Luo et al., 2009; Markson & Spelke, 2006). Thus, it is possible that infants' internal representations of the habituation event included information about self-propulsion, and this information may have altered infants' behavior in the test phase. Future research can address this possibility by eliminating self-propulsion information from the habituation event. For example, the prior-agent can stop short of an occluder and the prior-recipient can emerge from behind that occluder.

A final possibility to explain the failure to find evidence of generalization based on stopping is that the strong order effects observed in this study suppressed such patterns of looking. An examination of Figure 4 suggests that this may have been the case. Although the three-way interaction between habituation ball, test trial condition, and order is not significant, there appears to be a qualitatively different pattern of results when the prior-agent ball is presented first than the prior-recipient ball. Specifically, when the prior-agent is presented first

the pattern of results is similar to that of Experiment 1: infants tend to look longer at the prior-agent when it stops gradually than when it stops abruptly; no differences are observed for the prior-recipient. In contrast, no differences are observed for the prior-agent or prior-recipient when the prior-recipient test trial is presented first. This provides preliminary evidence that infants may, in fact, generalize based on stopping at 12 months. However, a much larger participant sample is needed to confirm the presence of a three-way interaction between all of the independent variables, and, most importantly, to demonstrate that the same pattern as found in Experiment 1 replicates for one of the test trial orders.

If such support is ultimately obtained, these observations raise an important question: why did order of presentation have a strong effect on the outcome of this study, but not on the outcome of Experiment 1? It is possible that the magnitude of the perceptual differences between the habituation and test phases in the present experiment was greater than that in Experiment 1, thereby eliciting longer looking on the first test trial. According to classic theories of information processing in infants, looking time is governed by the differences between the internally-represented information and the information available in the environment (Cohen, 1973). Experiment 1 displayed one continuous movement during habituation: as soon as the agent ball stopped, the recipient started moving. Similarly, in the test phase, each ball displayed one continuous movement until it came to a stop. In contrast, the present experiment displayed two distinct motions separated by a pause during habituation. The perceptual difference between this habituation display and the test display of a single continuous motion is greater than that of Experiment 1, which could have caused infants to look longer at the first test trial regardless of the identity of the ball in the test trial or the stopping condition. Note, however, that this is not a confound that could differentially affect performance in one stopping condition or for one type of habituation ball. Rather, it is a general perceptual difference that is the same between the

habituation phase and all four possible test trials, which manifests itself maximally during the first test trial.

In sum, Experiment 3 was designed to address the first question raised by Experiment 2, namely, what was the basis of 12-month-olds' generalization in Experiment 1? The experiment failed to provide definitive evidence that 12-month-olds' generalization about stopping in Experiment 1 was based on observed stopping properties during habituation. This finding could suggest that 12-month-olds attended to causal roles in Experiment 1 and used that information to form expectations about stopping properties. However, as discussed above, there may have been other factors, such as the nature of the habituation stimulus or order effects that could have obscured the results. In particular, it appears that when the prior-agent was presented first in the test phase, a similar pattern to that of Experiment 1 emerged, which could suggest that infants did, in fact, attend to stopping properties during habituation. However, these issues deserve further investigation by conducting follow-up experiments as discussed above.

It is now necessary to return to another question raised by Experiment 2: can 14-month-olds generalize about stopping when additional motion cues are provided? It may be that information about causal roles is not sufficient to activate expectations about stopping, but if additional cues that correlate with particular stopping patterns are provided, then infants may form expectations about stopping. Experiment 4 was designed to study this question.

Experiment 4

Experiment 2 demonstrated that 14-month-olds do not have expectations about the stopping properties of an entity based on its causal role: they look equally long when agents stop gradually and abruptly and when recipients stop gradually and abruptly. This raised the question as to whether infants have no expectations about stopping at this age, or if the information in the habituation event was insufficient to form generalizations about stopping. Prior research by

Cicchino et al. (2011) demonstrated that generalization can be induced when additional cues about animacy are provided: 14-month-olds could not generalize from self-propulsion to causal agency, but they could generalize between the two when additional motion information in the form of direction change and acceleration was provided to supplement information about self-propulsion. By similar logic, the present experiment tested the hypothesis that the presentation of an additional cue that correlates both with causal agency and with abrupt stopping may allow 14-month-olds to generalize in the test phase. For the present study, self-propulsion information was provided for the agent; this motion cue was chosen because it is considered to be one that correlates with agency because both are properties of animates (Rakison & Poulin-Dubois, 2001). Specifically, the habituation event was changed such that the agent was self-propelled prior to the causal launch of the recipient and again after the causal launch of the recipient. The test events remained the same. If the additional information allowed infants to generalize stopping properties to the agent, then it was expected that a similar pattern to Experiment 1 would be observed; that is, longer looking at an agent that stops gradually than at an agent that stops abruptly. It was expected that, as in Experiment 1, the looking times to the recipient would not differ based on the type of stop because no additional information about the recipient was provided in the present experiment.

Method

Participants. Twenty-seven healthy and full-term 14-month-old infants were recruited to participate in the experiment using birth records provided from the state of Pennsylvania. Of these infants, three were excluded from the final sample: one due to equipment failure, one for failure to complete the experiment, and one for extreme fussiness that caused the infant to go off-camera. Accordingly, the final sample consisted of 24 infants with a mean age of 14.12 months ($SD = 0.30$; range: 13.61 months to 14.63 months). The sample contained 11 males and 13
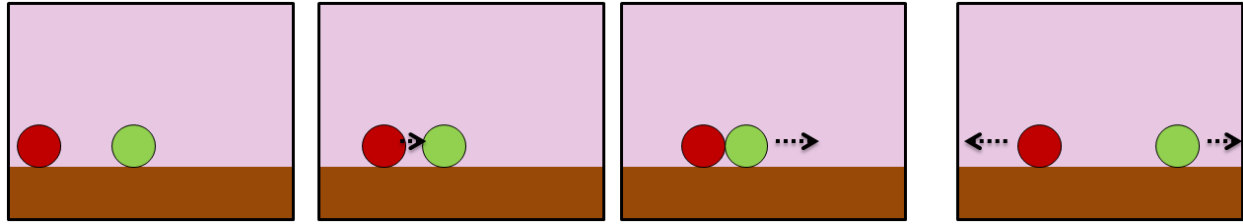
Figure 5. Modified causal launch habituation event used in Experiment 4. Both balls started stationary on-screen; the red ball (agent) moved and contacted the green ball (recipient); the green ball moved; after a delay, the red ball moved again in the opposite direction. Dotted lines indicate trajectories of motion.

females. Parents were given a small gift for their infants' participation in the study.

Stimuli. A new habituation stimulus was created for the present experiment. The stimulus depicted a causal launch event between a red ball, the agent, and a green ball, the recipient. However, unlike the habituation stimulus used in Experiments 1 and 2, both balls started stationary on-screen. Subsequently, after 0.5 seconds, the agent started to move without an external force, moved towards the recipient, and contacted it. Immediately upon contact, the agent stopped and the recipient began to move to off-screen. After 2.5 seconds of being stationary, as the recipient moved off-screen, the agent became self-propelled again and moved off-screen in the direction opposite from that of the recipient. Note that although the agent moved twice and the recipient moved only once, the total amount of movement was equated for the two balls. The balls were offset to the left of the screen such that the agent ball traversed two shorter segments that were equal in length to the single long segment traversed by the recipient. The entire event lasted 7.73 seconds. Figure 5 depicts the stimulus used in the experiment. The same four test stimuli that were used in Experiments 1, 2, and 3 were used in the present experiment: the agent stopping gradually and abruptly, and the recipient stopping gradually and abruptly.

Materials. The same materials were used in Experiment 4 as in Experiments 1, 2, and 3.

Design. The present experiment utilized a mixed design with two independent variables: test trial condition, abrupt or gradual stop, and causal role, agent or recipient. The former was a between-subjects independent variable, and the latter was a within-subjects independent variable. The dependent variable, as in previous experiments, was looking time during the test trials, measured in seconds. As in previous experiments, infants were randomly assigned to one test trial condition such that infants in the abrupt stop condition saw two test trials in which the agent and the recipient stopped abruptly, and infants in the gradual stop condition saw two test trials in which the agent and the recipient stopped gradually. The order of the test trials was counterbalanced across infants.

Two predictions were made for the present experiment. First, because no additional information was provided for the recipient ball, it was predicted that the looking time at both types of stops by the recipient would be the same, as was found in Experiment 2. Second, if additional information about the agent's ability to self-propel can induce generalization about stopping, then it was expected that 14-month-old infants would look longer when the agent stops gradually than when it stops abruptly, replicating the pattern of results found in Experiment 1 for 16-month-olds. That is, an interaction will be observed between test trial condition and causal role. However, if the additional information about the agent's self-propulsion is not sufficient to induce expectations about stopping, then 14-month-old infants' looking times should be the same for both types of agent stops and should be similar to the results found in Experiment 2. That is, there would be no main effects or interaction observed in the results.

Procedure. The procedure was the same as in Experiment 1.

Coding. Looking was coded online during the course of the experiment. The experimenter coded the infant's looking behavior by observing the infant on a monitor. A key was pressed when the infant looked at the screen and depressed when the infant looked away.

Reliability was assessed by having a second coder code a random subset of 25% of the infants offline from video recordings. The reliability of the original coding was determined in two ways. First, the mean difference between the scores was calculated, which showed that the reliability coder's scores differed from the original coder's scores by 0.65 seconds on average. Second, the Pearson product-moment correlation coefficient was computed between the two sets of scores. This yielded a strong correlation, $r = 0.95$

Results

      Habituation Phase. On average, infants required 77.97 seconds to habituate ($SD = 33.56$). The mean looking decrement, defined as one minus the ratio of total looking on the last three trials to total looking on the first three trials, was 0.61 ($SD = 0.09$). The effect of test trial condition on the total habituation time was analyzed using an independent-samples t-test. The analysis yielded no significant difference, $t(22) = 0.87$, $p = 0.39$: infants in the abrupt stop condition required 83.95 seconds ($SD = 35.64$) to habituate, and infants in the gradual stop condition took 71.98 seconds ($SD = 31.73$). The effect of test trial condition on the decrement was also analyzed using an independent-samples t-test. Once again, the analysis yielded no significant difference between the two conditions, $t(22) = 0.20$, $p = 0.84$: infants in the abrupt stop condition had a decrement of 0.62 ($SD = 0.10$), and infants in the gradual stop condition had a decrement of 0.61 ($SD = 0.09$). These analyses confirmed that the two groups started out as equivalent prior to the test phase, and that any differences observed in the test-phase could not have been due to different habituation rates.

      Test Phase. The means and standard deviations of infants' looking times for the four different test trials are reported in Table 4. Preliminary analyses indicated that sex of the infant and test trial order did not affect the results, so these variables were not included in the analysis. The effects of test trial condition and causal role on infants' looking times were analyzed using a

Table 4.

Fourteen-month-old infants' mean looking times, in seconds, during the test trials of Experiment 4 as a function of the test trial condition and the causal role of the ball seen in the event. Standard deviations are given in parentheses.

	Test Trial Condition	
Habituation Ball	Abrupt Stop (N = 12)	Gradual Stop (N = 12)
Agent	17.13 (9.00)	11.17 (9.03)
Recipient	13.83 (9.49)	14.95 (6.75)

2 (test trial condition: abrupt stop, gradual stop) x 2 (causal role: agent, recipient) mixed ANOVA with the former variable as between-subjects and the latter variable as within-subjects. There was no main effect of test trial condition, $F(1,22) = 1.57$, $p = 0.22$, $\eta_p^2 = 0.001$, no main effect of causal role, $F(1,22) = 0.01$, $p = 0.91$, $\eta_p^2 = 0.07$, and no interaction between causal role and condition, $F(1,22) = 1.31$, $p = 0.26$, $\eta_p^2 = 0.06$. Infants looked equally at all test trials regardless of their test trial condition and the causal role of the ball seen in the test trial. This suggests that the addition of self-propulsion information for the agent was not sufficient for 14-month-olds to form expectations about how agents stop.

Discussion

The goal of the present experiment was to assess if the presence of two cues, agency and self-propulsion, can induce 14-month-old infants to form expectations about stopping. Infants were habituated to a causal event in which the agent was self-propelled, and tested on four events in which the agent or the recipient exhibited an abrupt or a gradual stop. It was expected that if the presentation of two cues that are commonly associated with animacy and abrupt stopping induces generalization, then infants would look longer at an agent that stops gradually than an agent that stops abruptly. Contrary to the prediction, infants exhibited equal looking to all four

test events. Unlike the findings reported by Cicchino et al. (2011) in which the addition of

acceleration and direction change helped infants to generalize from self-propulsion to causal

agency, the addition of self-propulsion in the present experiment did not help infants of the same

age to generalize from causal agency to stopping. However, it is unclear how good of a cue to

animacy self-propulsion is for infants, and what their generalization abilities are with respect to

that motion cue. On the one hand, infants detect self-propulsion (Markson & Spelke, 2006) and

generalize other properties such as direction-reversal to self-propelled entities (Luo et al., 2009)

within the first year of life. On the other hand, infants fail to generalize causal agency to a self-

propelled object at 14 months (Cicchino et al., 2011). It is possible that self-propulsion is weakly

represented in infancy and cannot support generalization to properties such as causal agency, as

suggested by Cicchino et al., and stopping, as observed in the present experiment. The findings

from Experiment 3 provide some confirming evidence to this effect. Recall that Experiment 3

presented infants with a non-causal event, which entailed that the second ball that had been the

recipient in Experiments 1 and 2 was now self-propelled. Infants in Experiment 3 displayed

equal looking to abrupt and gradual stops by this self-propelled ball, indicating that they could

not generalize stopping properties based on self-propulsion. However, Experiment 3 studied 12-

month-old infants, so it could be the case that infants at an older age could generalize abrupt

stopping to self-propelled entities.

Taken together, Experiments 1, 2, 3, and 4 demonstrate several things. First, they provide

preliminary evidence of a U-shaped developmental trajectory regarding infants' expectations

about stopping: 12- and 16-month-olds display one pattern of behavior, and 14-month-olds

display a different pattern of behavior. Second, they provide preliminary evidence that indicates

that it is only 16-month-old infants who expect agents to stop abruptly but not gradually; 12-

month-old infants expect entities that have stopped abruptly before to continue stopping

abruptly. Third, they suggest that by 16 months infants do not have expectations about how

recipients in causal events stop. Finally, they show that self-propulsion does not activate

expectations about stopping in 12- and 14-month-old infants. These results have been primarily

discussed in light of the theoretical perspective presented by Cicchino et al. (2011). However, as

mentioned in the introduction, there is another domain-general theoretical account that could

provide a mechanistic explanation of the findings of the present work and that of Chicchino et al.

This account is presented and evaluated below.

Experiment 5

Experiments 1 through 4 extended prior research regarding infants' developing ability to

generalize about motion properties within the second year of life. From the perspective of

Cicchino et al.'s (2011) theoretical account, generalization abilities are supported primarily by

infants' experience with motion properties in the world. Specifically, infants do not see all

motion properties with equal frequency, which leads to differential strengths of the internal

representations of these motions and, in turn, determines the types of generalizations that they

can make. Cicchino et al. argued that infants generalize from strong representations to weak

representations, but not in the opposite direction. For example, infants experience many more

instances of causal agency than self-propulsion, form a stronger representation of the former than

the latter, and subsequently generalize from agency to self-propulsion but not in the opposite

direction. Although the account provides a satisfactory match between theory and the behavioral

evidence from Cicchino et al., there are several issues and outstanding questions that remain to

be addressed. The purpose of the present experiment is to attend to these issues by providing and

alternative theoretical account and testing it empirically.

