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Six-Month-Old Infants Predict Agents' Goal-Directed Actions on Occluded Objects

Jessica B. Applin
Department of Psychological & Brain Sciences
Boston University

Melissa M. Kibbe
Department of Psychological & Brain Sciences
Center for Systems Neuroscience
Boston University

Infants can infer agents' goals after observing agents' goal-directed actions on objects and can subsequently make predictions about how agents will act on objects in the future. We investigated the representations supporting these predictions. We familiarized 6-month-old infants to an agent who preferentially reached for one of two featurally distinct objects following a cue. At test, the objects were sequentially occluded from the infant in the agent's presence. We asked whether infants could generate action predictions without visual access to the relevant objects by measuring whether infants shifted their gaze to the location of the agent's hidden goal object following the cue. We also examined what infants represented about the hidden objects by removing one of the occluders to reveal either the original hidden object or the unexpected other object and measuring infants' looking time. We found that, even without visual access to the objects, infants made predictive gazes to the location of the agent's occluded goal object, but failed to represent the features of *either* hidden object. These results suggest that infants make goal-based action predictions when the relevant objects in the scene are occluded, but doing so may come at the expense of maintaining representations of the objects.

From a young age, infants can infer other agents' attitudes toward objects by observing agents' interactions with objects. In pioneering work, Woodward (1998) habituated infants to an agent who consistently reached for and grasped one of two objects (e.g., a bear and a ball), always selecting one object (e.g., the bear) and not the other. During test trials, the locations of the objects were switched. In one condition, the agent reached for and grasped the goal object in its new location. In another condition, the agent reached toward the same location as in the habituation trials and grasped the

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Correspondence should be sent to Jessica B. Applin, Department of Psychological & Brain Sciences, Boston University, 64 Cummington Mall, Boston, MA 02215. E-mail: jbeal1@bu.edu

other object that was now in that location. Infants looked longer when the agent reached for this other object, suggesting that they inferred the agent's goal from her reaching and grasping behavior during habituation, and expected her to continue to exhibit this goal, regardless of the goal object's current location.

Infants can infer an agent's goal from a variety of behaviors, including gaze direction (Woodward, 2003; Wu & Kirkham, 2010), pointing (Sodian & Thoermer, 2004; Woodward & Guajardo, 2002), and reaching or grasping (Luo & Baillargeon, 2006; Woodward, 1998). Infants also are sensitive to intentional but uncompleted reaches toward objects, and categorize these actions as goal-directed (Brandone & Wellman, 2009; Csibra, Bíró, Koós, & Gergely, 2003; Hamlin, Hallinan, & Woodward, 2008). Further, infants as young as 3 months of age attribute goals to self-propelled agents, even when those agents are nonhuman (e.g., Csibra, 2008; Luo, 2011; Luo & Baillargeon, 2005). But, infants do not attribute goals to nonagentive objects (Luo & Baillargeon, 2005; Woodward, 1998). These studies suggest that infants' ability to infer an agent's goal from her behavior is early developing and is robust across a range of agents and goal-directed behaviors.

Although studies examining infants' goal inferences generally employ looking time methods (e.g., habituation and/or violation of expectation) that measure infants' ability to evaluate a completed action, several studies have also used predictive measures (e.g., anticipatory looking), which examine infants' ability to anticipate an agent's future action (Gredebäck & Daum, 2015). For example, Cannon and Woodward (2012) found that, after being familiarized with an agent preferentially reaching for one object over another, 11-month-old infants made predictive gazes to the location of the agent's goal during test trials before the agent engaged in a goal-directed reach. Furthermore, infants as young as 6 months may be capable of goal-related action prediction. Kochukhova and Gredebäck (2010) found that 6-month-olds predicted the completion of goals involving actions they have experience with (e.g., a spoon being brought to a mouth) but failed to do so with less familiar actions (e.g., a comb to hair) (see also Hunnius & Bekkering, 2010). Using a method more similar to the classic Woodward (1998) paradigm, Kim and Song (2015) found that 6-month-old infants who were familiarized with an agent preferentially reaching for one shape over another made predictive gazes to the goal shape during test trials. This work suggests that infants in previous studies using looking time measures may not have simply been responding passively to the action taken by the agent, but may instead have actively generated a prediction about her behavior and responded when that prediction was violated. However, at 6 months, the ability to generate action predictions may still be developing; Gredebäck, Lindskog, Juvrud, Green, and Marciszko (2018) found individual differences in 6-month-olds' ability to generate action predictions, and further found that this ability correlates with infants' ability to evaluate whether actions unfold appropriately (e.g., an object placed in an agent's outstretched hand rather than on her head), suggesting an emerging competence for action understanding at 6 months. Indeed, action prediction may be supported at least in part by the motor system (Gredebäck & Falck-Ytter, 2015; Krogh-Jespersen & Woodward, 2018; Kanakogi & Itakura, 2010), which at 6 months is still developing.

There have been several studies examining the conditions under which infants will *attribute* goals to agents (i.e., during habituation/familiarization trials). The contrast between the objects during familiarization/habituation is essential: infants do not represent actions as goal-directed when an agent reaches for an object that is the only one present (Luo & Baillargeon, 2005; Yoon, Johnson, & Csibra, 2008), suggesting that the *visual distinctiveness* of the objects during learning plays a critical role in goal attribution. Several studies also have explored the representations supporting goal attribution in infants. Over the course of familiarization/habituation, infants form long-term associations between the agent's goal and the features of that object (Feiman, Carey, & Cushman, 2015; Robson & Kuhlmeier, 2016). Infants also learn the typical time course of the agent's goal-related action: For example, they learn that the agent will reach for her goal object following a cue (e.g., a tone; Cannon & Woodward, 2012; Kim & Song, 2015) and can use this information to make an action prediction at the appropriate time.

