Origins of the concepts cause, cost, and goal in prereaching infants

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Edited by Gergely Csibra, Central European University, Budapest, Hungary, and approved July 26, 2019 (received for review March 25, 2019)

We investigated the origins and interrelations of causal knowledge and knowledge of agency in 3-month-old infants, who cannot yet effect changes in the world by reaching for, grasping, and picking up objects. Across 5 experiments, $n = 152$ prereaching infants viewed object-directed reaches that varied in efficiency (following the shortest physically possible path vs. a longer path), goal (lifting an object vs. causing a change in its state), and causal structure (action on contact vs. action at a distance and after a delay). Prereaching infants showed no strong looking preference between a person's efficient and inefficient reaches when the person grasped and displaced an object. When the person reached for and caused a change in the state of the object on contact, however, infants looked longer when this action was inefficient than when it was efficient. Three-month-old infants also showed a key signature of adults' and older infants' causal inferences: This looking preference was abolished if a short spatial and temporal gap separated the action from its effect. The basic intuition that people are causal agents, who navigate around physical constraints to change the state of the world, may be one important foundation for infants' ability to plan their own actions and learn from the acts of others.

infancy | action understanding | causal reasoning | open materials and data | preregistration

As human adults, we view ourselves and others as causal agents, who devote our limited time and resources to actions that change the world in accord with our intentions and desires (1). This view is critical to our understanding of other minds (2, 3), our ability to learn from other people (4, 5) and, in some views, our very ability to make any causal attributions (6). Here, we explore the seeds of this understanding through studies of human infants who cannot yet pick up or manipulate objects, and who therefore cannot effect changes in objects through their own intentional actions.

By the time that infants begin to reach for and pick up objects (at about 4 to 5 months) (7) and manipulate them (at about 6 to 8 months) (8, 9), they begin to show sensitivity to the causes, costs, and goals of intentional action. Six- to 12-month-old infants attribute causal powers to agents: They expect hands to move, lift, or break objects only on contact (10, 11), and they infer that a person or animal who launches or entrains an inanimate object has caused the object's motion (12, 13). Infants at this age also are sensitive to the cost of other agents' actions, looking longer when someone takes a long, circuitous route to a goal when a shorter route was available (14, 15), and they interpret actions as directed toward goal objects, looking longer when a person reaches to a new object, even if the reach follows a familiar path (16). These findings do not reveal, however, whether infants' emerging action capacities give rise to, or merely allow infants to express, knowledge of the goals, costs, or causal efficacy of human actions.

What Do Infants Learn from Their Own Actions?

Throughout the second half of the first year, infants explore and manipulate objects tirelessly (8, 9, 17). There is strong reason to think that infants learn from these experiences, because milestones in motor development predict infants' understanding of other people's reaches (16), grasps (18), and multistep goal-directed actions (19). These observations have prompted the hypothesis that infants learn, through their own actions, to attribute mental states and causal powers to themselves and other agents (20–25).

The motor experience hypothesis is supported by evidence that action training enhances infants' action understanding (26–31). The most striking evidence for this hypothesis comes from studies of 3-month-old infants, who do not yet reach intentionally for objects (32), and who in past research showed no sensitivity to others' goals or to the cost of their actions. Training experiments suggest that such infants learn about the goals and intentions of other agents from their own action experiences (26, 27, 30). After a few minutes of experience wearing Velcro ("sticky") mittens that allow prereaching infants to bat at soft objects and pick them up, infants come to see other people's reaches as directed toward those goal objects, whereas untrained infants do not (26, 30). Nevertheless, 2 sets of findings from these experiments stand at odds with the motor experience hypothesis. First, infants' learning from wearing sticky mittens fails to generalize in ways that new action concepts should support. Mittens-trained infants attribute goals to another person only if she wears the same mittens as the infant, and only if she contacts the same objects that the infant encountered during training (31, 33), casting doubt on the thesis that mittens-training enhances infants' understanding of abstract intentions and goals. Second, infants' learning from sticky mittens generalizes too broadly to

Significance

We view ourselves and others as causal agents who pursue goals and act efficiently to make things happen, but where do these intuitions come from? Five looking-time experiments with 3-month-old infants show that infants interpret actions they cannot yet perform as causally efficacious. When people reach for and cause state changes in objects, young infants interpret these actions as goal-directed and look longer when they are inefficient rather than efficient. In contrast, infants show no consistent responses to similar actions that cause no changes in an object. An early-emerging sensitivity to the causal powers of agents, when they engage in costly, goal-directed actions, may provide one important foundation for the rich causal and social learning that characterizes our species.