The results of Experiment 2 point to one issue with the Cicchino et al. (2011) account. If

infants' generalization ability is governed primarily by the strength of the concept from which

they generalize, then the results of Experiment 2 are somewhat surprising given Cicchino et al.'s

empirical work. The authors found that 14-month-old infants can generalize from causality to

self-propulsion, yet Experiment 2 reported here suggests that they cannot generalize from

causality to stopping at the same age. Both types of generalizations should rely on the same

representation of causality, which according to Cicchino et al. is sufficiently strong. It is possible

that infants' representation of stopping is absent or substantially weaker than that of self-

propulsion at 14 months, which could explain the failure to generalize until 16 months. However,

this raises the issue of how strong the representation of the concept to which one is generalizing

needs to be for generalization to occur; this was left unspecified by Cicchino et al.

Another issue that arises relates to the direction in which generalization is thought to

proceed: a strong representation can activate a weak one but a weak representation cannot

activate a strong one. In support of this argument, Cicchino et al. (2011) cite the work of Quinn

and Eimas (1998) who also demonstrate an asymmetry in generalization. Quinn and Eimas

familiarized infants to images of humans, horses, or cats, and tested them on images of the

familiar or contrasting category. Infants habituated to humans did not dishabituate to horses or

cats, but infants habituated to horses or cats dishabituated to members of both contrasting

categories, thus demonstrating that habituation to humans was generalized to non-human

animals, but the reverse was not true. One interpretation of these findings is that infants are likely

to have more experience with, and stronger representations for, humans than cats or horses, so

generalization occurs only in a single direction from a strong to a weak representation. This

argument rests on the assumption that infants' prior experience with humans in the world was the

primary driving force behind their generalization in the lab. However, it is also possible that

infants' behavior relied primarily on their learning during the experiment. Infants may have

formed a very weak representation of humans after familiarization that generalized to cats and

horses because unique features of humans were not encoded. For example, if infants'

representation of humans only encoded the fact that they had eyes and legs but not the particular

characteristics of those features, then infants would not dishabituate to cats or horses because

both of those animals have eyes and legs. In contrast, infants habituated to cats or horses could

have formed a very strong representations of those categories that included many more unique

features such as the presence of fur or a tail and thus could not be generalized to humans. Thus,

the work of Quinn and Eimas could be interpreted as suggesting that generalization from a weak

to a strong representation is more likely than generalization from a strong to a weak

representation, the opposite of what is argued by Cicchino et al.

Similar support for an opposite pattern of generalization can be found in the literature on

adults' semantic representation, which suggests that a strong cue is less likely to access a weak

representation than a weak cue is to access a strong representation. For example, Frazier and

Rayner (1990) studied adults' representations of ambiguous words with multiple unbalanced

interpretations (i.e., one interpretation of the word occurs much more commonly in everyday

language than another interpretation). In the experiment, participants read sentences that

contained target words with multiple interpretations. Two of the conditions in the experiment are

particularly relevant to the present discussion: (1) sentences in which the ambiguous word

followed after a part of the sentence that disambiguated its meaning, and this disambiguation

suggested the less common interpretation; (2) sentences in which the ambiguous word was

placed before a part of the sentence that disambiguated its interpretation, and this disambiguation

suggested the more common interpretation. The former condition is an example of a strong cue

that should access a weak representation: there is a very clear context that is supposed to indicate

the less common and weakly-represented interpretation of the word. The latter condition is an

example of a weak cue that should access a strong representation: there is no clear contextual

disambiguation of which meaning to access, but the correct meaning is common and strongly-represented. Crucially, participants read the target words slower in the first condition than in the second condition, which suggests that it was easier to access a strong representation following a weak cue than the opposite. Taken together with an alternative interpretation of the Quinn and Eimas (1998) work, this could suggest that representation strengths could generate an opposite pattern of generalization than that suggested by Cicchino et al. (2011).

A final, and perhaps most important limitation of the account suggested by Cicchino et al. (2011), is that it is a mechanistic account of the asymmetry in generalization but not of generalization itself. That is, it explains how experience can give rise to particular patterns of generalization, but it does explain how the infant activates the representation of one motion property upon seeing another motion property. Representation strengths dictate whether the activation will occur, but there is no specification in Cicchino et al.'s account as to the link between different representations. It is possible that infants form direct associations between motion properties based on experience such that the activation of one motion property based on observed input activates the other motion property. Alternatively, generalization may rely on a second-order indirect association between motion properties because there is a common feature (e.g., legs) with which all properties are directly associated. According to this account, the motion property that is observed activates a common feature, which, in turn, activates the other motion property. Both of these possibilities are potentially consistent with the proposed account, but there is no empirical test of which, if any, is more appropriate.

To address some of the limitations of the Cicchino et al. (2011) account, a new theoretical account is proposed here that takes a different perspective on the information about motion that infants extract from their environment. Specifically, it is argued that infants extract *transitional probabilities* between motion events from their environments. In other words, they

track the probability of an entity displaying motion B given that it has displayed motion A,

which is calculated as the frequency of the AB sequence divided by the total frequency of A

(Miller & Selfridge, 1950; Aslin, et al., 1998). Tracking these probabilities enables

generalization because infants form an expectation of the next likely motion given the motion

that they have just observed. Infants encode a representation of the two motions in a particular

sequential order with the strength of the representation governed by the transitional probability:

higher transitional probabilities allow for stronger representations than lower transitional

probabilities. The input about the first motion allows infants to activate the representation of the

two-motion sequence and form an expectation of the second motion. Asymmetry in

generalization between two motion properties can arise if the transitional probability between

them varies depending on the order of the motions. For example, it may be the case that an entity

is highly likely to be self-propelled after being a causal agent, but it is not likely to be a causal

agent after being self-propelled. Based on these regularities, infants may have a strong

representation of the "causality then self-propulsion" sequence and a weak or non-existent

representation of "self-propulsion then causality" sequence. As a result, when infants see that an

entity acts as a causal agent they can activate a strong representation that allows them to form an

expectation regarding self-propulsion, whereas when they see that an entity is self-propelled

there may not be an internal representation to activate, so they have no expectations about causal

agency.

The plausibility of this account depends on two factors: first, infants' ability to parse

continuous visual input into discrete motion events, and second, infants' ability to encode

statistical regularities in their environments. A number of studies have shown that infants can

extract actions from a continuous stream of motion. For example, Wynn (1996) and Sharon and

Wynn (1998) have argued that 6-month-olds can separate such input into separate actions based

on the finding that infants who are shown a puppet that displays a particular motion without breaks a given number of times will dishabituate when the number of repetitions is changed. Hespos, Saylor, and Grossman (2009) showed that starting at 6 months, infants can also extract single actions from a more complex motion setting that involves three different actions of a ball (e.g., going inside a box, rolling under an arc, bouncing off of another object) rather than repetition of the same motion. When infants were habituated to a single action, they showed longer looking to test sequences of three actions that did not contain that single action than test sequences that did contain it. Conversely, when habituated to a sequence of three different actions, infants looked longer at a single action that was not in the sequence than one that was in the sequence. Finally, work by Baldwin, Baird, Saylor, and Clark (2001) has shown that infants can extract actions from continuous movement displayed by a human in a realistic setting. Infants were habituated to a video of an everyday action displayed by a person (e.g., picking up a towel that is on the floor) and tested on videos that included pauses either in the middle of the action (e.g., as the person was bent half way down) or on either end of the action (e.g., after the person has set down the towel on the table). Ten- and eleven-month-old infants looked longer at test events in which the pause was in the middle of the action than test events in which the pause was before or after, which demonstrated that this was not a novelty preference for videos with pauses. Crucially, this looking pattern could not be explained by an inherent preference for this type of pause as it only emerged after habituation. Taken together, these findings suggest that infants within the first year of life can extract a discrete motion event from a continuous stream of motion and can do so in settings that are akin to those encountered in their daily experience.

As mentioned above, the new theoretical account also rests on the assumption that infants can extract statistical regularities from their environments. A rich body of empirical work provides supporting evidence for this ability (for a review see Krogh, Vlach, & Johnson, 2013;

Saffran, 2003). When exposed to a continuous artificial language in which low transitional

probabilities between phonemes occur at boundaries between words and high transitional

probabilities occur within words, 8-month-old infants can extract the words in the language

without any additional cues other than the statistical regularities (Aslin et al., 1998; Saffran et al.,

1996). Crucially, this ability is not domain-specific and has been found for a range of input

stimuli. For example, infants show similar abilities to extract coherent tone strings from a

continuous stream of tones when those strings are defined by transitional probabilities (Saffran,

Johnson, Aslin, & Newport, 1999). They can also learn statistical regularities in visual

information such as static patterns of shapes that appear in predictable arrangements (Fiser &

Aslin, 2002) or sequential patterns of shapes in which certain shapes regularly follow other ones

(Kirkham, Slemmer, & Johnson, 2002; Kirkham, Slemmer, Richardson, & Johnson, 2007).

Statistical learning abilities are present at birth for both auditory (Teinonen, Fellman, Näätänen,

Alku, & Huotilainen, 2009) and visual stimuli (Bulf, Johnson, & Valenza, 2011), although

memory limitations constrain the complexity of the regularities that infants can learn early on

(Krogh et al., 2013). Thus, previous studies suggest that infants can extract motion events from

their environments and can learn regularities found in various domains of input. This implies that

infants may have the requisite abilities to learn the transitional probabilities among motion

events that they see on a daily basis, which could serve as a basis for generalization about motion

properties such as agency, self-propulsion, and stopping.

What is the advantage of the proposed account that is based on transitional probabilities

relative to the one proposed by Cicchino et al. (2011)? The first advantage is that it can provide

an explanation of the findings of Experiment 2 regarding infants' inability to generalize from

causal agency to abrupt stopping at the same age at which they succeed in generalizing from

causal agency to self-propulsion, a finding that is somewhat more difficult for Cicchino et al. to

explain, as discussed above. The success of generalization from the same motion to two different motions can vary if the transitional probabilities for those two motions are unequal. Specifically, if the transitional probability from causality to self-propulsion is higher than the transitional probability from causality to stopping, then infants may have a stronger representation of the "causality then self-propulsion" sequence than "causality then abrupt stop" sequence, which enables them to generalize in the former but not the latter case.

The second advantage is that it does not rely on theories regarding asymmetrical access of information based on representation strength, which are somewhat contradictory, as discussed above. Instead, generalization is governed by the strength of the representation of a particular sequence of events. Thus, this theoretical account avoids making commitments regarding how information is accessed based on strong or weak cues. Furthermore, it provides an explanation for the process of generalization: the observed motion property allows the infant to access a representation of a two-motion sequence, which governs their looking time to a subsequent motion.

A final advantage of the account is its consistency with prior research regarding infants' ability to learn frequency and transitional probability information. Studies that have directly compared these two types of information (e.g., Aslin et al., 1998; Fiser & Aslin, 2002) have shown that infants encode transitional probability information and not frequency information. That is, infants do not encode events that have a high frequency; instead, they encode events that have a high transitional probability. This has been found for auditory input (Aslin et al., 1998) and static visual input (Fiser & Aslin, 2002). It is possible that a similar pattern could occur for dynamic visual information: infants may preferentially encode transitional probabilities between motion events, as suggested in the present account, rather than the frequency of individual events, as suggested by Cicchino et al. (2011).

The new account has been discussed extensively in relation to prior research, but a more rigorous evaluation of the account is necessary. One component of this evaluation is to establish if infants can extract regularities from motion events, and if they preferentially extract regularities that are consistent with their experience daily experience. The goal of the present experiment was to address these issues. Twelve- and sixteen-month-old infants were habituated to a continuous stream of four motions, in which some pairs of motions had a transitional probability of 1.0 (e.g., after motion A motion B always happened), and some pairs had a transitional probability of 0.5 (e.g., after motion B motion C happened half of the time and motion D happened half of the time). The four motions were causal agency, self-propulsion, a bouncing motion, and an arc-shaped motion. Crucially, to test if infants preferentially encode one order of motion over another, there were two conditions: for half of the infants causal agency always occurred immediately before self-propulsion, and for the other half of the infants causal agency occurred immediately after self-propulsion. Numerous studies have shown that infants' prior experience can govern the types of regularities that they can learn (e.g., Madole & Cohen, 1995; Rakison, 2005, 2006; Saffran & Thiessen, 2003; Thiessen, 2010). If infants' generalization abilities are influenced by the order of events to which they are exposed in the real world, then in the present experiment they should encode preferentially those orders that are consistent with their experience and not those that are inconsistent. Specifically, if infants' ability to generalize from causality to self-propulsion but not in reverse is due to a higher transitional probability of the former than the latter, then infants in the present task should extract the statistical regularity when they are shown causality followed by self-propulsion, but not when they are shown self-propulsion followed by causality. Four test events were used to assess infants' learning in the task. The first event presented the same order of causality and self-propulsion to which the infant was exposed. The other three events presented various pairings of the four motion events from

the habituation phase; these pairings either had a low transitional probability or did not occur during habituation. It was predicted that infants who viewed causality followed by self-propulsion during habituation would look longer at these latter three events as compared to the first event, whereas infants who viewed self-propulsion followed by causality would look equally at all four test events. Additionally, a developmental difference was predicted such that 16- but not 12-month-old infants would display this pattern of looking. The predictions were based on the theory that infants experience statistical regularities with respect to the order of self-propulsion and causality, encode these regularities, and become constrained by them during subsequent learning. These constraints emerge as infants gain more experience thereby making older but not younger infants more likely to exhibit them.

Method

  Participants. Twelve- and sixteen-month-old infants were recruited to participate in this study using birth records provided by the state of Pennsylvania. All infants were healthy and full term. For the 12-month-old age group, 32 infants were recruited initially, but 9 were excluded due to fussiness (8 infants) or parental interference (1 infant). The final sample of 12-month-olds contained 24 infants with a mean age of 12.04 months ($SD = 0.26$ months; range: 11.57 months to 12.49 months); there were 14 females and 10 males. For the 16-month-old age group, 32 infants were recruited initially, but 8 were excluded due to fussiness (6 infants), equipment failure (1 infant), and failure to habituate (1 infant). Thus the final sample contained 24 infants with a mean age of 16.19 months ($SD = 0.23$ months; range: 15.72 months to 16.57 months); there were 13 females and 11 males.