Less is known about the representations supporting infants' goal-related behaviors *following* goal attribution—that is, when they must now evaluate and/or predict an agent's goal-related actions. In natural scenes, infants are unlikely to have visual access to all the information relevant for goal prediction at a single glance. Objects may become occluded as infant and agent navigate a three-dimensional environment. For example, when watching her mother prepare breakfast, the infant sees her mother place a bowl and a bottle of milk on the counter, retrieve the cereal box from the cabinet, pour some cereal into the bowl and the place the cereal box down on the counter in front of the milk bottle, obstructing the infants' view. Will the infant expect her mother to grasp the milk bottle the infant can no longer see in order to complete her cereal-preparation goal? In this simple example, the infant must keep track of an agent, her goal, and multiple objects that move in and out of occlusion in order to make sense of and predict another's actions.

How might occlusion impact infants' ability to make goal-related predictions? In previous work on infants' goal-related action predictions, infants viewed the agent and the two contrasting objects, and then made a saccade toward the goal object following a cue. One possibility is that infants' saccadic behavior may be based on low-level perceptual associations between the cue and the goal object. That is, infants learn that, following the cue, the agent will reach toward a particular object. When infants hear the cue, they may then shift their gaze to the location of the relevant object in the scene. Under this possibility, infants' saccades are driven by the *immediately available perceptual information* in the scene, so visual access to the array is required for action prediction. However, another possibility is that infants' agent–goal associations are not based simply on perceptual associations between the cue and features of the objects in the scene, but instead infants may be able to make predictions about an agent's goal-directed action even if the relevant objects move into occlusion. Under this possibility, infants may generate action predictions based on their *representations* of objects and/or agents; visual access to the objects is not necessarily required.

A related question concerns infants' representations of the objects in the scene once an action prediction is generated. In order to predict an agent's goal-related action, infants need to attend to the features of objects in the scene, decide which object matches the agent's goal, and predict that the agent will take an action on that object. But maintaining representations of objects and their features is attentionally demanding, especially as objects move into occlusion (Kibbe & Leslie, 2013; see Kibbe, 2015 for a review). Furthermore, generating action predictions may also be cognitively effortful: Krogh-Jespersen and Woodward (2014) found that 15-month-old infants who made predictive gazes in a Woodward (1998)-style task took longer to do so when their predictions were based on the agent's goal (e.g., the goal object in the new location) versus her previous reach direction (e.g., the old location), suggesting that generating goal-based action predictions may impose cognitive cost (see also Krogh-Jespersen & Woodward, 2018). When this cost is combined with the cost of maintaining representations of objects, once objects' features are used to generate an action prediction, infants may prioritize representing some objects over others. For example, infants may choose to allocate limited attention and working memory resources only to the goal-relevant object and fail to maintain a representation of non-goal-relevant aspects of the scene.

In the current study, we explored these questions. We familiarized infants to an agent who, following a cue, preferentially reached for one object over another, featurally distinct object. However, unlike in previous work (e.g., Cannon & Woodward, 2012; Kim & Song, 2015; Woodward, 1998), at test we *occluded* the objects prior to the cue, such that the objects were visible to the agent, but not visible to the infant. We chose to test 6-month-old infants, for two reasons. First, infants of this age have previously been shown to successfully infer agents' goals from their preferential reaching behavior (Luo & Baillargeon, 2005; Woodward, 1998) and to make gaze predictions based on agents' goals (Kim & Song, 2015; Kochukhova & Gredebäck, 2010), albeit with some variability (Gredebäck et al., 2018). Second, and most importantly, 6-month-olds' ability to maintain representations of two occluded objects (in the absence of a social agent) is well understood (Káldy & Leslie, 2005; Kibbe & Leslie, 2011, 2016, in press). In these studies, infants were familiarized with two featurally distinct objects (e.g., a disk and a triangle) placed sequentially on an otherwise empty stage. At test, the objects were placed sequentially behind opaque occluders. Infants' representations of these objects were examined by removing one of the occluders and revealing either the original hidden object or the unexpected other object, and measuring infants' looking times to these outcomes. This method has shown that, when objects are featurally distinct, 6-month-old infants represent the featural identity of the object that was hidden *last*, looking longer when the object is revealed to have changed (Káldy & Leslie, 2005; Kibbe & Leslie, 2016). However, 6-month-olds consistently fail to remember the featural identity of the object that was hidden *first* (Káldy & Leslie, 2005; Kibbe & Leslie, 2011, in press). This robust, frequently replicated signature pattern in 6-month-old infants' ability to represent two sequentially hidden objects can serve as a baseline for us to examine how their representations may be impacted when one of the objects is the target of an agent's goal-directed reach.

In our study, we combined the method of Woodward (1998) with that of Kibbe and Leslie (2011, 2016, in press; Káldy & Leslie, 2005). Thus, our design deviated from Woodward's (1998) basic design in three respects. First, following the design of Kibbe and Leslie (2011, 2016, in press; Káldy & Leslie, 2005), on each trial, the two objects (a disk and a triangle) were placed sequentially in front of the agent on an empty stage and then moved sequentially to the back of the stage by an experimenter whose gloved hand was visible to infants. Second, across trials, we counterbalanced the location of the shapes in both familiarization and test so that infants could not form long-term associations between particular objects and locations (Káldy & Leslie, 2005; Kibbe & Leslie, 2011, 2013, 2016, in press). This allowed us to examine infants' trial-specific representations. Third, we introduced occlusion during the test trials. After the objects were initially placed on the stage, they were then moved sequentially behind separate occluders, such that they were visible to the agent but not visible to infants. Critically, the goal object was always hidden *first*. Since 6-month-old infants typically remember the features of only the last-hidden of two sequentially hidden objects, and fail to remember the identity of the first-hidden of two sequentially hidden objects, hiding the goal object first allowed us to examine whether infants may differentially allocate resources to maintaining representations of the objects when the first-hidden object is highly relevant to an agent's goal.