Author contributions: S.L., N.B.B., and E.S.S. designed research; S.L. and N.B.B. performed research; S.L. analyzed data; and S.L., N.B.B., and E.S.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: Preregistrations for Experiments 4 and 5 have been deposited on the Open Science Framework (Exp. 4, https://osf.io/a5byn/; Exp. 5, https://osf.io/f2hvd/). All stimuli, data, and code from this paper are also available on Open Science Framework (https://osf.io/rcsns/).

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1904410116/-/DCSupplemental.

Published online August 20, 2019.

warrant the interpretation that they knew nothing about others' actions prior to this experience. When mittens-trained infants view another person who reaches repeatedly over a barrier to obtain an object, they subsequently look longer, after the barrier is removed, when the person reaches for the object using the same circuitous path, than when she reaches for the object directly. These findings have been interpreted as showing that infants represent the reaches as goal-directed and costly, even though their own training session involved no barriers or indirect reaches (27). Infants' generalization from direct to constrained reaches suggests that some prior understanding of action supported their learning.

Based on these considerations, we suggest a new interpretation both of the effect of mittens training and of the preexisting capacities of prereaching infants. To reach for, grasp, and pick up an object, one must adapt the position of hands and fingers to the object's position, shape, weight, and consistency (34). When 3-month-old infants attempt to perform object-directed reaches like those of the people around them, they fail to pick up the objects or move them closer: Their actions, at best, lead them to bump into and bat away the objects that they seek to entrain. When such infants observe the reaches of others, moreover, the visual information they receive does not clearly indicate how people lift and move objects: How is a ball supported when it is grasped from above, as in Fig. 1? In the light of these challenges, experience with sticky mittens may simplify the act of picking up an object for a prereaching infant into an instance of "action on contact," a fundamental property of causal events (35). If this interpretation is correct, then 3-month-old infants should already be capable of viewing people as causal agents whose intentional actions aim to transform objects on contact, even though the infants themselves cannot effect such transformations.

Research Overview

The present experiments test for this aspect of causal understanding in prereaching infants who have received no action training. In 5 experiments, we presented 3-month-old infants with visual information about the causal affordances of reaching, as in past studies of sensitivity to contact causality (10, 11, 35–37), without intervening on their motor experience. We measured their visual attention to video recordings of people reaching for objects first on indirect paths constrained by the presence of a barrier, and then on either indirect or direct paths after removal of the barrier, as in past studies of infants' sensitivity to action efficiency (27, 38). Although there is no evidence that infants interpret physical interactions between objects as causal before 6 months of age, younger infants are sensitive to the spatiotemporal properties of physical collisions between objects, perhaps from birth (39), as they distinguish between object motions with and without direct contact and with or without a temporal delay (36, 40, 41). In the present research, we test the thesis that prereaching infants see other people as causal agents, who act with specific intentions and limited energy, by presenting them with actions that do or do not conform to the spatiotemporal properties of causal events.

Experiments 1 and 2: Object-Directed Reaching and Grasping Actions

Experiment 1. We began by replicating the finding that 3-month-old infants, who have received no action training and are habituated to an actor reaching over a barrier, show no differential looking to efficient versus inefficient reaching actions after the barrier is removed (27). In Exp. 1, we tested for infants' sensitivity to action efficiency using events based directly on past research (27), featuring reaches by an actor wearing a glove rather than a mitten (Fig. 1). Three-month-old infants ($n = 20$; mean age = 108 d; range = 92 to 122 d; 11 female) viewed video clips of an actor who reached over a barrier, grasped and lifted a ball, and moved the ball to her side of the barrier (Fig. 1 *A*, H1). The height of this barrier varied across trials, and the person always adapted her reach to the barrier. After infants either habituated to these events (i.e.,