  Stimuli. Four new animations were created that were combined in various orders to make the habituation and test events. Each animation lasted 5 seconds and began with a rise of a blue curtain and ended with a fall of the same curtain. The first animation depicted a causal launch
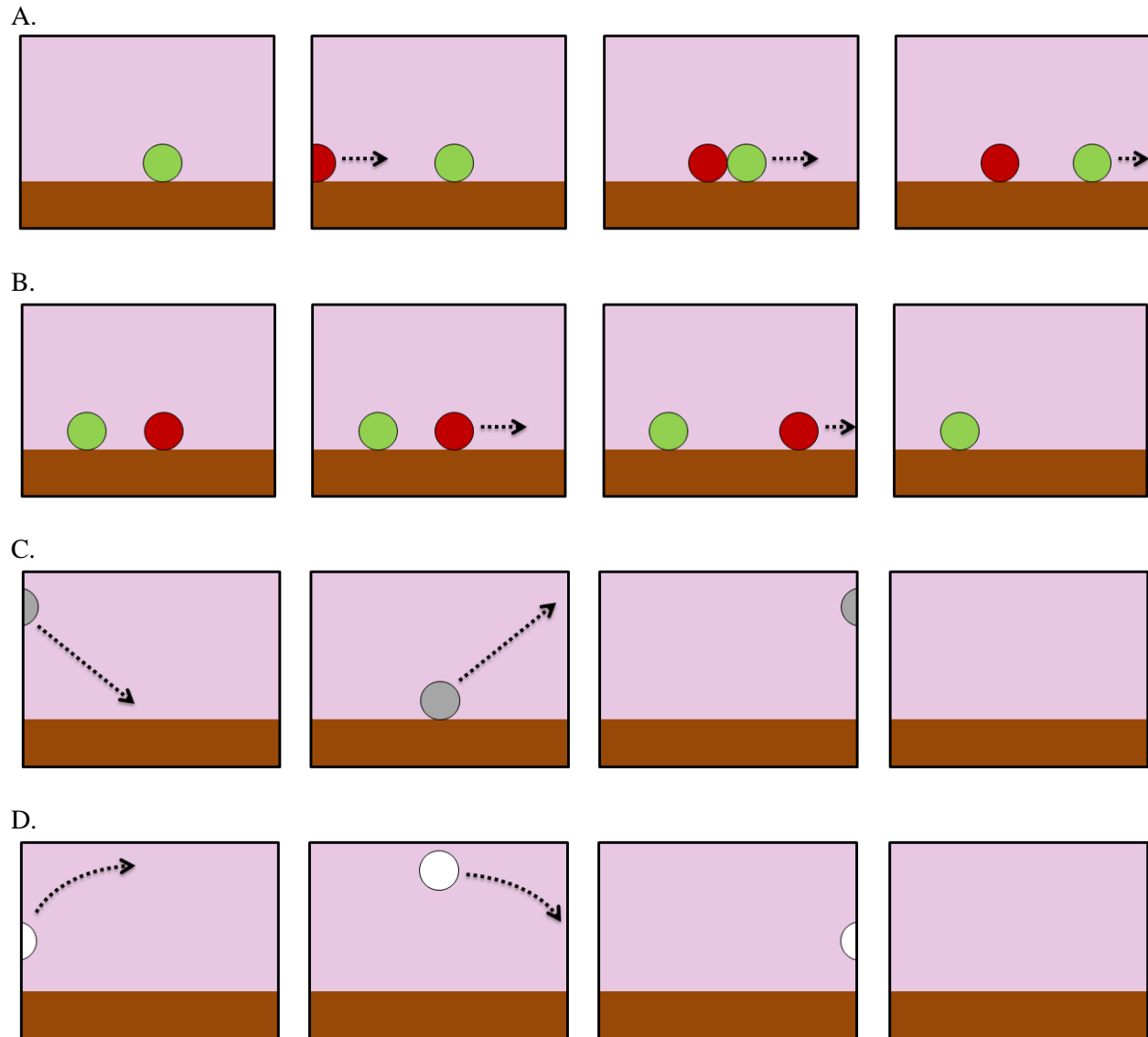
A.

B.

C.

D.

Figure 6. Motion events that were combined to create the habituation stimuli used in Experiment 5. Panel A displays a causal event in which a red ball (agent) caused a green ball (recipient) to move. Panel B displays a self-propulsion event in which a red ball started moving on its own while the green ball remained stationary. Panel C displays a bouncing event in which a grey ball bounced in a V-shaped trajectory. Panel D displays an arc event in which a while ball traveled along an inverted-U-shaped path. Dotted lines indicate trajectories of motion.

event: a green ball was stationary on the screen, then a red ball appeared from the left side of the screen, contacted the green ball, and caused it to move such that it moved to off-screen on the right side (see Figure 6A). The red ball stopped upon contact with the green ball. The second

animation depicted a self-propulsion event: the same red and green ball were on the screen with the green ball on the left and the red ball on the right; after 2 seconds the red ball began to move to the right and exited the stage on that side (see Figure 6B). The third animation depicted a bouncing motion: a gray ball came onto the screen from the upper-left, traveled along a diagonal path towards the ground, bounced off the ground in the middle of the screen, traveled along a diagonal path towards to upper-right corner, and exited off-screen (see Figure 6C). The fourth animation depicted an arc-shaped motion: a white ball came on-screen from the lower left, moved upward and then downward across the screen in an inverted U-shaped trajectory, and then exited on the lower-right of the screen (see Figure 6D). The third and fourth animation contained balls that were different from the first and second animation because the goal was to study infants' ability to learn sequences of agency and self-propulsion displayed by the same entity but not other motions. Because other motions were necessary to create a probabilistic environment, those motions needed to be performed by different entities.

> *Habituation events.* All four of the above events were strung together in different orders to create habituation events. There were four possible orders: (1) causality, self-propulsion, arc, causality, self-propulsion, bounce; (2) causality, self-propulsion, bounce, causality, self-propulsion, arc; (3) self-propulsion, causality, arc, self-propulsion, causality, bounce; (4) self-propulsion, causality, bounce, self-propulsion, causality arc. Infants were randomly assigned to one of these orders, and within each habituation trial they saw up to two continuous repetitions of their assigned sequence for a maximum trial length of 60 seconds.

> *Test events.* For the test events, pairs of the above stimuli were strung together in one of six possible orders: (1) causality, self-propulsion; (2) self-propulsion, causality; (3) causality, arc; (4) causality, bounce; (5) self-propulsion, arc; (6) self-propulsion, bounce. Within each test trial, the pair of stimuli shown in that test trial repeated up to six times, with a 1-second black

screen inserted between repetitions for a maximum trial length of 66 seconds. The black screen

was used to indicate that this was a two-event sequence that was repeated, rather than a

continuous 12-event sequence.

Materials. The same materials were used as in Experiments 1-4.

Design. A mixed design was used for the experiment with three independent variables:

age, habituation condition, and test trial type. Age was a between-subjects independent variable

with two levels: 12 months and 16 months. Habituation condition was also a between-subjects

independent variable with two levels: causality followed by self-propulsion (which will be

referred to as *C-SP*) and self-propulsion followed by causality (which will be referred to as *SP-*

C). Test trial type was a within-subjects variable with four levels: consistent, reverse, part-

sequence, non-sequence.

Habituation Condition. The structure of the habituation sequence was the same across all

infants: there were 6 motion events in an A-B-C-A-B-D order where each unique letter indicates

a unique motion event. Thus, the transitional probability from A to B was 1.0, from B to C was

0.5 and from B to D was 0.5. However, across infants the identities of the events that appeared in

the A, B, C, and D locations in the sequence varied. Within each age group, 12 infants were

randomly assigned to the C-SP habituation condition and 12 infants were randomly assigned to

the SP-C condition. Six of the infants in the C-SP condition viewed habituation trials that

depicted the order "causality, self-propulsion, arc, causality, self-propulsion, bounce" on every

trial, and the other six infants viewed the order "causality, self-propulsion, bounce, causality,

self-propulsion, arc" on every trial. In the SP-C condition, six of the infants viewed habituation

trials that depicted "self-propulsion, causality, arc, self-propulsion, causality, bounce" on every

trial, and six viewed "self-propulsion, causality, bounce, self-propulsion, causality arc" on every

trail. For infants in the C-SP condition, self-propulsion always followed causality, so the

transitional probability between them was 1.0. In contrast, arc or bounce could follow self-propulsion, so the transitional probability between self-propulsion and either of those events was 0.5. For infants in the SP-C condition, causality always followed self-propulsion, so the transitional probability from self-propulsion to causality was 1.0. Causality could be followed by arc or bounce, so the transitional probability in that case was 0.5. Thus, the two conditions were different with respect to which event sequences were more or less probable.

      Test Trial Type. All infants viewed all four test trials types. However, the actual stimuli depicted for the given type varied as a function of the infant's condition. The *consistent* test event depicted the A-B event pair: the same sequence of causality and self-propulsion to which the infant was habituated. Thus, for C-SP infants, the consistent test event depicted causality followed by self-propulsion, and for SP-C infants the consistent test event depicted self-propulsion followed by causality. This event was used as a baseline for comparison. The *reverse* test event depicted the B-A event pair: the opposite order of causality and self-propulsion from what the infant saw during habituation. For C-SP the reverse event depicted self-propulsion followed by causality, and for SP-C infants it depicted causality followed by self-propulsion. This test event was used to assess if infants are sensitive to the order in which causality and self-propulsion occur after the habituation phase, and if this interacts with their habituation condition. The *part-sequence* test event depicted one of the low transitional probability pairs of events that was shown during habituation, either B-C or B-D. For C-SP infants this was either self-propulsion followed by arc, or self-propulsion followed by bounce; half of the infants were randomly assigned to each of those pairings. For SP-C infants this was either causality followed by arc, or causality followed by bounce; again, half of the infants were randomly assigned to each. This test event was used to determine if infants have extracted the A-B sequence but not the B-C or B-D sequence as a coherent unit based on the transitional probabilities. Finally, the

non-sequence test event depicted the first motion event from the habituation phase followed by a

motion that never followed it in the sequence, either A-C or A-D. For C-SP infants the non-

sequence test event showed causality followed by arc or causality followed by bounce (half of

the infants randomly assigned to each); for SP-C infants the event showed self-propulsion

followed by arc or self-propulsion followed by bounce (half of the infants were randomly

assigned to each). This event was used to test if infants have learned the events that occupy the

first and second positions in the two-event sequence.

Test events were blocked such that the first two test events that infants viewed were

consistent and reverse, in counterbalanced order across infants; the second two test events that

the infants viewed were part-sequence and non-sequence, in counterbalanced order across

infants. Blocking was used because the primary goal of the study was to assess which order of

self-propulsion and causality infants are able to learn, and this was tested by the consistent and

reverse test events. Thus, these test events were placed first to ensure that the part-sequence and

non-sequence test events did not interfere with test trial performance. All possible combinations

of habituation and test events for the two conditions are outlined in Appendix A.

Predictions. If infants learned a pair of events with high transitional probability, then

their looking in the test phase should be low to the consistent event because it displayed the same

pair of events. Their looking should be high to the reverse event because it presents the opposite

order than that which was seen during the habituation phase. If infants have extracted the high

transitional probability pair as a coherent unit, akin to the way infants extract words from an

artificial language (see Saffran, 2001), then they should show elevated looking to the low

transitional probability part-sequence event. Finally, infants should display elevated looking to

the non-sequence test event if they have formed an expectation regarding the test event that was

presented second in the sequence. If infants display similar looking to the consistent and non-

sequence test events, it would suggest that they only learned the event that comes first, but not

the event that comes second.

Based on the theoretical account proposed above, the pattern of elevated looking to the

reverse, part-sequence, and non-sequence events as compared to the consistent was expected to

be found for 16-month-old infants in the C-SP condition but not in the SP-C condition. Infants in

the C-SP condition were habituated to a sequence of causality followed by self-propulsion. This

is what they may see in their daily experience, so the sequence may have been relatively easy to

acquire. In contrast, infants in the SP-C condition were habituated to a sequence that is

inconsistent with their daily experience, so it may have been difficult to acquire. Thus infants in

the SP-C condition may display equal looking to all test trials because they have failed to learn

the regularities in the input. Twelve-month-old infants could display two possible patterns of

behavior, depending on the amount of experience they have obtained. If at 12 months infants

have not had sufficient experience with transitional probabilities between self-propulsion and

causality, then they may be unconstrained in their learning and acquire the regularities in both

conditions. In this case, their performance would be akin to 16-month-olds' in the C-SP

condition. It is also possible that the task may be too difficult for infants at this age and they

could fail to learn the regularities in both conditions. In this case, their performance would be

akin to 16-month-olds' in the SP-C condition. Crucially, a difference between the two conditions

is predicted only for the older age group.

Procedure. The testing procedure was the same as in previous experiments. The same

criteria for habituation were used. The only difference in this experiment was that the minimum

look-away time to end a trial was raised from 1 second to 2 seconds. That is, when an infant

looked away from the screen, a trial ended only if the infant did not look back within 2 seconds.

The look-away criterion was raised to maximize infants' exposure to the habituation stimuli.

Coding. Coding was performed the same way as in prior experiments. To ensure

reliability of the coding, 25% of the infants were coded offline by a second coder. Reliability was

assessed in two ways. First, the mean difference between the two coders was calculated, which

was 0.65 seconds. Second, a Pearson product-moment correlation was calculated between the

times of the original and the second coder, which yielded a strong correlation, $r = 0.90$.

Results

Manipulation check. In the present experiment, the transitional probabilities between the

four types of test events were designed to be either 1.0 or 0.5. However, the presentation of the

habituation stimulus was infant-controlled. Therefore, actual transitional probabilities may have

varied depending on the time point at which infants looked away during each test trial. For

example, consider the case of an infant who is exposed to the sequence "causality, self-

propulsion, bounce, causality, self-propulsion, arc." If the infant looked away at some point after

bounce but before the second instance of self-propulsion on every trial the observed transitional

probability between self-propulsion and bounce would be 1.0 because the arc event was never

observed. This would alter the infant's performance on the part-sequence trial, particularly

depending on which of the two possible part-sequence trials is used for testing (i.e., "self-

propulsion, bounce" or "self-propulsion, arc"). Thus, it was necessary to perform a manipulation

check to determine the actual transitional probabilities to which infants were exposed as a result

of the habituation procedure. A significant deviation from the intended transitional probabilities

would make the part-sequence trial data uninformative.

To calculate the observed transitional probabilities, individual habituation trials for every

infant were analyzed. For every trial, the motion events that the infant saw before looking away

were recorded. Then, across all of the habituation trials, the frequency of each of the four events

was calculated as well as the frequency of adjacent event pairs. Transitional probabilities from

the first to the second event in a pair were calculated as the frequency of the event pair divided

by the frequency of the first event in the pair. For example, returning to the infant who viewed

the sequence "causality, self-propulsion, bounce, causality, self-propulsion, arc," the transitional

probability from causality to self-propulsion was calculated as the number of times the infant

saw causality followed by self-propulsion divided by the number of times the infant saw

causality. Note that although nothing else followed causality, this transitional probability can be

lower than 1.0 if the infant looked away before seeing the self-propulsion event during some

trials.

      The transitional probabilities that were observed for the 12- and 16-month-olds are

presented in Tables 5 and 6, respectively. The tables list the average transitional probability and

the range of transitional probabilities observed for each possible event pair by condition across

all infants. Recall that all infants viewed a repeating 6-event sequence with the consistent A-B-

C-A-B-D structure, although the identities of the individual events in the sequence varied. The

tables collapse across these individual differences and present the observed transitional

probabilities for the A-B, B-C, and B-D event pairs. Additionally, because it was possible for

infants to look away after the A event before observing the B event, or after the B event before

observing the C or D event, the tables also present the probability of the sequence ending at A or

B, indicated as A- and B-, respectively. The tables demonstrate that infants experienced a range

of transitional probabilities, in some cases very far from those that were intended by the

experimental design. For example, some 12- and 16-month-olds in the C-SP condition never saw

the D event in the sequence as indicated by the fact that the range of transitional probabilities for

the B-D sequence has a minimum of 0. Thus, for some infants the B-C sequence was much more

likely than intended because they never saw the alternative D event after B.

      To assess the degree to which the observed transitional probabilities differed from those

Table 5.

Expected and observed transitional probabilities during the habituation phase for 12-month-old infants.
Probabilities are split by event pairs and habituation conditions. The average transitional probability and the
range are provided to indicate the broad variability of probabilities experienced by different infants.

Event Pair	Expected Transitional Probability	Observed Transitional Probability in C-SP Condition		Observed Transitional Probability in SP-C Condition	
		Average	Range	Average	Range
A-	0	0.25	0.00-0.44	0.29	0.06-0.60
A-B	1.0	0.75	0.56-1.00	0.71	0.40-0.94
B-	0	0.33	0.00-0.67	0.22	0.00-0.50
B-C	0.5	0.50	0.29-0.75	0.58	0.29-0.80
B-D	0.5	0.16	0.00-0.50	0.20	0.00-0.40

Table 6.

Expected and observed transitional probabilities during the habituation phase for 16-month-old infants.
Probabilities are split by event pairs and habituation conditions. The average transitional probability and the
range are provided to indicate the broad variability of probabilities experienced by different infants.