We had two dependent measures. First, we examined whether infants would make predictive gazes to the location of the occluded goal object following the cue. This measure allowed us to examine infants' expectations about the agent's action. We reasoned that, if infants' goal-related action predictions are based on low-level perceptual associations between cue and object, then they should require visual access to the objects in the scene in order to generate action predictions, and therefore should not reliably make predictive saccades to the location occluding the goal object. However, if infants' goal-related action predictions are supported by more robust associations between agent and goal-action, infants should be able to deploy these predictions at the time of the cue, even when the objects are occluded. Thus, they should reliably make predictive gazes to the location of the occluded goal object.

Second, we examined what infants represented about the occluded objects by removing one of the occluders (either the one occluding the *first-hidden [goal] object* or the one occluding the *last-hidden [non-goal] object*, between subjects), revealing either the original hidden object or the unexpected other object, and measuring infants' looking time to these outcomes. This measure allowed us to examine what infants encoded or maintained about the features of the objects in the scene. In nonsocial contexts (e.g., Káldy & Leslie, 2005; Kibbe & Leslie, 2011, 2016, in press), infants show a robust pattern of remembering the features of the last-hidden object, but not the first-hidden object, a pattern that emerges from the attentional demands of trying to maintain an object representation (i.e., the first-hidden object) while tracking and subsequently representing another object (i.e., the last-hidden object) as it moves into occlusion (Kibbe & Leslie, 2013; Baillargeon et al., 2012). Hiding the goal object first allowed us to examine how infants encode objects when the objects' features are socially relevant. We reasoned that, when the first-hidden object is *goal relevant,* infants may prioritize encoding its identity, maintaining a representation of this object even as they observe another object move into occlusion. We thus predicted that infants would look longer when the first-hidden (goal) object is revealed to have changed. With regard to the last-hidden (non-goal) object (which 6-month-olds typically remember in nonsocial contexts), we did not have a strong prediction. If infants at 6 months are capable only of remembering a single object identity, and they prioritize encoding the goal-relevant object, infants may fail to remember the identity of the last-hidden object. Alternatively, highlighting the relevance of the first-hidden object may help infants to encode the identities of both objects, the object they typically remember (last-hidden) as well as the object they typically forget (first-hidden).

METHOD

Participants

Participants were 44 healthy, full-term infants (17 girls) between 5 months 1 day and 7 months 5 days of age (mean = 6 months 6 days). An additional seven infants were excluded due to fussiness (two), equipment malfunction (two), or experimenter error (three). Participants were recruited from the local area through family events and phoning lists. The present study was conducted according to guidelines outlined in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before data collection took place. All procedures involving human subjects were approved by the Institutional Review Board at Boston University. Infants received a small gift for their participation. Infants completed one of two conditions: 21 infants (mean age = 6 months 9 days, 6 girls) participated in the *first-hidden (goal) revealed* condition and 23 infants (mean age = 6 months 3 days, 11 girls) participated in the *last-hidden (non-goal) revealed* condition.

Design

Infants were first familiarized to an agent who watched as a gloved hand placed two objects, a disk and a triangle, sequentially at the front of an empty stage, and then moved them sequentially to the back of the stage. On each familiarization trial, following a squeaking sound, the agent reached out and grasped the disk. The order of object presentation (*disk first* or *triangle first*) and the objects' locations (*disk* or *triangle* on left) were counterbalanced across trials. Thus, during familiarization trials, the agent's goal object could be placed on the left or right side of the stage and could be placed first or last. During test trials, the agent watched as two opaque screens were first placed on the stage. Then, the objects were placed first in front of the screens and then moved one at a time behind their respective screens. The agent's goal object (the disk) was always hidden *first*. The objects were thus hidden from the infant but visible to the agent. As in the familiarization trials, following the placement of the objects behind the screens, infants heard the anticipatory signal (squeaking sound). After a brief anticipatory period (3 sec), one of the screens was lifted to reveal either the object that was hidden there originally (*control* outcome) or the other object (*swap* outcome) (within-subjects design). For infants in the *first-hidden (goal) revealed* condition, the screen occluding the first-hidden, goal object was removed. For infants in the *last-hidden (non-goal) revealed* condition, the screen occluding the last-hidden, non-goal object was removed.

To assess whether infants anticipate an agent's goal-directed action, we measured the direction of infants' first eye movements following the onset of the anticipatory signal (as in previous work examining predictive gaze in goal contexts; Cannon & Woodward, 2012; Kim & Song, 2015) but before the screens were removed. To assess whether infants remembered the identity of the hidden objects, we measured infants' looking time to the swap and control outcomes following the removal of the screen (as in previous work examining infants' representations of occluded objects; Káldy & Leslie, 2005; Kibbe & Leslie, 2011, 2016, in press).

Apparatus

Infants were seated on a caregiver's lap in an enclosed booth surrounded by curtains, approximately 110 cm away from a black-painted puppet stage (129 × 54 × 54 cm). Stimuli consisted of two wooden shapes painted red, a disk (diameter = 11.5 cm) and a triangle (base = 14.5 cm, height = 13 cm), and two black foam-core occluders (33.5 × 21.5 cm). Three researchers conducted the experiment: the agent, the experimenter, and the observer. The agent was visible through a 45 × 31 cm opening in the back of the stage and wore a black shirt and a yellow hat that obscured her eyes. The experimenter manipulated the wooden shapes from above the stage. She wore a long red glove over her hand and arm, and a bracelet of jingle bells around her wrist which she used to attract the infant's attention to the actions on the stage. The observer watched infants on a monitor located behind the stage and measured infants' gaze duration during test trials. A black curtain could be raised to cover the stage or lowered to reveal it. A camera embedded in the stage captured the infants' gaze, and a camera mounted behind the infant captured the stage. These were digitally mixed and recorded on a computer located behind the stage. The experimenter used a metronome to time her actions.