Event Pair	Expected Transitional Probability	Observed Transitional Probability in C-SP Condition		Observed Transitional Probability in SP-C Condition	
		Average	Range	Average	Range
A-	0	0.15	0.00-0.36	0.18	0.00-0.50
A-B	1.0	0.85	0.64-1.00	0.82	0.50-1.00
B-	0	0.29	0.00-0.71	0.10	0.00-0.38
B-C	0.5	0.49	0.29-0.67	0.59	0.50-0.75
B-D	0.5	0.22	0.00-0.33	0.31	0.13-0.44

intended, one-sample t-tests were performed comparing the A-B, B-C, and B-D pairs to the intended transitional probability for each age group and condition (note that there was no need to compare A- and B- probabilities because those were not independent and were derived by subtracting A-B from 1 or B-C and B-D from 1, respectively). For the 12-month-old infants in the C-SP condition, A-B was significantly less than 1.0, $t(11) = 5.84$, $p < 0.0005$; B-C was not significantly different from 0.5, $t(11) = 0.11$, $p > 0.90$; B-D was significantly less than 0.5, $t(11) = 6.83$, $p < 0.0005$. For the 12-month-old infants in the SP-C condition, A-B was significantly less than 1.0, $t(11) = 5.72$, $p < 0.0005$; B-C was significantly greater than 0.5, $t(11) = 2.23$, $p < 0.05$; B-D was significantly less than 0.5, $t(11) = 7.10$, $p < 0.0005$. For the 16-month-old infants in the C-SP condition, A-B was significantly less than 1.0, $t(11) = 4.86$, $p < 0.0005$; B-C was not significantly different from 0.5, $t(11) = 0.26$, $p > 0.80$; B-D was significantly less than 0.5, $t(11) = 8.89$, $p < 0.0005$. For the 16-month-old infants in the SP-C condition, A-B was significantly less than 1.0, $t(11) = 3.92$, $p < 0.005$; B-C was significantly greater than 0.5, $t(11) = 3.93$, $p < 0.005$; B-D was significantly less than 0.5, $t(11) = 7.66$, $p < 0.0005$.

The above results indicate that the intended manipulation of transitional probabilities did not work in most cases for both age groups. A-B pairs were less likely than expected because infants were prone to look away before the B event. B-D pairs were also less likely than expected; infants needed to accumulate at least 25 seconds of looking to see the D event. Significant deviations from the expected probabilities impact the interpretability of the part sequence event, which presents infants with the B-C or B-D sequence. In particular, if infants display low looking to the B-C event, it could be that they did not learn the statistical regularities of the input, or that they never saw the D event, so the B-C sequence had a high probability of occurring. Therefore, given the lack of clarity regarding infants' performance on the part sequence test event, the data from that event were not included in the final analyses.

Habituation Phase. Infants' performance in the habituation phase was analyzed using a

2(age: 12-, 16-month-olds) x 2(condition: C-SP, SP-C) mixed groups ANOVA with both factors

as between-subjects variables. One analysis was conducted with total habituation time as the

dependent variable. A second analysis was conducted with decrement in looking as the

dependent variable. Decrement was defined as the one minus the ratio of total looking over the

last three trials to the total over the first three trials. The first analysis yielded no significant

effect of condition, $F(1,44) = 0.16$, $p = 0.69$, $\eta_p^2 = 0.004$, a trend towards a significant effect of

age, $F(1,44) = 2.68$, $p = 0.11$, $\eta_p^2 = 0.06$, and a trend towards an interaction between the two,

$F(1,44) = 2.41$, $p = 0.13$, $\eta_p^2 = 0.05$. Infants in the C-SP condition took the same amount of time

to habituate at 12 and 16 months ($M = 143.63$ s, $SD = 82.62$ and $M = 145.38$ s, $SD = 58.42$,

respectively) as indicated by an independent-samples t-test, $t(22) = 0.06$, $p = 0.95$. In contrast,

infants in the SP-C condition took significantly longer to habituate at 16 months than 12 months

($M = 103.01$ s, $SD = 58.69$ and $M = 169.37$ s, $SD = 84.05$, respectively) as indicated by an

independent-samples t-test, $t(22) = 2.24$, $p = 0.04$. These results suggest that some differences

were present in the amount of time it took infants to habituate, which were a function of the

infants' age and habituation condition.

The second analysis, which had decrement as a dependent variable, did not yield

significant effects of age, $F(1,44) = 1.04$, $p = 0.31$, $\eta_p^2 = 0.02$ and condition, $F(1,44) = 0.20$, $p =$

0.66, $\eta_p^2 = 0.004$, and no significant interaction between the two, $F(1,44) = 0.13$, $p = 0.72$, $\eta_p^2 =$

0.003. Thus, infants at both ages decreased in looking during habituation by the same amount in

both conditions.

The apparent difference in habituation time with no difference in decrement suggests that

infants' habituation trajectories may have varied across age or condition. That is, it is possible

that infants' initial or final looking times were not uniform across those variables. To investigate

this, a final analysis of the habituation data compared initial and final looking using a 2(age: 12,

16 months) x 2(condition: C-SP, SP-C) x 2(habituation block: first three trials, last three trials)

mixed ANOVA with looking time as the dependent variable, age and condition as between-

subjects independent variables, and habituation block as a within-subjects independent variable.

The analysis yielded a significant main effect of habituation block, $F(1,44) = 175.09$, $p < 0.0005$,

$\eta_p^2 = 0.80$, with longer looking during the first three ($M = 86.05$, $SD = 40.96$) than the last three

trials ($M = 31.45$, $SD = 17.01$). The effect of condition was not significant, $F(1,44) = 1.10$, $p =$

0.30, $\eta_p^2 = 0.02$, and there was a trend towards an effect of age, $F(1,44) = 2.25$, $p = 0.14$, $\eta_p^2 =$

0.05, with longer habituation times of 16- than 12-month-olds ($M = 64.76$, $SD = 24.90$ and $M =$

52.74, $SD = 30.09$, respectively). No interactions were significant (all ps > 0.25). The absence of

interactions implies that habituation patterns were uniform across age and condition.

Test Phase. Infants' performance in the test phase is shown in Figures 7A (12-month-

olds) and 7B (16-month-olds); the means and standard deviations appear in Table 7. Preliminary

analyses indicated that sex of the infant and test trial order did not have a significant effect on

looking time. Accordingly, the data were collapsed across the levels of these variables. The

Table 7.
Mean looking times, in seconds, during the test trials of Experiment 5 as a function of infants' age, assigned habituation condition, and the test trial type. Standard deviations are given in parentheses.

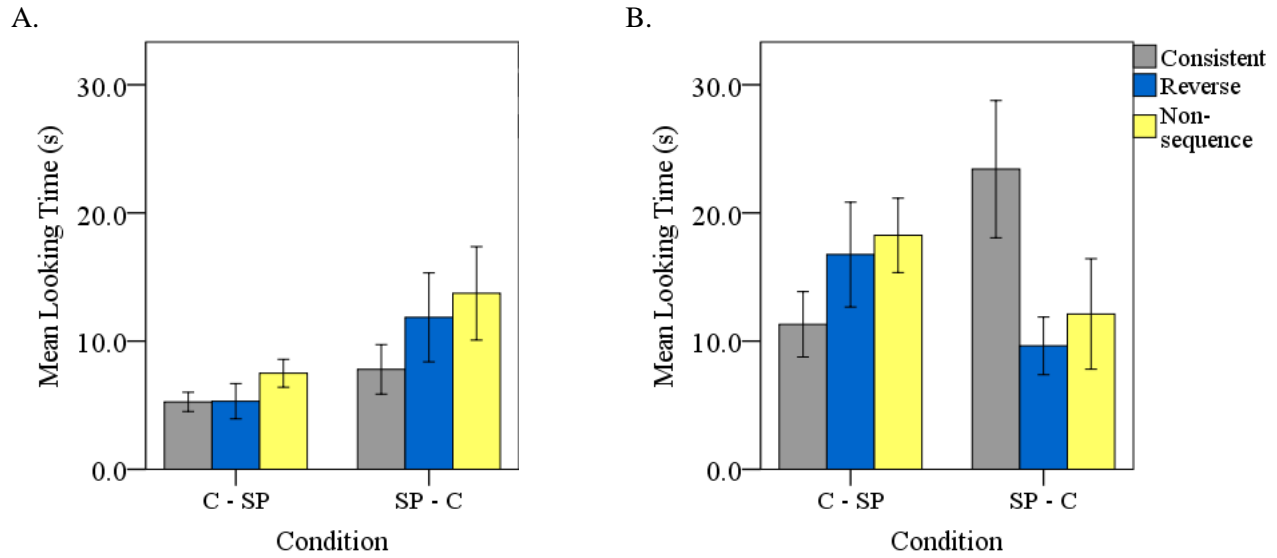| Test Trial Type	12-month-olds (N=24)		16-month-olds (N=24)	
	C-SP Condition (N=12)	SP-C Condition (N=12)	C-SP Condition (N=12)	SP-C Condition (N=12)
Consistent	5.26 (2.59)	7.79 (6.69)	11.31 (8.85)	23.42 (18.54)
Reverse	5.31 (4.77)	11.85 (12.01)	16.75 (14.16)	9.63 (7.79)
Non-Sequence	7.49 (3.78)	13.73 (12.64)	18.25 (10.06)	12.12 (14.93)

A.   B.

Figure 7. Infant's performance in the test phase of Experiment 5 as a function of age and habituation condition. Panel A displays 12-month-olds' data, and Panel B displays 16-month-olds' data. Both age and condition influenced performance on the test trials.

primary goal of the test phase analysis was to investigate the effects of age, condition, and test trial type on infants' looking time. To do so, a 2(age: 12, 16 months) x 2(condition: C-SP, SP-C) x 3(test trial: consistent, reverse, non-sequence) mixed ANOVA was performed, with age and condition as between-subjects independent variables, test trial as a between-subjects independent variable, and looking time as the dependent variable. The analysis yielded a main effect of age, $F(1,44) = 9.79$, $p = 0.003$, with 16-month-olds looking longer overall than 12-month-olds. The main effects of condition and test trial were not significant, $F(1,44) = 1.23$, $p = 0.27$, $\eta_p^2 = 0.03$, and $F(2,88) = 0.52$, $p = 0.60$, $\eta_p^2 = 0.01$, respectively. There was a marginal interaction between test trial and condition, $F(2,88) = 2.39$, $p = 0.10$, $\eta_p^2 = 0.05$, and a significant three-way interaction between test trial, age, and condition, $F(2,88) = 5.50$, $p = 0.01$, $\eta_p^2 = 0.11$. The three-way interaction was explored further with separate analyses for each age group.

Twelve-month-olds. To explore the effects of test trial and condition on infants' looking

time at 12 months, a 2(condition: C-SP, SP-C) x 3(test trial: consistent, reverse, non-sequence) mixed ANOVA was conducted with condition as a between-subjects factor and test trial as a within-subjects factor. Looking time was the dependent measure. The analysis yielded a significant main effect of condition, $F(1,22) = 4.66$, $p = 0.04$, $\eta_p^2 = 0.18$: infants in SP-C looked longer overall than infants in C-SP, regardless of which test trial they were viewing. There was also a trend towards a main effect of test trial, $F(2,44) = 2.09$, $p = 0.14$, $\eta_p^2 = 0.09$; follow-up paired-samples t-tests indicated that infants looked marginally longer at the non-sequence than the consistent test trial $t(23) = 1.91$, $p = 0.07$ ($M = 10.61$ s, $SD = 9.66$ and $M = 6.53$, $SD = 5.13$, respectively), and there was a non-significant tend of longer looking at the reverse than the consistent test trial $t(23) = 1.35$, $p = 0.19$ ($M = 8.57$ s, $SD = 9.54$ and $M = 6.53$, $SD = 5.13$, respectively). The interaction between test trial and condition was not significant, $F(2,44) = 0.62$, $p = 0.54$, $\eta_p^2 = 0.03$. These results conform to the original predictions that 12-month-olds would not show different performance in the two conditions.

Sixteen-month-olds. Similar to the 12-month-olds' data, the 16-month-olds' looking time data were analyzed using a 2(condition: C-SP, SP-C) x 3(test trial: consistent, reverse, non-sequence) mixed ANOVA with condition as a between-subjects factor and test trial as a within-subjects factor. The analysis yielded no significant effect of condition, $F(1,22) = 0.01$, $p = 0.92$, $\eta_p^2 = 0.001$, and no significant effect of test trial, $F(2,44) = 0.76$, $p = 0.48$, $\eta_p^2 = 0.05$. However, the interaction between test trial and condition was significant, $F(2,44) = 5.09$, $p = 0.01$, $\eta_p^2 = 0.34$. Follow-up paired-samples t-tests were used to compare the consistent trial to the reverse and the non-sequence separately for each condition. In the C-SP condition, infants looked equally long at the consistent and reverse trials, $t(11) = 1.06$, $p = 0.31$, and they looked longer at the non-sequence trial than the consistent trial, $t(11) = 2.58$, $p = 0.03$. In the SP-C condition, infants looked longer at the consistent trial than the reverse trial, $t(11) = 2.43$, $p = 0.03$; they also

looked longer at the consistent trial than the non-sequence trial $t(11) = 2.25$, $p = 0.05$. Thus, the 16-month-olds showed a familiarity preference in the SP-C condition and a novelty preference in the C-SP condition, but only to the non-sequence trial. These results are consistent with the broad prediction of an interaction between condition and test trial for 16-month-old infants, but they are inconsistent with the specific predictions for differences between test trials.

Discussion

The goal of Experiment 5 was to investigate 12- and 16-month-old infants' abilities to learn two-event sequences that are presumed to be consistent or inconsistent with their daily experience. In particular, it was hypothesized that infants' generalization between causality and self-propulsion is based on daily experience in which self-propulsion is more likely to come after causality than before it. Accordingly, it was expected that if infants obtain such experience in the real world, then they should be more likely to learn a "causality then self-propulsion" sequence in the laboratory, than a "self-propulsion then causality" sequence. Furthermore, this pattern should emerge over time such that older infants, who have more experience, would be more likely to show learning of only one order of events. To test this, half of the infants were habituated to a four-event sequence in which causality always came before self-propulsion, and half of the infants were habituated to a four-event sequence in which self-propulsion always came before causality. Following this, infants were tested on the familiar ordering of self-propulsion and causality, the reverse of that ordering, and the first event of the ordering followed by an arc or bounce event, which never appeared in the second position. The data from the fourth test event were not analyzed because preliminary analyses indicated that the transitional probability manipulation did not perform as expected.

The results from the habituation phase indicated that the amount of drop in infants' looking over the habituation phase was relatively uniform across both age groups and conditions.

However, the amount of time it took infants to habituate varied. In particular, 16-month-old infants in the SP-C condition took longer to habituate than 12-month-old infants, but no such difference was observed in the C-SP condition. An analysis of the test phase data yielded a complex pattern of performance in which age, condition, and test trial type interacted in their influence on looking time. For the 12-month-old infants, performance was consistent in the two conditions: infants showed a trend of looking longer at the reversed ordering of events and the non-sequence pair of events that never occurred together relative to the familiar order of the causality and self-propulsion events. For the 16-month-old infants, performance was not uniform in the two conditions. In the C-SP condition, infants showed a novelty preference to the non-sequence trial relative to the consistent trial, and no difference between the consistent and the reverse trials. In the SP-C condition, infants showed a familiarity preference for the consistent trial relative to the reverse and the non-sequence trials.

The results of the present experiment provide some preliminary support for the hypothesis that infants preferentially encode some orders of motion events over others, and that they become constrained in doing so over developmental time. Twelve-month-olds showed the same pattern of looking in both conditions of tending to look longer at events that did not accord with the ordering that they saw during habituation. Thus, at this age, infants were not better at learning one order of causality and self-propulsion than the other order. In contrast, 16-month-olds did show different patterns in the two conditions, although these patterns did not agree with the original predictions with respect to the expected differences between individual pairs of test trials. In the C-SP condition, infants showed only partial evidence of learning the sequential information. They did not dishabituate to the reversal of the causality-self-propulsion sequence, but they did dishabituate when causality was followed by an arc or a bounce. Thus, infants appear to have learned that the arc or bounce event does not follow causality and that self-

propulsion does follow causality. However, they do not appear to have learned that causality

does not follow self-propulsion. In the SP-C condition, infants' familiarity preference could

indicate that the information in the habituation phase was difficult to acquire. Prior research on

familiarity and novelty preferences has shown that the difficulty of the input determines infants'

looking such that information that is very complex can elicit familiarity preferences (Kidd,

Piantadosi, & Aslin, 2012; Roder, Bushnell, & Sasseville, 2000). Infants did not form a complete

representation of the SP-C sequence during habituation, so they continued to exhibit elevated

looking to that event relative to the others in the test phase. It is possible that the difficulty of the

SP-C condition was due to the fact that the condition did not align with the expected order of

causality and self-propulsion that infants experience on a daily basis. Taken together, the test

trial data from the 12- and 16-month-old infants also provide some tentative evidence for a

developmental trajectory in which younger infants are less constrained in their learning than

older infants. This is supported by the habituation data as well: although in the C-SP condition

both age groups took the same amount of time to habituate, in the SP-C condition 16-month-olds

took longer than 12-month-olds, which could suggest that the "self-propulsion then causality"

sequence becomes more difficult to acquire than the reverse as children develop. Constraints on

learning can emerge as a result of experience: as infants gain more experience in the world, they

come to preferentially learn new information that is consistent with that experience rather than

information that is inconsistent (Rakison & Lupyan, 2008; Yermolayeva & Rakison, 2011).

Thus, it is possible that the real-world transitional probability from causality to self-propulsion is

higher than the transitional probability from self-propulsion to causality, which causes infants to

encode the former order of events but not the latter order of events in the laboratory.

Although the present study has provided some preliminary evidence for an emergence of

preferences for a particular order of causality and self-propulsion, it does not provide conclusive

evidence that a specific order does occur in infants' experience. This line of evidence was

pursued in the next study, which systematically examined infants' daily experience. The goal of

the study was to calculate the transitional probabilities between motion events that infants

observe in the real world to determine if statistical regularities between them exist.

Observational Study

The theoretical account of infants' generalization of motion cues that was introduced in

Experiment 5 proposed a connection between the probability of particular motion event pairs in

infants' experience and their ability to generalize between those two motions. It was

hypothesized that the probabilities of different motion event orders displayed by the same entity

are not uniform in infants' experience: some orders are more likely than others, and this enables

infants to generalize from the first motion property in the order to the second motion property.

This account has two implications. First, if infants do, in fact, encode sequential information

from their environment, then infants' learning of sequences in the laboratory should reflect the

hypothesized sequences to which they are exposed in the real world. Specifically, sequences that

are more probable should be easier to learn than sequences that are less probable. This

implication was supported by Experiment 5 in relation to the ordering of causal agency and self-

propulsion: agency followed by self-propulsion proved easier for infants to learn than self-

propulsion followed by agency. This was consistent with the hypothesis that the latter was less

probable in infants' daily experience than the former based on previously-demonstrated

generalization patterns by Cicchino et al. (2011). The second implication of the theoretical

account is that an analysis of infants' experience should show that the orders of various motion

events for individual entities are not uniform. The goal of the present study was to evaluate this

implication by quantifying infants' daily visual experience using data that were collected using a

head-mounted camera worn by a single infant in various contexts at 3, 8, and 12 months of age.

Specifically, the infant's experience with causal agency, recipiency, self-propulsion, and

stopping was coded. Based on this coding, the frequencies of individual motions, the frequencies

of motion pairs for unique entities, and the transitional probabilities within motion pairs for

unique entities were calculated. These three types of information were compared to behavioral

patterns of infants' generalization to assess which, if any, provided sufficient information to

support generalization. Note that frequencies of motion pairs as well as transitional probabilities

were evaluated because both encode sequential information but in different ways: the first

encodes how often a particular pair occurs regardless of other pairs that start with the same first

motion, whereas the second encodes how likely the second event is to occur after the first event.

Although comparisons have been made that show that infants attend to probability rather than

frequency (Aslin et al., 1998; Fiser & Aslin, 2002), these comparisons have not been made for

dynamic visual events. Thus, both types of sequential information were compared against the

frequency of individual events. It should be emphasized that the analysis tracked the order in

which a given entity (e.g., the primary caregiver, a particular toy) engaged in motion events. This

analysis was employed because the goal was to study infants' ability to generalize about an

unobserved motion property of an entity given its observed motion properties. It was theorized

that such generalization abilities about multiple motion properties of individual entities should be

supported by the sequential regularity of the motions in which single entities engage in the

world.

In recent years, numerous studies have explored young children's visual experience using

head-mounted cameras or head-mounted eye trackers. As discussed previously, Cicchino et al.

(2011) used data from a head-mounted camera to compare infants' visual experience with

motion properties to their generalization about motion properties. Yu et al. (2009) used a head-

mounted camera to examine the coupling between 18- and 24-month-olds' perception and action

while interacting with objects, particularly the role that children's actions play in constraining the amount of information that appears in their visual field (see also Smith, Yu, & Pereira, 2007 for a comparison between adults and children in a similar task). Aslin (2009) examined where infants look in natural environments such as a home or a store by collecting video using a head-mounted camera on an infant, showing the video to other infants, and measuring where they look using an eye tracker. Franchak et al. (2011) studied the implications of infants' physical constraints on their visual experience during free play with their mothers by using a head-mounted eye tracker. Such research on infants' visual experience not only has strong theoretical implications (e.g., Cicchino et al.'s account of generalization), but practical applications as well. For example, Noris, Benmachiche, Meynet, Thiran, and Billard (2007) have suggested that video collected by a head-mounted camera on an infant could be parsed by automatic face-detection algorithms and analyzed for different attention patterns to faces and objects, which could serve as a foundation for early detection of autism.

One concern that can arise with the use of a head-mounted camera to track children's visual experiences relates to the degree to which the information recorded by the camera reflects where the child is looking. Unlike a head-mounted eye tracker, which typically provides cross-hairs for the location of the child's gaze, the head-mounted camera only provides information about the general visual scene that is accessible to the infant and necessitates the assumption that the direction of the head correlates with the direction of the infant's gaze. This assumption is not unfounded: Von Hofsten and Rosander (1996) have shown that between 3 and 5 months of age, infants begin to turn their heads as they engage in smooth pursuit of objects with their eyes. Furthermore, Yoshida and Smith's (2008) systematic comparison of the image captured by a head-mounted camera to the true direction of 18- and 24-month-olds' gaze has shown agreement in 87% of the cases. Thus, although it is not apparent at which elements of the scene the infant is

looking, the head-mounted camera does provide an indication of all of the available information in the infant's environment that the infant could learn. It is more informative than simply collecting video around the infant with a fixed camera because it takes into account the constraints imposed by the infant on the available visual information.

The goal of the present study was to make predictions for the statistical regularities that should be found in infants' daily experience based on the behavioral work of Cicchino et al. (2011) and to evaluate those predictions based on measurements of that experience. Specifically, the focus was on the behavioral findings that 14-month-olds generalize from agency to self-propulsion, but they do not generalize from self-propulsion to agency or generalize from recipiency to self-propulsion, and they do not generalize from self-propulsion to recipiency. There are three possible types of regularities that infants could track: frequency of individual events, frequency of event pairs in a particular order, and transitional probabilities within pairs of events. For each type of regularity, the behavioral findings could be used to make predictions about the distribution of experience that would give rise to infants' generalization performance. That is, if it is assumed that infants' generalization performance depends on their experience with motion in the world, then there must be a particular pattern of event frequency, event pair frequency, or transitional probability that should be observed when their experience is examined systematically.

Frequency of individual events. Cicchino et al. (2011) argued that infants track how often individual events such as agency and self-propulsion occur, and infants' generalization ability depends on the strength of their representations. Because agency is more common than self-propulsion, it generates a stronger representation that can support generalization, unlike the representation of self-propulsion, which is too weak to do so. In accordance with the findings of Cicchino et al. that infants only generalize from causal agency to self-propulsion, it was expected

that if infants' generalization depends on frequency information, then agency should occur more often in infants' experience than self-propulsion. The behavioral finding that infants to do not generalize from recipiency to self-propulsion and that they do not generalize from self-propulsion to recipiency would necessitate that the two types of motion events be equally frequent in infants' experience. However, it appears unlikely that this prediction would be met because agent events by definition require recipient events, so if agent events are more common than self-propulsion then recipient events should be similarly more common than self-propulsion.

Frequency of event pairs. According to this account, infants do not track frequencies of individual events but rather frequencies of pairs of events that involve the same entity and occur in a particular sequential order. Event pairs that are more frequent generate stronger internal representations such that when the first event in the pair is presented, the second event in the pair is activated. If this account is accurate, three types of regularities should be observed in infants' environments. First, the pair "agency, self-propulsion" should be more common than "self-propulsion, agency" to explain the asymmetry in generalization between the two motions. Second, the pair "recipiency, self-propulsion" should be less common than "agency, self-propulsion" to explain why self-propulsion is only generalized to agents and not recipients. Finally, the pair "recipiency, self-propulsion" should be just as common as "self-propulsion, recipiency" to explain the finding that no generalization occurs between those motion properties.

Transitional probability within event pairs. Lastly, it is possible that infants track transitional probabilities between motion events, which, as discussed above, are calculated as the frequency of a particular order of two motion events divided by the total frequency of the first event. If infants track this type of information, then their asymmetrical generalization should be underwritten by a higher transitional probability from agency to self-propulsion than from self-

propulsion to agency. The absence of generalization from recipiency to self-propulsion should be supported by a lower transitional probability from the former to the latter as compared to the transitional probability from agency to self-propulsion. Finally, the absence of generalization from self-propulsion to recipiency should be supported by a comparable transitional probability from the former to the latter as the transitional probability from the latter to the former.

The infant's experience with causal agency, causal recipiency, self-propulsion, and stopping events was coded and the regularities discussed above were calculated to assess the accuracy of the predictions. Note that although no specific predictions were made about stopping, this event was coded because Experiment 1 demonstrated that infants are sensitive to this motion property. No predictions were made about stopping because it proved too difficult to develop a systematic way of coding stops as abrupt or gradual due to poor video quality. However, stopping was still included as a collapsed category without disambiguation between abrupt and gradual to ensure that transitional probability estimates were accurate for the other three event types. Note that collapsing abrupt and gradual stops does not affect these estimates.

Method

Data Source. The video data were collected by the Rochester Baby Lab at the University of Rochester and provided by Dr. Richard N. Aslin. These data were used previously for analyses of infants' looking at natural scenes by Aslin (2009) and for coding of self-propulsion and agency experience by Cicchino et al. (2011).

Participant. The videos were collected from one male infant who came from a suburban environment. The infant participated in the recording sessions as 3 months, 8 months, and 12 months.

Recording procedure. Videos were collected using a camera that was mounted on a headband worn by the infant. The camera fed video data to a digital video recorder, which stored

video clip segments of up to 9.45 minutes in length. Recordings were conducted in naturalistic

settings that were intended to be representative of the infant's daily experience such as feeding,

playing, or going for a walk and included settings both inside and outside of the home. The

settings were not identical across age groups: for example, at 8 months a recording was made

while the infant was brought along when his mother picked up a sibling at school, whereas

recordings in this setting were not made at 3 and 12 months. The settings provided a range of

interactions with objects and people but consistently included the mother and at least one

researcher from the Rochester Baby Lab. The total amount of video collected was 138.82

minutes at 3 months, 189.90 minutes at 8 months, and 140.78 minutes at 12 months.

Video samples. From the entire corpus of video provided by the Rochester Baby Lab,

samples of video were selected for coding. These samples were designed to provide a diverse

snapshot of experience at each age. Additionally, only videos that were of the maximum length

of 9.45 minutes were used. Because sequential analyses were employed that examined the order

of actions conducted by an individual entity, these videos provided the maximum amount of data

for the exploration of continuous action sequences. The final sample consisted for 6 videos at

each age which added up to 56.70 minutes of video (a range of 30-40% of the total video

collected at each age). At three months the videos depicted interactions in the home (2 videos), in

the car (1 video), at a grocery store (2 videos), and at a department store (1 video). The home and

car videos only included the mother and one researcher, whereas the grocery and department

store videos included other people as well. At eight months, the videos depicted interactions at

home during feeding (1 video), at home during play (1 video), at home during a large play group

(2 videos), and on a walk to pick up an older sibling at school (2 videos). The feeding at home

and the play videos included the mother and two researchers, and the play group and school

pickup videos included multiple adults and children. At 12 months, the videos depicted feeding

at home (1 video), play at home (2 videos), a car ride (1 video), a walk outside (1 video), and a

trip to the library (1 video). At this age, all environments except for the trip to the library

included only the mother and two researchers. These samples analyzed here are similar to those

analyzed by Cicchino et al. (2011).

      Coding. The videos were coded using openSHAPA software, an open-source software

that allows one to import a video and to mark events in that video. Four types of motion events

were coded: causal agency, causal recipiency, self-propulsion, and stopping. Additionally, the

identity of the entity engaged in the motion was coded with a number, to keep track of the order

of events in which a particular entity engaged. For example, if the video began with the mother

starting to move, then a rolling ball stopping, and then the mother stopping her motion, the

mother and ball were numbered 1 and 2, respectively, and the events were coded as "1-self-

propelled, 2-stop, 1-stop". Subsequently, whenever the mother or the ball engaged in additional

motion events later in the video, their motions were coded with those same numbers. Motion

events were recorded as single time point events with the time of the event recorded as the onset

of the motion. The output of this coding for each video was a sequential list of motion events in

which the humans and objects engaged throughout that video. The coding specifications for each

motion category are provided below. Examples of the different motions can be found in Table 8.

      Causal agency. A causal agency event was coded for an entity when that entity was

visibly in motion, came in contact with a stationary entity, and the stationary entity began to

move after contact either in conjunction with the agent (e.g., a hand picked up a ball) or on its

own (e.g., a hand pushed a ball and it rolled away). The onset of the contact demarcated the time

point at which the event was coded. The onset of the contact between the two entities and the

onset of the movement of the stationary entity must have been visible on the screen for causal

agency to be coded. Note that this is a more conservative estimate of causal agency than one

Table 8.

Examples of visual motion events coded for each event type.

Motion event	Example
Causal agency and recipiency	• The researcher (agent) picks up a cup (recipient) during lunch. • A rolling ball (agent) knocks over a toy (recipient) during play time. • A mother (agent) picks up her baby (recipient) during a play date. • The mother (agent) grabs the handle of a cabinet (recipient) and opens it.
Self-propulsion	• A car pulls away after stopping at a traffic light. • The researcher's head moves out of the frame after being stationary in front of the infant while making faces at him. • A baby starts crawling across the floor during a play session. • A toy hammer moves out of the infant's view after it was held in front of him and he did not take it.
Stopping	• The mother walks into a room and stops in the middle. • A cup is placed on a table. • A spoon comes into the infant's view and stops near his mouth during feeding time. • A researcher sits down in a chair.

used by Cicchino et al. (2011) who coded all events in which the movement of two entities

occurred as causal agency, regardless of whether or not the onset of contact was visible. This

more conservative estimate was adopted because it does not make assumptions about infants'

ability to assign agent and recipient roles for cases where two objects were in contact and began

to move simultaneously without any clear evidence of which entity caused the motion of the

other entity.

  Causal recipiency. Whenever causal agency was coded for one entity, causal recipiency

was coded for one or more entities because the definition of causal agency implies that there is a

recipient of the agentive action. Recipiency was coded for any entity that was previously

stationary and was set in motion after the agent came in contact with it. As with agency, the

onset of the contact marked the time point of the event, and both the contact and the motion

onset needed to be visible for recipiency to be recorded. Multiple recipients could be coded for a single agent because the agent could cause more than one thing to move. For example, a hand could pick up two toy blocks, both of which would be considered recipients.