Procedure

Calibration

Before beginning the experiment, the experimenter lowered the stage curtain to reveal the empty stage (no agent or objects were present). The experimenter then reached in from above the stage, and drew infants' attention to the front and back corners, front and back center, and to the upper boundaries of the stage, by jingling the bells around her wrist at each location. This allowed the observer, who was watching the infant on a monitor, to get a sense of each individual infant's eye movements relative to the stage. The experimenter then raised the curtain, hiding the stage.

Familiarization

At the start of each trial, the experimenter lowered the stage curtain. Infants saw an agent seated behind the empty stage, with her head and shoulders visible through the opening in the back of the stage and her folded arms resting on the stage floor, one arm on top of the other (see Figure 1). The experimenter reached in from above the stage and placed two shapes (a disk and a triangle) one at a time toward the front of the stage, 13 cm apart. After 4 sec, the experimenter moved the shapes to their final positions toward the back of the stage, on either side of the agent (87 cm apart). The agent followed the trajectory of each shape with her gaze (note that since the agent's eyes were obscured by her hat, gaze direction was communicated by the agent's head movement, which was accentuated by the brim of her hat). After placing the last shape in its final position, the experimenter drew infants' attention to the center of the stage by jingling the bells on her wrist (positioned roughly in front of the agent's face) and saying, "Look!" She then removed her hand and played the 2 sec anticipatory signal (a squeaking noise). One second after the anticipatory signal ended, the agent reached out and grasped the *disk* using a cross-body reach (e.g., if the disk was on the agent's left, she used her right arm to reach and grasp the disk). The agent's gaze and body were likewise turned in the direction of the disk. The agent maintained this position for the duration of the trial. This display was visible to infants for 8 sec, after which the curtain was raised and the trial ended. Figure 1 shows a sample familiarization trial.

Across the four familiarization trials, the order of object presentation and location of placement were counterbalanced, so that infants could not form long-term bindings between particular shapes and locations or between the agent's reach direction and a particular location or temporal order. The agent's arm position on each trial was not a

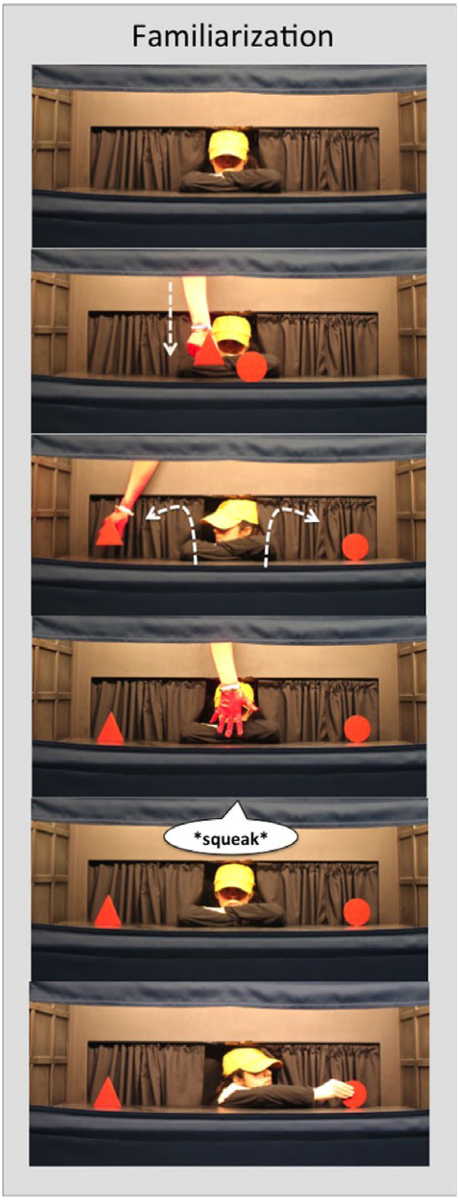

Figure 1 Sample familiarization trial. An experimenter placed two wooden shapes sequentially on a puppet stage and then sequentially moved them to the back of the stage. An agent watched the experimenter's actions. Once the objects were in their final positions, the experimenter played the anticipatory signal (a squeaking sound) and then the agent reached for and grasped the disk. Infants saw these actions unfold live. Infants observed four total familiarization trials, with order and side of object placement counterbalanced across trials.

reliable cue as to the direction of her reach. All infants viewed the same four familiarization trials in a consistent order: Familiarization Trial 1: disk (goal) first on left, triangle (non-goal) second on right; Familiarization Trial 2: disk (goal) first on right, triangle (non-goal) second on left; Familiarization Trial 3: triangle (non-goal) first on left, disk (goal) second on right; and Familiarization Trial 4: triangle (non-goal) first on right, disk (goal) second on left.

Test trials

There were four test trials. At the beginning of each test trial, as in the familiarization trials, the experimenter lowered the curtain to reveal the agent at the back of the stage seated with her arms crossed on the stage floor. The position of the agent's arms was consistent across test trials (e.g., on each test trial, the agent's left arm was always positioned on top of her right arm, see Figure 2). The experimenter placed two opaque screens on the stage (87 cm apart), one to the left and one to the right of the agent. The experimenter then placed the two shapes one at a time at the front of the stage, 13 cm apart, placing the goal shape (disk) *first*. After 4 sec, the experimenter moved the shapes one at a time to their final locations behind their respective screens in the order in which they were initially placed on the stage, such that the goal object was always hidden first. As in the familiarization trials, the agent followed the experimenter's actions with her gaze. In their final positions, the shapes were hidden from the infant but visible to the agent.

After the final object was placed, the agent directed her gaze to a neutral point at the center of the stage and remained still. The experimenter then drew the infants' attention to the center of the stage by jingling the bells around her wrist and saying, "Look!" This ensured that infants' gaze was fixed at the center of the stage (and, consequently, on the agent) prior to the anticipatory period. Once the experimenter confirmed that the infant's gaze was directed to the center of the stage, she played the 2 sec anticipatory signal (the squeaking sound). One second after the offset of the anticipatory signal, the experimenter then drew infants' attention to one of the screens by jingling the bells in front of the screen. She then lifted the screen to reveal either the object that was hidden there originally (e.g., disk hidden, disk revealed; *control* outcome) or the other object (e.g., disk hidden, triangle revealed; *swap* outcome). For infants in the *first-hidden (goal) revealed* condition, the experimenter always removed the screen occluding the first-hidden, goal object. For infants in the *last-hidden (non-goal) revealed* condition, the experimenter always removed the screen occluding the last-hidden, non-goal object. Infants were allowed to look at the display until they looked away for two consecutive seconds, as measured by the observer (using JHab software, Casstevens, 2007), after which the observer signaled the experimenter to raise the curtain, ending the trial.

All infants viewed a total of two *control* and two *swap* trials. These trial types were presented in pairs with outcome order (*control* first or *swap* first) counterbalanced within each pair and across infants (e.g., *swap* trial, *control* trial, *control* trial, *swap* trial; or, *control* trial, *swap* trial, *swap* trial, *control* trial). Figure 2 shows a sample test trial.

Dependent Measures

We had two dependent measures: an anticipatory looking measure and a violation of expectation measure. For the anticipatory looking measure, we assessed whether infants anticipated the target location of an agent's goal-directed reach by measuring

the location of infants' first saccade during an anticipatory period, which lasted from the beginning of the anticipatory signal (the squeaking sound) until the experimenter's hand reentered the scene (approximately 3 sec total duration). There was no minimum

Figure 2 Sample test trial. The experimenter placed the occluders on the empty stage. The experimenter then placed the objects sequentially on the stage and then moved them sequentially behind the occluders. Across four test trials, the positions of the shapes were counterbalanced, but the goal object (the disk) was always hidden *first*. Once the objects were occluded, the experimenter played the anticipatory signal and infants were given the opportunity to make a saccade. Following this anticipatory period, the experimenter then removed one of the screens to reveal either the original hidden object (control) or the other object (swap), and infants' looking time was measured. Infants were tested either on the first-hidden (goal) location or the last-hidden (non-goal) location (between-subjects design). Infants saw these actions unfold live.

distance away from center and no minimum look duration to designate a "look" during this window (for similar procedures see Kim & Song, 2015; Woodward, 2003). The length of the anticipatory looking window was sufficient to allow infants to engage in a goal-related gaze shift (Gredebäck & Daum, 2015). Infants' first saccades could be coded as either "left," "right," or "other" (e.g., up, down). However, all observed saccades were coded as "left" or "right," none were coded as "other"; that is, when infants made a first saccade following the tone, it was to either the right or the left side of the stage, and not, for example, upward or downward. Infants who did not make a saccade during this period (e.g., who failed to disengage from the agent's face) were coded as "center."

For the violation of expectation measure, we assessed infants' memory for the objects' shapes by measuring infants' total gaze duration to control and swap outcomes following the removal of the screen. Infants were coded as looking if their gaze was directed anywhere within the bounds of the puppet stage.

Infants' anticipatory looks and gaze duration were coded offline frame-by-frame using Preferential Looking Coder software (Libertus, 2011) by two independent coders who were naive to goal object location and trial outcome (*control* vs. *swap*). The first coder's scores were used. Inter-coder reliability was high (anticipatory looks: coders agreed on 167/176 trials (94.5%); looking time: $r = 0.98$).

RESULTS

Anticipatory Looking

For each trial, infants received a 1 if they looked at the target occluder, a -1 if they looked at the opposite occluder, and a 0 if they failed to make an anticipatory look to either occluder (see Figure S1 for trial-by-trial information on the number of infants coded as 1, -1, or 0). We then averaged these scores across the four test trials to obtain an anticipatory looking score for each infant, resulting in 44 mean anticipatory looking scores. Positive scores indicate reliable anticipatory looking to the goal location, negative scores indicate reliable anticipatory looking to the non-goal location, and scores close to 0 indicate no reliable preference or no anticipatory looks. We compared these mean anticipatory looking scores to 0 using a one-sample t-test. Since infants could have potentially made anticipatory looks to either location (or not at all), we used a two-tailed test. We found that infants reliably made anticipatory looks to the goal location (mean anticipatory looking score = 0.17; $t_{43} = 3.10$, $p = .003$ two-tailed, 95% CI [0.059, 0.281], $d = 0.47$; Figure 3a). We also conducted a Bayes factor analysis on these mean anticipatory looking scores. Bayes factor analysis allows us to quantify the strength of the evidence for the alternative hypothesis (H_1) that infants made more anticipatory looks to the goal location by yielding the odds for H_1 over the null hypothesis (H_0) that infants fail to reliably make predictive gazes to the goal location, given the data. Bayes factors <3 suggest anecdotal evidence in favor of H_1, between 3 and 10 suggest moderate evidence, >10 suggest strong support (Jeffreys, 1961), and a Bayes factor of 3 is roughly equivalent to the $p = .05$ significance level in traditional null hypothesis significance testing (Gallistel, 2009). Bayes Factor analyses on mean anticipatory looking scores revealed odds of 10.01:1 in favor of H_1, offering "strong" support for the alternative hypothesis that infants reliably made anticipatory looks to the goal location. Figure 4a shows the cumulative probability distribution of the mean anticipatory looking scores for each infant.