      Self-propulsion. Self-propulsion was coded for an entity when the entire visible portion of the entity went from stationary to moving either horizontally or vertically while on-screen without visible contact from another entity. That is, although there may have been other portions of the entity that were stationary, self-propulsion was coded as long as the stationary portions were not visible. Furthermore, no other entity could have come in contact with the target entity prior to the onset of its motion. For example, consider the event of a person who is sitting at a table with one hand resting on the table. After a period of time, the person lifts up the hand and begins gesticulating. If the entire person is visible to the infant, then the event would not be coded as self-propulsion. If only the person's hand is visible to the infant, then the event would be coded as self-propulsion. According to this definition, it is assumed that self-propulsion is a motion property that is attributed to whole entities rather than parts of entities, consistent with the way in which it has been tested in previous work (e.g., Cicchino et al., 2011; Luo et al., 2009; Markson & Spelke, 2006; Rakison, 2006), and that self-propulsion is attributed to the entire entity when all visible portions of an entity are consistently moving. The latter point avoids making assumptions about the ways in which infants interpret various motion events in which only some parts of objects or people are visible. Consider four cases of partially-visible entities that are initially stationary in view and then begin to move: (1) a person's hands; (2) a person's feet; (3) a spoon; (4) a file cabinet drawer. The off-screen portions in those four cases could be engaged in very different things while the on-screen portions exhibit similar motion onsets: (1) the person may be sitting down and simply shifted their hands out of the infant's view; (2) the person may have walked away; (3) a person may have picked up the spoon and caused it to move

so that although the entire spoon is moving, it is actually not moving on its own; (4) a hand that is not visible has moved the drawer but the rest of the cabinet is stationary. Furthermore, one can imagine that even for a single example of visible self-propulsion, multiple alternatives could be happening off-screen: a drawer that is seen as moving could have moved because a person's hand that is it out of view pushed it, or because the entire cabinet was moved. To avoid making assumptions about what infants expect to occur off-screen for similar on-screen motion onsets, the stance was adopted to code all such events as self-propelled.

      Stopping. A stopping event was coded for an entity that went from moving horizontally or vertically to not moving either because it came in contact with another entity, or because it simply stopped moving on its own. Similar to self-propulsion, only events in which the entire visible portion of the entity went from moving to stationary were considered stopping events. Again, this was done to avoid attempts at guessing as to what may have occurred off-screen and making assumptions about infants' abilities to make such inferences. Although Experiments 1-4 focused on the distinction between abrupt and gradual stopping, it proved too difficult to code this distinction from the video, particularly because of the frequent motion of the camera as well as the difficulty in coding stopping events which occurred towards the infant or away from the infant. Thus, stopping was coded as a collapsed category. As mentioned above, because the present studies have shown infants' sensitivity to stopping, this event category was coded to ensure the proper calculation of transitional probabilities.

      Data processing. The coding of individual events for all videos was the first step in assessing infants' experience. The next step involved processing the data to calculate the frequencies of individual events, frequencies of event pairs, and transitional probabilities within event pairs. To calculate the frequency of individual events, the total number of occurrences of agency, causal recipiency, self-propulsion, and stopping was computed separately for each age at

which the infant was studied.

With respect to the frequency of event pairs, there were 16 possible event pairs that could have occurred based on the four individual motions (this included event pairs that consisted of the same motion such as "causal agency, causal agency"). To calculate the frequency of each of these event pairs, the complete sequence of events for each video was parsed into separate sequences for individual entities (e.g., the order of the events in which the mother engaged; the order of the events in which the toy hammer engaged). Then, for each entity the number of times each of the 16 event pairs occurred was counted. These counts were added across all entities and across all videos within the same age to generate the total number of occurrences of each pair that the infant experienced at 3, 8, and 12 months.

Finally, to calculate the transitional probabilities from the first event in a motion pair to the second event for all of the 16 possible pairs, the frequency information for individual events and pairs of events was combined. Specifically, the frequency of each event pair was divided by the frequency of the first event in the pair; these calculations were performed separately for each age group. For example, to calculate the transitional probability from agency to self-propulsion, the frequency of the order "agency, self-propulsion" was divided by the frequency of agency overall. This generated the probability of an entity displaying the second event in the pair, given that the first event has occurred in the infant's experience at 3, 8, and 12 months.

Results

There were four behavioral findings of Cicchino et al.'s (2011) work on infants' generalization that the present study sought to relate to infants' experience. First, infants generalize from agency to self-propulsion. Second, they do not generalize from self-propulsion to agency. Third, they do not generalize from recipiency to self-propulsion. Fourth, they do not generalize from self-propulsion to recipiency. As discussed above, these behavioral data could be

Table 9.

The number of individual motion events in the infant's experience at 3 months, 8 months, and 12
months during the 6 videos with a combined time of 56.70 minutes at each age.

	Motion Event			
Age	Agency	Recipiency	Self-Propulsion	Stopping
3 months	25.00	27.00	63.00	79.00
8 months	75.00	100.00	104.00	174.00
12 months	84.00	184.00	61.00	219.00

explained by infants' experience with the frequency of individual events, frequency of event

pairs, or transitional probabilities within event pairs. The results below report on the regularities

that were found in the environment for each of these three types of information to assess if these

regularities could, in fact, support generalization about motion properties.

Frequency of individual events. Table 9 presents the number of times the four

individual events occurred overall, as well as split by age group. As discussed above, there were

two predictions made from the perspective of this theoretical account. First, agency should be

more common than self-propulsion. Second, recipiency should be equally common to self-

propulsion. The first prediction was evaluated using chi-square analyses. A preliminary analysis

indicated that age and motion event type were not independent, $\chi^2(2) = 20.29$, $p < 0.0005$;

accordingly, the distribution of self-propulsion and agency was analyzed separately for each age

group. At 3 months and 8 months, agency was less common than self-propulsion, $\chi^2(1) = 16.41$,

$p < 0.0005$ and $\chi^2(1) = 4.70$, $p < 0.05$. At 12 months, agency was marginally more common than

self-propulsion $\chi^2(1) = 3.65$, $p < 0.10$. Thus, there appears to be no support for the prediction at 3

and 8 months, and only limited support at 12 months.

It is possible that the findings did not accord with those of Cicchino et al. (2011) because

they only examined agency and self-propulsion for animate entities whereas the present analysis

included animates and inanimates. The analyses above were rerun using only events in which

animates engaged in these motions. At 3 months, self-propulsion was more common than

agency, $\chi^2(1) = 5.39$, $p < 0.05$ (43.00 versus 24.00 instances, respectively). At 8 months, the two

motion properties were equally common, $\chi^2(1) = 1.18$, $p > 0.20$ (78.00 instances of self-

propulsion and 65 instances of agency). At 12 months, agency was more common than self-

propulsion, $\chi^2(1) = 13.79$, $p < 0.0005$ (78 versus 38 instances, respectively). Thus there appears

to be shift from self-propulsion being more common to agency being more common as the child

develops, but only for animate entities. Suggestions for the source of this finding as well as the

discrepancy between these results and those of Cicchino et al. are addressed below in the

discussion section.

The second prediction that was evaluated for this account was that recipiency and self-

propulsion should be equally common in infants' experience. A preliminary chi-square analysis

indicated that age and motion event were not independent, $\chi^2(2) = 64.99$, $p < 0.0005$, so analyses

were conducted separately for each age group. A 3 months, self-propulsion was more common

than recipiency, $\chi^2(1) = 14.40$, $p < 0.0005$; at 8 months, self-propulsion and recipiency were

equally common, $\chi^2(1) = 0.08$, $p > 0.70$; at 12 months, recipiency was more common than self-

propulsion, $\chi^2(1) = 61.75$, $p < 0.0005$. These findings provide support for the prediction only at 8

months, but not at 3 or 12 months.

As with the comparison of agency and self-propulsion, it is possible that the results

depend on the animacy status of the moving entity. Specifically, it may be the case that

recipiency and self-propulsion are equally frequent only among inanimates. The analyses were

rerun for each age group only on the data from inanimate motion events. At 3 months, self-

propulsion was as frequent as recipiency (27 instances and 20 instances, respectively), $\chi^2(1) =$

Table 10.

The number of event pairs that occurred in the infant's experience across the three ages during

all 18 videos with a combined time of 170.1 minutes. Each cell in the table represents the

frequency of a single event pair, with the first event in the pair indicated by the row name on

the left, and the second event in the pair indicated by the column name at the top.

			Second Event in Pair		
First Event in Pair	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	104.00	4.00	25.00	22.00	29.00
Recipient	8.00	80.00	6.00	129.00	88.00
Self-Propulsion	16.00	10.00	33.00	117.00	52.00
Stopping	28.00	105.00	106.00	98.00	135.00

1.04, $p > 0.30$. At 8 months, recipiency was more frequent than self-propulsion (99 instances

and 26 instances, respectively), $\chi^2(1) = 42.63$, $p < 0.0005$. At 12 months, recipiency was also

more frequent than self-propulsion, $\chi^2(1) = 125.22$, $p < 0.0005$ (184 instances and 23 instances,

respectively). These results provide little support for the prediction that recipiency and self-

propulsion are equally frequent in infants' experience. Taken together with the findings

regarding agency and self-propulsion, it appears that there is no strong evidence for both of the

predictions made by the present account.

Frequency of event pairs. Table 10 presents the frequency of all possible event pairs for

the three ages combined (similar tables split by age group can be found in Appendix B); each

cell of the table represents a pair of events where the event listed in the row name is the first

event and the event listed in the column name is the second event. For example, the first cell in

the second row presents the number of times the infant saw an entity engage in recipiency

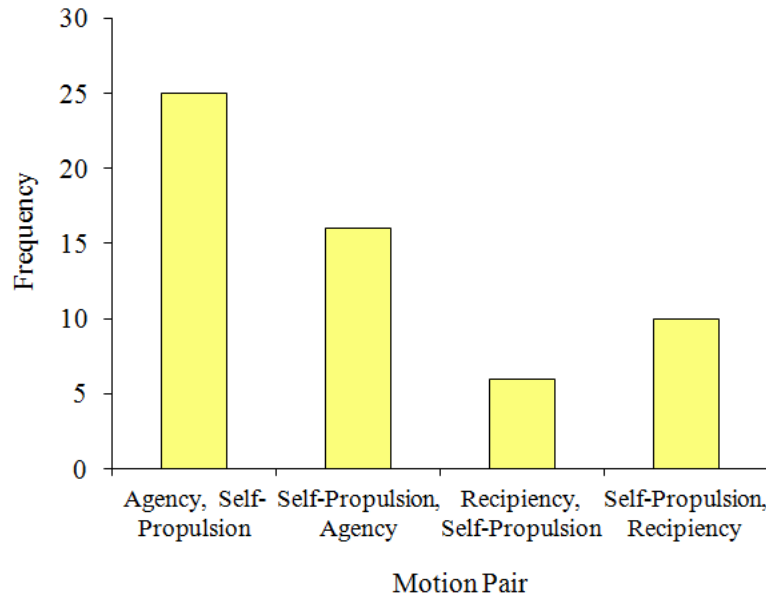followed by agency, which occurred 8 times over the 56.70 minutes of coded video. Note that

Figure 8. The frequency of particular motion event pairs in the infant's experience across all three ages.

the table also includes an additional column of frequencies for cases where only one event occurred without a second event. Chi-square analyses were used to compare three specific predictions for the expected distributions of event pairs. The frequencies of the event pairs relevant to the predictions are depicted graphically in Figure 8.

First, it was predicted that "agency, self-propulsion" should occur more frequently than "self-propulsion, agency". A preliminary analysis indicated that age was independent of motion event, $\chi^2(2) = 1.08$, $p > 0.50$, so this prediction was tested for the combined data across the three age groups. The combined analysis showed a non-significant trend of in the predicted direction, with "agency, self-propulsion" being more common than the reverse, $\chi^2(1) = 1.98$, $p < 0.20$, providing very tentative evidence in support of the prediction.

A second prediction stated that "recipiency, self-propulsion" should be less common than "agency, self-propulsion" because infants only generalize from agency to self-propulsion but not from recipiency. Overall, the "recipiency, self-propulsion" pair was rare in infants' experience, so individual analyses by age could not be performed due to low cell counts of less than 5 for

each age group. Accordingly, a chi-square analysis was used to compare the frequency of

"recipiency, self-propulsion" to the frequency of "agency, self-propulsion" for the three age

groups combined. The analysis indicated that the two event pairs were not equally frequent in

infants' environments, $\chi^2(1) = 11.65$, $p < 0.001$. Specifically, in agreement with the original

prediction, the pair "agency, self-propulsion" was more common than the pair "recipiency, self-

propulsion."

A third prediction stated that "recipiency, self-propulsion" should be as common as "self-

propulsion, recipiency" because infants do not generalize in either direction between the two

motion properties. Once again, because both motion pairs were very rare in infants' experience,

an aggregate chi-square analysis across all ages was conducted to compare the frequency of the

two event pairs. The analysis indicated that they were equally frequent, $\chi^2(1) = 1.00$, $p > 0.30$, in

accordance with the prediction. Taken together, the data for event pair frequencies provide solid

evidence for two of the three predictions, and a preliminary trend in support of the remaining

prediction.

Transitional probabilities within event pairs. The final type of information that infants

may encode is the transitional probability between pairs of motion events. There were three

specific predictions made for the regularities that should be found in infants' environments if this

type of information truly supports infants' generalization abilities. Due to the fact that this was a

very preliminary analysis of a corpus of visual data, the predictions were evaluated by a

qualitative examination of the obtained transitional probability values rather a statistical

comparison between them. The transitional probabilities for all possible motion event pairs for

the combined data across age are listed in Table 11 (similar tables of transitional probabilities for

each age group can be found in Appendix C); each cell in the table represents the transitional

probability from the motion indicated by the cell's row to the motion indicated by the cell's

Table 11.
The transitional probability within pairs of motion events. Each cell represents the transitional probability from the first event, as indicated by the row label on the left, to the second event, as indicated by the column label. Results are collapsed across age.

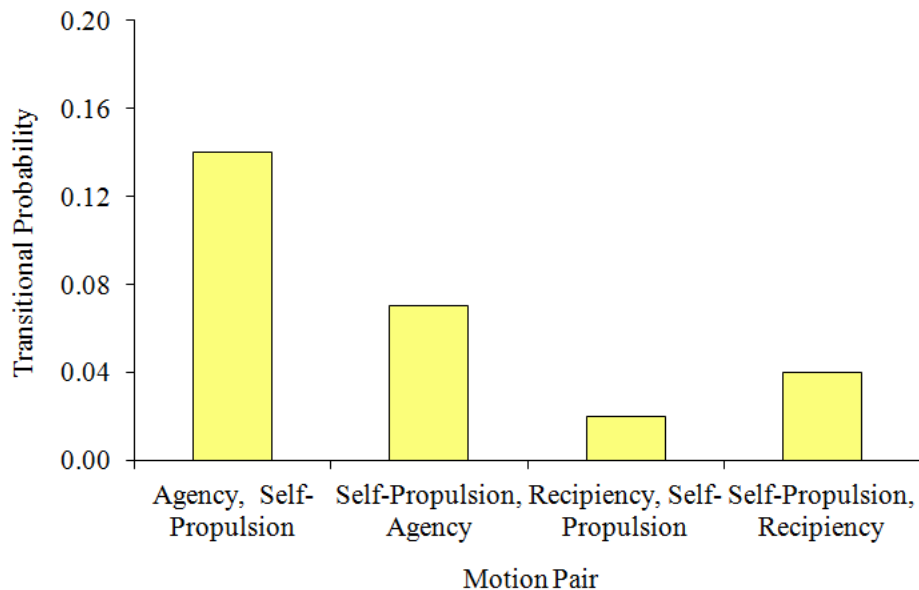| First Event in Pair	Second Event in Pair				
	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	0.57	0.02	0.14	0.12	0.16
Recipient	0.03	0.26	0.02	0.41	0.28
Self-Propulsion	0.07	0.04	0.14	0.51	0.23
Stopping	0.06	0.22	0.22	0.21	0.29

Figure 9. The transitional probability from the first event to the second event in each motion pair based on the infant's experience across the three ages.

column. Once again, the last column in the table represents cases where no motion event happened after the motions indicated by the rows of the column. The particular transitional probabilities that are relevant for the evaluation of the main predictions are depicted in Figure 9.