On some trials, infants failed to disengage from the agent's face, and thus failed to generate saccades to either location. To further examine the robustness of infants' pattern of anticipatory looks to the goal location, we looked at only those trials in which infants made a gaze shift (i.e., disengaged from the agent and made a saccade). Removing trials in which infants' looks were coded as "0" left 100 total trials from our original sample of 176. Six infants failed to make anticipatory saccades on any of the four trials, leaving 38 infants from our original sample of 44. We again computed a mean anticipatory looking score for each infant and conducted the same analyses as above. Infants reliably made anticipatory looks to the goal location (mean = 0.28; $t_{37} = 2.75$, $p = .009$, 95% CI [0.075, 0.496], $d = 0.45$), with Bayes factor analysis providing "moderate" support for H_1 ($BF_{10} = 4.47$). Figure 4b shows the cumulative probability distribution of the mean anticipatory looking scores, including only gaze shifts, for each infant.

We also asked whether infants' anticipatory looking preferences varied as a function of trial (1st, 2nd, 3rd, or 4th) or condition (*first-hidden [goal] revealed* or *last-hidden [non-goal] revealed*). To do so, we conducted a multinomial logistic regression on infants' anticipatory looks (1, 0, or −1) with Trial and Condition as factors. While inspection of Figure 3a suggests that infants made more anticipatory looks to the goal

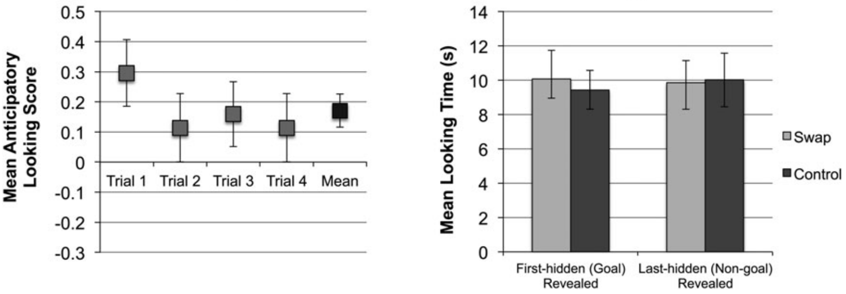

Figure 3 Panel (a) shows infants' mean anticipatory looking scores on each test trial, and their average anticipatory looking scores across trials. Scores could range from −1 to 1, with a positive score indicating anticipatory looks to the location of the (first-hidden) goal object, and negative scores indicating anticipatory looks to the location of the last-hidden (non-goal) object. Panel (b) shows infants' mean looking time to each outcome (swap or control) for each condition. Error bars represent ±1 *SEM*.

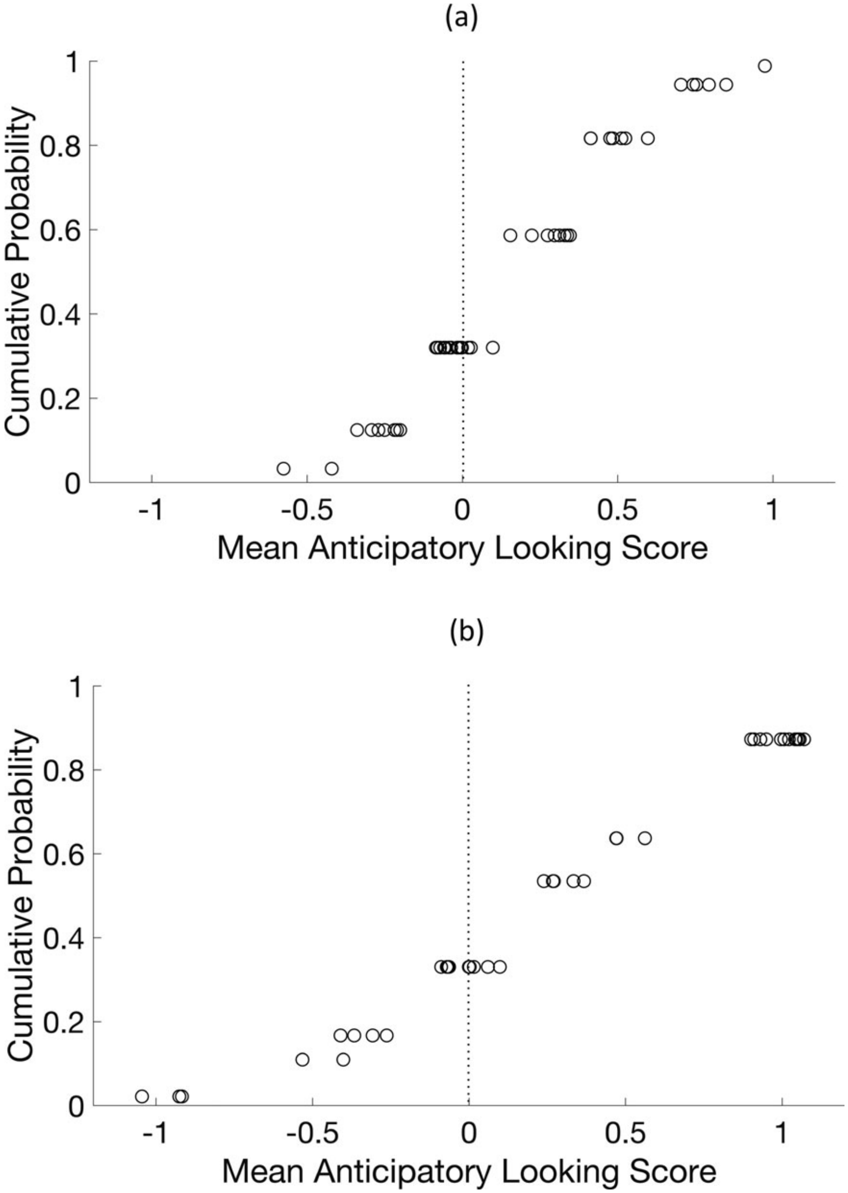

Figure 4 Cumulative probability distributions of each infant's overall mean anticipatory looking scores (n = 44, panel (a) and each infant's anticipatory looking scores including only gaze shifts (n = 38, panel (b). Circles represent individual infants' mean anticipatory looking scores. Jitter was applied to the plot to allow overlapping data points to be viewed. Vertical dashed lines mark the theoretical mean of 0. Scores above 0 indicate preference for the goal location; scores below 0 indicate preference for the non-goal location.

location on the first trial (see also Figure S1), they do not do so significantly; we found no main effect of Trial (χ^2 = 2.34, p = .87). We also found no main effect of Condition (χ^2 = 2.67, p = .24); infants made anticipatory looks similarly across conditions.