The first prediction was that if infants' asymmetric generalization is based on transitional probability information, then the transitional probability from agency to self-propulsion should

be higher than the transitional probability from self-propulsion to agency. The probabilities

presented in Table 11, in which the data for all three age groups were collapsed, demonstrated

this expected pattern: the transitional probability from agency to self-propulsion was 0.14, and

the transitional probability from self-propulsion to agency was 0.07. Crucially, the only other

motion event that was considerably more likely to follow agency than was self-propulsion was

another instance of agency (0.57 probability), whereas in the case of self-propulsion, both

stopping and another instance of self-propulsion were more likely to follow than agency (0.51

and 0.14, respectively). An examination of the data for the separate ages found similar patterns at

3 and 8 months, but not at 12 months. At 3 months, the likelihood of self-propulsion after agency

was more than three times higher than the likelihood of agency after self-propulsion (transitional

probabilities of 0.16 and 0.05, respectively). At 8 months, the likelihood of self-propulsion after

agency was 2.5 times higher than the likelihood of agency after self-propulsion (0.20 versus 0.08

respectively). However, at 12 months, the likelihoods of both were nearly equal: 0.07 transitional

probability from agency to self-propulsion and 0.08 from self-propulsion to agency. Taken

together, the data provide some support for the fact that regularities in the order of self-

propulsion and causality exist, although there may be differences in these regularities across

development.

        The second prediction was that the transitional probability from agency to self-propulsion

should be higher than the transitional probability from recipiency to self-propulsion because

infants generalize self-propulsion to agents but not to recipients. The aggregate data for the three

age groups provide evidence in support of this prediction: the transitional probability from

agency to self-propulsion was 0.14, whereas the transitional probability from recipiency to self-

propulsion was 0.02, a considerable difference. Furthermore, all other motion events were more

probable after recipiency than was self-propulsion. Individual patterns were not examined at

each age for the same reason as discussed above for the analysis of event pair frequency: the "recipiency, self-propulsion" pair was rare at each age (e.g., it occurred only once at 3 months), so it was unclear that the transitional probability for that event was reliable when the data were separated by age.

The final prediction was that the transitional probability from recipiency to self-propulsion should be comparable to the transitional probability from self-propulsion to recipiency because infants do not generalize in either direction between these two motion properties. The aggregate data did not support these predictions: recipiency after self-propulsion was more likely (0.04) than self-propulsion after recipiency (0.02). However, it should be noted that self-propulsion was the least likely event after recipiency and that recipiency was the least likely event after self-propulsion, which could suggest that in fact, these event pairs are comparable with respect to how unlikely they are relative to other events. Once again, individual analyses at each age were not conducted due to the rarity of these events. Taken together, the transitional probability data provide solid support for one of the three hypotheses, as well as some tentative support for the other two hypotheses.

Discussion

The goal of the present observational study was to compare the new proposed account of the representations that underlie infants' generalizations about object motion to two other accounts. Specifically, the three accounts were used to generate predictions regarding the distribution of experiences that infants should have in the world given their generalization behavior observed in the laboratory. Subsequently, these predictions were evaluated by quantifying infants' experience using data collected by a head-mounted camera worn by an infant and assessing which predictions were supported by the observed data. The target theoretical account proposed that there are regularities in infants' environments with respect to

the likelihood of an entity displaying motion events in particular orders, that infants learn these

regularities by encoding the transitional probabilities within pairs of motion events, and that

infants' generalization is underpinned by their ability to activate sequential information about the

second event in the pair when they observe the first motion event. The first contrasting

theoretical account was one proposed by Cicchino et al. (2011): individual motion events are not

uniformly frequent in infants' environments, infants form stronger representations of more

frequent events than less frequent events, and they generalize from stronger representations to

weaker representations. The second contrasting theoretical account posited that there are

regularities in infants' environments with respect to the frequency of event pairs occurring in a

particular order, infants encode these regularities, and their ability to generalize about motion

events depends on their ability to activate the second event in the pair when presented with the

first event in the pair.

A summary of the predictions made by each account and the evaluation of those

predictions can be found in Table 12. As can be seen from the table, the first contrasting account,

which focused on frequencies of individual events, made two predictions: agency should be more

frequent than self-propulsion, and recipiency should be as frequent as self-propulsion. There was

very limited support for both of these predictions. The first prediction was supported only by the

animate data at 12 months, and the second prediction was supported only by the inanimate data

at 3 months. The lack of supporting evidence for the same age suggests that it is unlikely that the

frequencies of individual events underwrite infants' generalization abilities.

The second contrasting account, which focused on frequencies of event pairs, made three

predictions. The first prediction, that agency followed by self-propulsion should be more

common than the reverse, received some limited support with a trend in the predicted direction

across age. The second prediction, that agency followed by self-propulsion should be more

Table 12.

Predicted regularities that were expected to be found for different types of motion event information in infants' environment that would allow infants to display particular patterns of generalization behavior. Each prediction was evaluated using measurements of infants' environments.

Behavioral Finding	Frequencies of Individual Events		Frequencies of Event Pairs		Transitional Probability	
	Predicted Regularities	Evaluation of Prediction	Predicted Regularities	Evaluation of Prediction	Predicted Regularities	Evaluation of Prediction
Infants generalize from agency to self-propulsion but not in reverse	Agency should be more frequent than self-propulsion	Limited support, only for animate entities at 12 months	The pair "agency, self-propulsion" should be more frequent than the reverse pair	Limited support, trend towards predicted pattern across age	Transitional probability from agency to self-propulsion should be higher than the reverse	Supported by data at 3 and 8 months, but not at 12 months
Infants do not generalize from recipiency to self-propulsion	Recipiency and self-propulsion should occur equally often in infants' experience	Limited support, only for inanimates at 3 months	The pair "recipiency, self-propulsion" should be less frequent than the pair "agency, self-propulsion"	Supported	Transitional probability from recipiency to self-propulsion should be lower than that from agency to self-propulsion	Supported
Infants do not generalize from self-propulsion to recipiency	Recipiency and self-propulsion should occur equally often in infants' experience	Limited support, only for inanimates at 3 months	The pair "recipiency, self-propulsion" should be as frequent as the reverse pair	Supported	Transitional probability from recipiency to self-propulsion should be equal to the reverse	Limited support, probabilities different from each other but equally low relative to other events

common than recipiency followed by self-propulsion, was supported across age. Finally, the last prediction, that recipiency followed by self-propulsion should be equally common to self-propulsion followed by recipiency, was supported across age as well. Thus, the observational data provide considerable support for the theory that infants encode frequencies of event pairs in their environment.

The target account, which focused on transitional probabilities within pairs of motion events, also made three predictions. The first prediction, that the transitional probability from agency to self-propulsion should be higher than the transitional probability from self-propulsion to agency, received some tentative support but only at 3 and 8 months. The second prediction, that the transitional probability from agency to self-propulsion should be higher than that from recipiency to self-propulsion, was supported across all ages. The last prediction, that the transitional probability from recipiency to self-propulsion should be higher than the reverse, received some limited support: although the former was less likely than the latter, both transitional probabilities were equally low relative to other possible events that could follow recipiency and self-propulsion. These findings provide some evidence in support of the proposal that infants generalize based on transitional probabilities; however, this evidence is not conclusive.

Taken together, the observational data provide the strongest evidence for the theory that infants encode frequencies of event pairs and the weakest evidence for the theory that infants encode frequencies of individual events. This was somewhat surprising given that prior research has shown that infants tend to encode transitional probabilities rather than frequencies in auditory tasks (Aslin et al., 1998) and visual tasks with static information (Fiser & Aslin, 2002). However, it is possible that the dynamic nature of the visual information examined in this study made it easier to encode frequencies rather than transitional probabilities.

Several caveats should be addressed in relation to the present findings. First, the data do not accord with the previous findings with respect to the frequency of agency and self-propulsion reported by Cicchino et al. (2011). Whereas their data showed more frequent agency than self-propulsion at all ages, the present data showed this pattern only at 12 months. The likely source of this discrepancy is the more conservative coding scheme adopted in the present study. Specifically, Cicchino et al. counted agency for events in which the onset of contact between two entities was not visible, but the present work did not count these events. It is unclear that infants can assign agent and recipient roles in such cases, so the present approach avoided making this potentially unfounded inference.

This limitation relates to a second, broader caveat of the observational data: the degree of inference about infants' perception and cognition in the coding scheme. Many motion events that occur in the infant's field of view are ambiguous, most often because the entity that is engaged in the motion is only partially visible. Adults can draw on their knowledge to interpret such events: for example, if they saw a part of an object moving in and out of their field of view, it is likely that they would infer that someone is moving that object and that the object is not moving on its own. It is unclear what types of prior knowledge infants have about motion that would help them to interpret such events, and how this knowledge may change over developmental time. As in the case of the definition of agency, the present coding scheme attempted to make as few assumptions as possible regarding infants' ability in this regard. However, in avoiding making unfounded assumptions, the present study may have underestimated infants' knowledge of motion.

A third limitation relates to the assumptions made about infants' memory abilities. The videos coded for the present study were nearly 10 minutes long, and continuous sequences of motion events were tracked throughout the entire video. Although in most cases the same entity

engaged in multiple motion events very close in time, there may have been cases where a single entity engaged in one motion event at the beginning of the video and a second motion event at the end of the video, with a gap of close to 10 minutes between them. This instance was still counted as an event pair, and it was assumed that infants can remember which entity engaged in which motion for up to 10 minutes. Studies of deferred imitation have shown that 6-month-old infants can imitate actions after a 24-hour delay (Barr, Dowden, & Hayne, 1996; Hayne, Boniface, & Barr, 2000), and 6-week-old infants can imitate facial expressions after a 24-hour-delay (Meltzoff & Moore, 2002), suggesting that even very young infants can remember dynamic information over considerable delays. However, these studies did not examine infants' ability to remember the link between identity and action, and they presented multiple training trials, unlike the motion events in the present study which occurred briefly and only once. Work by Bahrick and Newell (2008) has shown that 7-month-old infants can remember the identity of a person, and the action that person performed over a 1-minute delay, but longer delays were not tested. In future research, the observational data can be restricted to delays between event pairs of a particular maximum length. This will assess if the regularities in transitional probability and pair frequency are still present when only the events that occurred close in time are counted. Such analyses were not possible for the present study because the limited amount of data did not permit the deletion of event pairs due to long delays.

A fourth limitation relates to the degree to which the present video data are representative of infants' daily experience. Most obviously, the data from a single male infant in a suburban environment with no pets in the home and one sibling do not represent the wide range of experiences that infants around the world may have. Additionally, the samples of contexts that have been studied may not represent the distribution of these contexts in infant's daily experience. Consider the contexts examined at 8 and 12 months in the present study. At 8

months, two of the videos depicted "infant-centered" contexts that were specifically focused on

interactions with the child wearing the camera: feeding and playing with the mother and the

researchers. At 12 months, four of the videos depicted such contexts: feeding, playing with the

mother and the researchers (2 videos), and reading books during a trip to the library. The

proportion of time that infants spend in direct interaction with others can influence the types of

motion events that they see: for example, playing with blocks on the floor or being fed may give

the infant very little experience with self-propulsion and more experience with agency. In

particular, research on infant-directed motions has shown that adults change their motions when

interacting with infants (e.g., Brand, Baldwin, & Ashburn, 2002; Brand, Shallcross, Sabatos, &

Massie, 2007). Thus, infant-centered contexts in which infants receive direct social interaction

may provide a very different distribution of motion events than contexts in which infants observe

adults interacting with each other or engaged in solo activities. On the one hand, it is possible

that these differences in contexts across age reflect true differences in infants' experience: as

infants begin walking and talking, their interactions with the world may change such that a

greater portion of their day is spent interacting with others. As a result, there may be a shift in the

proportion of time that they experience agency and self-propulsion, as found in the frequency

data. On the other hand, it is possible that these differences reflect poor sampling, and that the

types of interactions and resulting experiences in infants' environments do not change as infants

develop. To address this issue, head-camera data for the entire day need to be collected to

examine the distribution of various contexts and potential changes in this distribution over

development.

A final limitation of the present study is the lack of information regarding the locus of the

infant's attention. Infants attend more to dynamic over static information (Lewkowicz, 2008;

Shaddy & Colombo, 2004), so in contexts where only one thing is moving in the infant's view it

is not unreasonable to expect that the infant is attending to that entity. However, in contexts where multiple things are moving (e.g., during a play group or a trip to the grocery store), the present analysis likely oversampled the number of motion events that the infant experienced, as it is unlikely that he attended to every motion event that was available in his field of view. This limitation can be addressed by the use of a head-mounted eye-tracker instead of a head-mounted camera.

In sum, the present study suggests that infants' ability to generalize between self-propulsion and causal agency may depend on their experience with the frequency of the two possible orders of those motion events. Agency followed by self-propulsion is more common than self-propulsion followed by agency, so infants have a stronger representation of the "agency, self-propulsion" sequence than the "self-propulsion, agency" sequence. Thus, when infants are shown instances of agency, they have a strong representation of the next motion event, but when they are shown instances of self-propulsion, they do not have a strong representation of the next motion event. This enables infants to generalize only in one direction between the two motion properties. The findings from the present study also accord with the findings of Experiment 5, which showed that the "agency, self-propulsion" sequence was easier for infants to learn than the reverse sequence. Infants' prior experience with the order of these events may have constrained their ability to learn about these events in the laboratory, particularly in the case of older infants who have had more experience in the world.

General Discussion

The goal of the present set of studies was three-fold: first, to probe infants' generalization in the domain of motion by using habituation experiments to examine their expectations about the manner in which agents and recipients stop; second, to develop a new account of infants' generalization about motion; third, to evaluate this account using experimental and behavioral

data. Experiments 1 through 4 were designed to address the first goal, and Experiment 5 and the

Observational Study were designed to address the second and third goals.

The findings from Experiments 1-4 demonstrated that by 16 months, infants have

expectations about the manner in which agents stop, but they do not have expectations about the

manner in which recipients stop. Specifically, infants expect agents to stop abruptly but not

gradually. Although a similar behavioral pattern was observed at 12 months, the results of

Experiments 2 and 3 suggested that this pattern may have been due to younger infants' attention

to perceptual cues about stopping during the habituation phase, rather than their ability to form

expectations about stopping based on observed causal agency. Additionally, infants younger than

16 months could not be induced to form expectations about stopping when additional motion

information was provided during the habituation phase. In Experiment 4, 14-month-old infants

did not exhibit different looking times to abrupt and gradual stopping of the target ball when the

habituation phase displayed both agency and self-propulsion of that ball; these findings were

similar to those of Experiment 2, in which 14-month-olds failed to generalize when the

habituation phase presented information only about agency.

A crucial question related to these findings and those of previous generalization studies

(e.g., Cicchino et al., 2011; Luo et al., 2009) relates to the nature of the underlying mechanism

that allows infants to form expectations about one motion property of an entity when they

experience that entity display another motion property. One possibility is that infants employ

domain-specific mechanisms to acquire information about animates and inanimates; these

mechanisms are typically considered to be innate and are specialized towards learning only about

the animate/inanimate distinction (Baillargeon, Li, Ng, & Yuan, 2009; Gelman, 1990; Gergely,

2011; Kinzler & Spelke, 2007; Leslie, 1994, 1995; Premack, 1990). When faced with a particular

motion event in the world, infants activate the appropriate animate or inanimate mechanism, core

knowledge system, or skeletal structure, which in turn activates the motion properties associated with that class of entities. Another possibility is that infants employ domain-general mechanisms that are not particularly targeted towards learning only about animates and inanimates to acquire the statistical regularities among the static and dynamic features of these classes of objects (Eimas, 1994; Madole & Oakes, 1999; Quinn & Eimas, 1996; Rakison & Lupyan, 2008; Rogers & McClelland, 2004). These associative links allow infants to generalize between properties of animates and inanimates. Crucially, unlike the domain-specific approach, the domain-general approach places a strong emphasis on the role that infants' experience plays in the development of the representations of animate and inanimate features and generalization between those features. Empirical evidence that has shown a close coupling between infants' experience and their expectations about motion properties (e.g., Cicchino et al., 2011; Cicchino & Rakison, 2008) has provided support for the domain-general account over the domain-specific account.

The present work attempted to further examine the domain-general account, and to specify the type of information infants extract from their environment that allows them to generalize about motion. Three potential alternatives were evaluated. The first was that infants extract information about the frequency of individual motion events (as suggested by Cicchino et al., 2011). The second was that they extract information about the frequency of event pairs in a particular sequential order for a single entity. The final alternative was that they extract information about the transitional probability within an event pair in a particular sequential order for a single entity. The advantage of the last two accounts in relation to the first account is their ability not only to explain the observed behavioral patterns of generalization but also their specification of the mechanism by which the presentation of one motion property activates the representation of another motion property, thus enabling generalization. Specifically, both accounts suggest that infants form representations of pairs of events, and the strength of the

representation is governed either by the frequency of the event pair in infants' experience
(second account) or the likelihood of the second event given the first event (third account). Once
the first motion event in the pair is presented, the representation of the entire pair is activated if it
is sufficiently strong, and the infant can generalize by forming a representation about the motion
event that is likely to occur next. In contrast, the first account, which is based on infants'
attention to individual motion events, does not specify how the input regarding one motion can
activate expectations about another motion.

The three accounts were evaluated using a combination of experimental and
observational work. The experimental work was designed to assess if particular sequences that
are thought to be more common or probable in infants' environments are easier to learn than
sequences that are thought to be less common or probable. In particular, the study focused on the
empirical finding that infants generalize from agency to self-propulsion but not in reverse
(Cicchino et al., 2011), which was theorized to be due to a stronger sequential representation of
"agency, self-propulsion" than "self-propulsion, agency." Consistent with the hypothesis, 16-
month-old infants showed more difficulty in learning the latter sequence than the former
sequence, which could suggest that their generalization about these motion properties is
governed by the order in which these events occur in their experience. Furthermore, the
experiment showed a developmental difference such that the 12-month-old infants displayed the
same pattern of learning regardless of the order to which they were habituated, which may
indicate that experience-based constraints on generalization emerge over time. This experimental
work was supplemented by an observational study that made direct measurements of infants'
experience with respect to the frequency of individual events, the frequency of event pairs, and
the transitional probabilities within event pairs. Specific predictions were made with respect to
the types of regularities that should be observed in the environment to explain infants'

generalization behavior. The analysis suggested that information about the frequency of event pairs was the most likely to give rise to infants' behavior, and the information regarding the frequency of individual motion events is least likely to give rise to infants' behavior.

Taken together, the experimental and observational studies suggest that there are regularities in infants' environments with respect to the order in which particular motion events occur, and that infants are sensitive to these orders, as demonstrated by their difficulty in learning an order that is inconsistent with their experience. These findings provide evidence against domain-specific theories in three respects. First, theorists who espouse the domain-specific point of view have suggested that specialized mechanisms are necessary because the information in infants' environments is too unconstrained and ambiguous for infants to be able to learn any coherent information with respect to animates or inanimates (Baillargeon & Carey, 2012; Gelman et al., 1995; Keil, 1991, 1994). However, the systematic coding of infants' experience in the Observational Study demonstrated that there are regularities in infants' environments with respect to the order in which particular motion events such as agency, recipiency, and self-propulsion occur. Furthermore, the results of Experiment 5 suggested that this information is not only available to infants: infants encode it and it constrains their future learning. Thus, infants' environments are not too complex for infants to be able to extract the information that allows them to generalize about motion properties of animates and inanimates. Second, domain-specific mechanisms or skeletal structures that support generalization leave little room for developmental change. The activation of a concept of animacy or inanimacy should support generalization about all associated motion properties at the same age. However, the results of Experiments 1 and 2 in conjunction with those of Cicchino et al. (2011) demonstrate that this is not the case, and that developmental lags are observed with respect to infants' generalization about different types of motion properties. For example, 14-month-old infants

cannot generalize from causal agency to abrupt stopping, but they can generalize from causal agency to self-propulsion. Third, according to domain-specific theorists, infants activate a representation of animacy when they observe particular motion events. However, the regularities found in the Observational Study did not draw on information about animates or inanimates. The motion events of these two classes of entities were analyzed together, yet informative regularities that were consistent with infants' generalization patterns still emerged. These findings suggest that infants may not need to activate a representation about animacy or inanimacy during generalization and can generalize directly from one motion property to another.

Although the Observational Study did not involve coding abrupt or gradual stops, some insights from this study can be made in relation to infants' generalization about stopping as studied in Experiments 1-4. First, according to the data in Table 10, the sequence "recipiency, stopping" was the most frequent sequence in infants' experience. However, infants failed to generalize abrupt or gradual stopping to recipients in Experiment 1. This could suggest that this failure was not due to a lack of experience with how recipients stop. Rather, although this type of sequence is common, it may be split between abrupt and gradual stops, such that infants experience "recipiency, abrupt stop" and "recipiency, gradual stop" equally frequently. This can explain their failure to generalize to one particular type of stop. Second, 14-month-old infants' failure to generalize about stopping when presented with multiple motion cues in Experiment 4 may have been due to the way in which these cues were presented in the habituation phase. Specifically, infants saw a ball that was self-propelled, then acted as a causal agent, and then was self-propelled again. The initial presentation of self-propulsion followed by causality may have confused infants because this sequence is not as common in their experience. As a result, they were unable to activate the appropriate representations that could support generalization about stopping. The last insight that can be drawn from the observational data relates to the

developmental trajectory of generalization from causal agency to self-propulsion and to abrupt stopping. Infants generalize from causal agency to self-propulsion at 14 months (Cicchino et al., 2011), but it is not until 16 months that they generalize from agency to abrupt stopping (Experiment 1). As seen in Table 10, the sequence "agency, stopping" is only slightly less common than "agency, self-propulsion" in the infant's experience. However, the former represents a sum of experience with abrupt and gradual stopping. Thus, it is possible that "agency, abrupt stopping" is less common than "agency, self-propulsion," which can account for the observed developmental trajectory in generalization about these motion properties: its takes infants longer to acquire the former sequence and use it in generalization.

There are several limitations of the present work that should be addressed. First, the behavioral experiments related to stopping only provided indirect evidence that 16-month-olds, unlike 12-month-olds, attend to causal roles during habituation and generalize based on those causal roles. To provide more definitive evidence, Experiment 3 should be conducted with 16-month-old infants to demonstrate that they do not show the same pattern of looking when causal roles are removed from the habituation stimulus. Second, the stimuli in the stopping experiments presented a very unrealistic manner of stopping that is not exhibited by most animate or inanimate entities other than balls. The bouncing motion did make the stopping more salient, but additional experiments need to determine if infants' expectations remain the same when stopping manner is presented in a way that is more similar to infants' experience in the world: for example, a horizontal abrupt or gradual stop that has no component of vertical movement. Twelve-month-old infants' performance in Experiment 3 provided some preliminary evidence that they can generalize from a horizontal abrupt stop to a bouncing abrupt stop, which suggests that infants are able to detect the manner of horizontal stops. It remains to be seen if infants would extend such stops to causal agents or recipients. Third, the experimental work on infants'

learning of sequences of motion events (Experiment 5) only demonstrated that they can learn these sequences, but it did not address whether infants encode frequency of motion event pairs or transitional probabilities between them due to the fact that the most frequent sequence in the habituation event was also the one with the highest transitional probability. The observational work has given some indication that infants may encode information about frequency and not transitional probability. However, this needs to be addressed experimentally by habituating infants to events that manipulate both frequency and transitional probability to assess any preferences in learning of either type of regularity in the input. Fourth, as discussed extensively in the Observational Study, the video data provide a very limited set of experiences and need to be expanded to a more representative sample that includes a wider range of infants from different backgrounds, as well as more sampling of their activities throughout the day. Finally, the observational data were subject to bias due to the fact that an adult coder may have made assumptions or interpretations of ambiguous motion events using knowledge that is unavailable to infants (e.g., being less likely to code a seemingly self-moving object as self-propelled because it is impossible for it to do so). The coding of the observational data can be improved by applying some of the existing video parsing algorithms that can automatically identify motion events that occur in the visual input (e.g., Efros, Berg, Mori, & Malik, 2003; Fujiyoshi & Lipton, 1998; Robertson, & Reid, 2005) to eliminate the bias inherent in human coding.

In addition to addressing some of the limitations found in the research reported here, future research can address a number of new questions related to infants' generalization about motion. First, more comprehensive coding of the observational data can be performed to examine infants' experience with other motion properties that are typically involved in the distinction between animates and inanimates (e.g., spontaneous change of direction), to assess how infants' experience with the sequential information about these motion properties compares

to their ability to generalize about them. Second, to provide experimental support for the coupling between infants' experience and generalization, training studies can be conducted with infants that manipulate their experience with various motion sequences to assess the impact on generalization between motion properties. Third, the relationship between stopping, agency, and recipiency can be explored in more detail. In the present work, causal agency was only examined in the context of an entity that causes the motion of another entity. However, an entity that stops the motion of another entity can also be thought of as a causal agent. Similarly, an entity that is stopped by something else can be thought of as a causal recipient. Future research can explore if infants expect entities that cause motion to be able to stop motion, and entities that are caused to move also to be caused to stop moving. Fourth, future research can explore the degree to which the motion regularities found in infants' environments are a product of the constraints imposed by the visual field of the infant. Specifically, it is unclear whether particular sequences of motion emerge because that is how the people and objects that surround the infant move or because the infant only sees some of the motion events due to the narrow field of view and constraints on attention (e.g., the infant may see many objects as self-propelled simply because the causal agent that moved the object is out of view and thus it appears that the object moved by itself). This line of work would coordinate with previous studies that have demonstrated the way in which the infant's view can serve to constrain the input in a manner that is beneficial for learning (e.g., Yurovsky, Smith, & Yu, in press). Finally, the findings of Experiment 5 in which older infants showed more constraint in learning than younger infants could be pursued further to assess if they are part of an N-shaped developmental trajectory that has been considered a marker of domain-general learning (Rakison & Yermolayeva, 2011). Specifically, infant learning across domains has shown a consistent developmental trajectory characterized by four steps: (1) infants initially are unable to acquire any information in the domain; (2) subsequently, infants acquire all

available information; (3) following that, infants acquire only information that is consistent with their experience; (4) at some point in later life, children and adults can acquire any information that is presented to them within the domain. The results of Experiment 5 potentially highlight two points on the trajectory: 12-month-olds' data gave some preliminary indication of unconstrained learning and 16-month-olds' data suggested constrained learning. Studies with infants younger than 12 months and older than 16 months could confirm if those groups fall into the expected N-shaped pattern, thereby providing support for domain-general learning of motion information.

In sum, the empirical and observational work reported herein has addressed the primary goals that were presented at the outset. First, the existing knowledge base on infants' expectations about motion has been expanded by the addition of empirical evidence that demonstrates infants' ability to generalize from agency to stopping. Second, the theoretical understanding of infants' generalization has been improved by the development and evaluation of a new account. Specifically, the results of the present work suggest that the basis of generalization lies in infants' ability to encode sequential information from their experience and to activate representations of these sequences when faced with motion events. This type of learning of sequential input is not specialized for learning about motion and has been demonstrated for a variety of inputs such as dynamic auditory information (e.g., Saffran et al., 1996) and static visual information (Kirkham et al., 2002). Thus, the present work provides further evidence that learning about motion properties that can be useful for forming the distinction between animates and inanimates is not fundamentally different from learning about other types of information.

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Appendix A

All possible combinations of the habituation and test events that were used in Experiment 5.

C-SP Condition

Habituation Event	Consistent Test	Reverse Test	Part-Sequence Test	Non-Sequence Test
Causality, Self-Propulsion, Arc, Causality, Self-Propulsion, Bounce	Causality, Self-Propulsion	Self-Propulsion, Causality	Self-Propulsion, Arc	Causality, Bounce
Causality, Self-Propulsion, Arc, Causality, Self-Propulsion, Bounce	Causality, Self-Propulsion	Self-Propulsion, Causality	Self-Propulsion, Bounce	Causality, Arc
Causality, Self-Propulsion, Bounce, Causality, Self-Propulsion, Arc	Causality, Self-Propulsion	Self-Propulsion, Causality	Self-Propulsion, Arc	Causality, Bounce
Causality, Self-Propulsion, Bounce, Causality, Self-Propulsion, Arc	Causality, Self-Propulsion	Self-Propulsion, Causality	Self-Propulsion, Bounce	Causality, Arc

SP-C Condition

Habituation Event	Consistent Test	Reverse Test	Part-Sequence Test	Non-Sequence Test
Self-Propulsion, Causality, Arc, Causality, Self-Propulsion, Bounce	Self-Propulsion, Causality	Causality, Self-Propulsion	Causality, Bounce	Self-Propulsion, Arc
Self-Propulsion, Causality, Arc, Causality, Self-Propulsion, Bounce	Self-Propulsion, Causality	Causality, Self-Propulsion	Causality, Arc	Self-Propulsion, Bounce
Self-Propulsion, Causality, Bounce, Causality, Self-Propulsion, Arc	Self-Propulsion, Causality	Causality, Self-Propulsion	Causality, Bounce	Self-Propulsion, Arc
Self-Propulsion, Causality, Bounce, Causality, Self-Propulsion, Arc	Self-Propulsion, Causality	Causality, Self-Propulsion	Causality, Arc	Self-Propulsion, Bounce

Appendix B

Tables of event pair frequencies by age group. For each cell, the first event in the pair is indicated by the row name on the left, and the second event in the pair indicated by the column name at the top.

Table A-1.
Event pair frequencies that occurred in the infant's experience at 3 months (6 videos, 56.7 minutes).

First Event in Pair	Second Event in Pair				
	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	10	1	4	1	9
Recipient	0	4	1	9	13
Self-Propulsion	4	3	5	33	18
Stopping	4	6	27	13	29

Table A-2.
Event pair frequencies that occurred in the infant's experience at 8 months (6 videos, 56.7 minutes).

First Event in Pair	Second Event in Pair				
	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	34	1	15	13	12
Recipient	7	17	2	31	43
Self-Propulsion	7	4	18	51	24
Stopping	14	24	49	29	58

Table A-3.
Event pair frequencies that occurred in the infant's experience at 12 months (6 videos, 56.7 minutes).

First Event in Pair	Second Event in Pair				
	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	60	2	6	8	8
Recipient	1	59	3	89	32
Self-Propulsion	5	3	10	33	10
Stopping	10	75	30	56	48

Appendix C

Tables of transitional probabilities within event pairs. Each cell's value is the transitional

probability from the event indicated by the row label to the event indicated by the column label.

Table B-1.
Transitional probabilities at 3 months across 6 videos (56.70 minutes).

| | Second Event in Pair | | | | |
First Event in Pair	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	0.40	0.04	0.16	0.36	0.04
Recipient	0.00	0.15	0.04	0.48	0.33
Self-Propulsion	0.06	0.05	0.08	0.29	0.52
Stopping	0.05	0.08	0.34	0.37	0.16

Table B-2.
Transitional probabilities at 8 months across 6 videos (56.70 minutes).

| | Second Event in Pair | | | | |
First Event in Pair	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	0.45	0.01	0.20	0.17	0.16
Recipient	0.07	0.17	0.02	0.31	0.43
Self-Propulsion	0.07	0.04	0.17	0.49	0.23
Stopping	0.08	0.14	0.28	0.17	0.33

Table B-3.
Transitional probabilities at 12 months across 6 videos (56.70 minutes).

| | Second Event in Pair | | | | |
First Event in Pair	Agent	Recipient	Self-Propulsion	Stopping	No Second Event
Agent	0.71	0.02	0.07	0.10	0.10
Recipient	0.01	0.32	0.02	0.48	0.17
Self-Propulsion	0.08	0.05	0.16	0.54	0.16
Stopping	0.05	0.34	0.14	0.26	0.22