Violation of Expectation

We conducted a repeated measures ANOVA on infants' gaze durations following the removal of the screen with Outcome (*control* or *swap*) and Trial Pair (*1*st or *2*nd) as within-subjects factors, and Condition (*first-hidden (goal) revealed* or *last-hidden (non-goal) revealed*) as a between-subjects factor. This analysis revealed a main effect of Trial Pair ($F_{1,42} = 5.74$, $p = .021$, $\eta_p^2 = .12$) and no Trial Pair × Outcome ($F_{1,42} = 1.33$, $p = .25$, $\eta_p^2 = .031$) or Trial Pair × Condition ($F_{1,42} = 0.005$, $p = .94$, $\eta_p^2 < .001$) interaction; overall, infants looked longer during the first trial pair versus the second trial pair regardless of outcome or condition. There was no main effect of Outcome ($F_{1,42} = 0.032$, $p = .86$, $\eta_p^2 = .001$) and, crucially, no Outcome × Condition interaction ($F_{1,42} = 0.097$, $p = .75$, $\eta_p^2 = .002$); infants did not look longer at the *swap* outcome versus the *control* outcome in either condition. There was no main effect of Condition ($F_{1,42} = 0.04$, $p = .84$, $\eta_p^2 = .001$), suggesting that infants' look duration was similar across conditions. Bayes factor analysis on mean looking times yielded evidence in favor of the null hypothesis in both the first-hidden (goal) revealed condition ($\text{mean}_{\text{swap}} = 10.08$ sec; $\text{mean}_{\text{control}} = 9.44$ sec; $\text{BF}_{01} = 4.14$) and the last-hidden (non-goal) revealed condition ($\text{mean}_{\text{swap}} = 9.87$ sec; $\text{mean}_{\text{control}} = 10.02$ sec; $\text{BF}_{01} = 4.55$), providing "moderate" support for the null hypothesis that infants fail to remember the shape of the hidden object. Figure 3b shows infants' mean looking times to each outcome (*swap* or *control*) for each condition.

We also asked whether infants who more reliably made anticipatory looks to the goal location may have shown a different pattern of looking time across outcomes or conditions versus unreliable anticipators. We identified those infants whose mean Anticipatory Looking scores were above or below the group mean and then conducted a repeated measures ANOVA with the above factors, but also included Anticipation Reliability (defined by mean Anticipatory Looking scores above the mean or below the mean) as a between-subjects factor. We again found a main effect of Trial Pair ($F_{1,40} = 5.16$, $p = .029$, $\eta_p^2 = .114$), and no other significant main effects (all ps > .05). Critically, we found no three-way interaction between Outcome, Condition, and Anticipation Reliability ($F_{1,40} = 0.10$, $p = .74$, $\eta_p^2 = .003$), suggesting that infants who did and did not reliably make anticipatory looks to the goal location showed a similar pattern of looking across outcomes in both conditions.

DISCUSSION

The current study investigated the representations supporting 6-month-old infants' ability to generate predictive saccades based on learned goal-related associations between an agent and a particular object. We familiarized infants to an agent who, across four trials, preferentially reached for one of two distinct shapes following a cue. During test, we then occluded the objects sequentially, so that they were visible to the agent but no longer visible to infants. The agent's goal object was always hidden *first*. We used two measures to explore infants' representations during test trials. First, we measured infants' anticipatory first looks following the anticipatory cue. We hypothesized that infants would be able to generate predictive gazes to the location of the goal object following the auditory cue, even though the relevant objects were not visible to infants. Our results supported this hypothesis: infants' first looks following the auditory cue were reliably made toward the location of the hidden goal object at rates significantly above chance.

Second, we examined infants' representations of the hidden objects. Previous work has shown that, in nonsocial contexts, 6-month-old infants consistently can remember the featural identity (e.g., shape) of one of two hidden objects: infants who viewed two featurally distinct objects hidden sequentially remembered the featural identity of the last-hidden object, but not the first-hidden object (Káldy & Leslie, 2005; Kibbe & Leslie, 2011, 2016, in press). Following the anticipatory measure, we removed the screen occluding either the first-hidden (goal) object or the last-hidden (non-goal) object (between subjects) and showed infants either the expected original shape or the unexpected other shape (within subjects). We predicted that infants would prioritize encoding the shape of the goal object, either instead of or in addition to the shape of the last-hidden (non-goal) object, and would look longer when this object is revealed to have changed identity. However, contrary to this hypothesis, our results suggest that infants failed to remember the identity of *either* hidden object.

These results add to the growing literature evidencing infants' ability to represent and predict agents' goals. Our results suggest that 6-month-old infants can learn a goal-related association between an agent and an object over four familiarization trials and can do so even when the goal object occupies a different spatial location across familiarization trials. Our results also suggest that 6-month-olds can make predictive gazes based on these associations. Further, our results suggest that infants' goal-related predictions can be generated in the absence of perceptually available information about the objects in the scene. That is, infants are not passive responders glancing toward a previously highlighted object following a trained cue. Instead, infants' gaze behavior is driven by information that is no longer perceptually available at the time of the cue. However, our results also suggest that, once an action prediction is generated, infants may fail to represent the identities of the objects in the scene.

These results also add to the growing literature on the *inferences* that infants can make in the absence of visual information in goal attribution contexts. For example, previous work showed that, by 12 months (but not at 9 months), infants can infer agents' goals after observing agents' incomplete actions toward objects and can infer the causes of agents' actions without visual access to those causes (Csibra et al., 2003). Our work suggests that, by 6 months, infants may be able to predict an agent's future action without being able to immediately observe the relevant objects. In our study, infants did not have to make an inference about the agent's goal, but they did have to make an action prediction when the relevant objects were not visible. Together, this work suggests that infants' ability to make inferences about an agent's actions on occluded objects may be earlier-developing than their ability to make inferences about an agent's incomplete or occluded actions.

The pattern of results we obtained in this study suggests some potential time courses for infants' goal-related action predictions, at least under the conditions tested here. One possibility is that infants may have maintained a representation of one or both objects just long enough to use these representations to generate an action prediction at the time of the auditory cue. Upon hearing the cue, infants may have then generated an action prediction, along with the appropriate oculomotor response, based on representation(s) of the hidden object(s) stored in working memory. Once the action prediction is generated, infants may then fail to actively maintain those representations. Another possibility is that infants may generate an action-based association between the agent and the goal object just before or immediately after the goal object is hidden. They may then store this agent–object relationship in limited working memory, leaving little space to encode additional information about the scene, including the specific identities of the objects themselves. At the time of the auditory cue, infants can then use this representation to make predictive gazes. Or, infants may use the path of the goal object to encode a relationship between the agent and the specific *location* in which the goal object is hidden. Under this possibility, infants would store an association between an agent and a location in working memory (without storing what is hidden in that location) and use this location-based association to make predictive gazes (see Daum, Attig, Gunawan, Prinz, & Gredebäck, 2012; Fawcett & Gredebäck, 2013). This could explain why infants in our study succeeded in making predictive gazes to the goal object's location but failed to notice a change in the goal object's identity. Since infants have limited working memory capacity (Kibbe, 2015), prioritizing encoding agents' goal-related actions may be strategic given the importance of goal understanding in successful social functioning (Baldwin & Moses, 2001; Krogh-Jespersen, Liberman, & Woodward, 2015). Further work is needed to explore these possibilities.

While infants in our task failed to remember the features of the hidden objects, our results also suggest that maintaining the representations that support action prediction may be more robust to interference than representations of objects. In our study, the agent's goal object was always hidden *first*. In nonsocial contexts, infants' typically fail to remember the identity of this object, and this has been shown to be due to interference from the second hiding event: after the first object is hidden, infants' attention is drawn to the new hiding event, taking limited attentional resources away from maintaining bindings between features and object (Káldy & Leslie, 2005; Kibbe & Leslie, 2013). Our results suggest that, in social contexts, infants may be able to maintain in working memory the relevant information required to make goal-related predictive gazes even as they observe additional distracting events. It is possible that relational information (e.g., between agent and object or between agent and location) may be more robust and less prone to interference than nonrelational information (e.g., individual objects). This possibility is consistent with recent work showing that older infants can use social relationships and attitudes to support object individuation (Stahl & Feigenson, 2014, 2018).

Our results suggest that representations of agents' goal-related actions may be prioritized over representations of individual objects, at least in some contexts. There are multiple sources of cognitive demands in our task, including the cognitive cost of processing and anticipating the agent's goal-related actions (e.g., Krogh-Jespersen & Woodward, 2014, 2018), as well as the cognitive cost of tracking objects through sequential occlusion, which imposes considerable attentional demands that limit infants' ability to maintain bindings between features and objects (Kibbe & Leslie, 2011, 2013). It is currently unclear to what extent each of these sources influenced infants' failure to maintain representations of either hidden object. It is possible that, if the cognitive demands of the object-tracking task were reduced (e.g., by hiding the objects simultaneously, or by hiding the goal object *last* instead of *first*), infants may be able to maintain a representation of at least the goal object even in a goal attribution context. It is also possible that, if the cognitive demands of the action prediction task were reduced (e.g., by giving infants more experience with the agent's goals, or by giving them experience with reaching for the objects themselves; Krogh-Jespersen &

Woodward, 2018), infants may have more cognitive resources available to represent the occluded objects. Another possibility is that infants may prioritize representing agent-action relationships over representations of individual objects *regardless* of the cognitive demands of the task. Future work would examine how different sources of cognitive load influence infants' representations in social contexts.

Our study also has some limitations. Our results suggest that 6-month-olds generate and deploy goal-related action predictions when objects are occluded, but fail to remember the features of the hidden objects. We speculate that, since 6-month-old infants typically can remember at least one of two featurally distinct objects in nonsocial contexts, that the source of this latter failure is the social context of the scene; that is, the process of parsing the scene based on socially relevant knowledge interferes with infants' ability to encode or maintain representations of hidden objects. However, it is possible that infants would fail to maintain representations of the objects in any scene that is more complex than in previous work on infants' object working memory in nonsocial contexts. For example, perhaps the presence of an agent, even one who had not previously been shown to have a goal for one object over another, would limit infants' ability to encode the objects in the scene. We think this possibility is less likely. For example, previous work has shown that infants do encode the features of a single object in the presence of an agent if the agent performs an ostensive cue (e.g., pointing; Yoon et al., 2008), suggesting that specific social context can impact how infants represent objects. And 6-month-olds can remember more object identities when the objects are from distinct social categories (Kibbe & Leslie, in press), suggesting that infants may encode objects differently depending on their social relevance. Further work is needed to examine the social and nonsocial sources of limitations on infants' representations of multiple objects during complex scenes.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Number of infants who looked to the occluded goal location (coded as "1"), to the occluded non-goal location (coded as "-1"), or who remained fixed on the agent (coded as "0") during the anticipatory looking window on each of the four test trials.