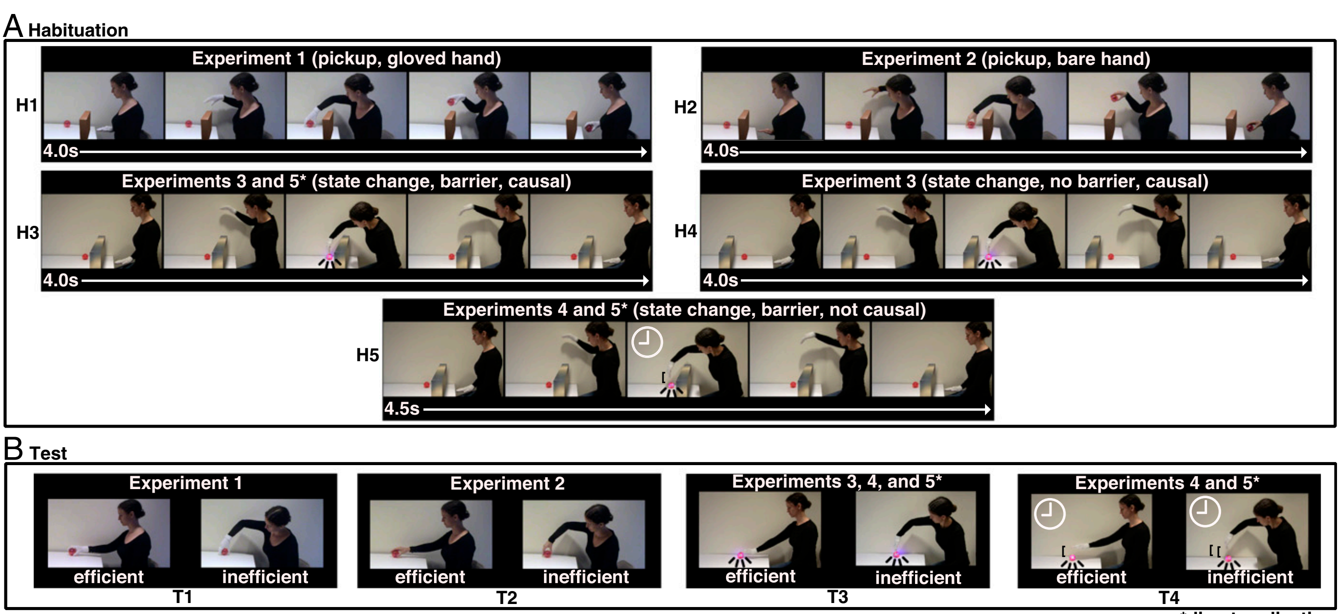

Fig. 1. Still frames from videos shown to participants in Exps. 1 to 5, including stimuli from habituation (*A*) and test (*B*). In each video, a person reached for and picked up the object (H1-H2, T1-H2), or caused it to illuminate (H3-H5, T3-T4), over a barrier (H1-H3, H5) or empty space (H4, T1-T4). The person either acted on the object by contacting it (H1-H4, T1-T3) or produced the same effect from a distance of 50 pixels, after a 0.5-s delay (H5, T4), and either performed these actions while wearing a glove (H1, H3-H5, T1, T3-T4) or with a bare hand (H2, T2). During the test (*B*), the person either reached directly for the object on a novel but efficient trajectory (*Left*), or in a curvilinear fashion on the familiar but inefficient trajectory (*Right*). Clocks indicate temporal delays, black line segments indicate spatial gaps, and black line segments around the object indicate frames in which it illuminated. An asterisk (*) indicates direct replication (Exp. 5).

their attention declined by 50%), or looked for 12 trials, whichever came first, we measured their attention to alternating test events in which the person reached for the same ball as during habituation, but with no obstacles in her way (Fig. 1 *B*, T1). On alternating test trials, she reached on the same curvilinear path toward the ball (a familiar but newly inefficient action) or on a direct path (a novel but newly efficient action). The only differences between these events and the events from past studies (27) were that the actor in this study wore a tight-fitting white glove instead of a brown mitten, and she kept her hand in the same grasping position during the entire reach, instead of turning the ball over in the mitten after retrieving it. Thus, the shape and positions of her fingers remained visible throughout the action.

Across all experiments, we calculated the average looking time toward the efficient versus inefficient reach over 3 pairs of test events, and we analyzed these data using linear mixed-effects models (42). For details about our analysis strategy, see *Materials and Methods*. In light of past findings that prereaching infants fail to interpret reaching actions by a mittened hand as costly (27), we expected infants to look equally at the 2 test events in Exp. 1. Consistent with this prediction, infants looked equally to the inefficient and the efficient reach of the gloved hand ($\text{mean}_{\text{ineff}}$ = 18.029 s, mean_{eff} = 16.844 s, 95% CI [−0.089, 0.238], standardized β-coefficient [β] = 0.155, unstandardized B coefficient [*B*] = 0.074, SE = 0.079, *P* = 0.359, 2-tailed), replicating past findings (27) (Fig. 2*A*). Nevertheless, looking preferences in this experiment differed marginally from those in the experiment on which this study was based (27), with relatively greater looking at the familiar but inefficient reach ([−0.015,0.464], β = 0.43, *B* = 0.224, SE = 0.122, *P* = 0.074, 2-tailed).

Experiment 2. Do 3-month-old infants struggle to represent the cost of mittened and gloved reaches because of the gloves and mittens themselves? In Exp. 2, infants (*n* = 20; mean = 108 d; range = 93 to 120 d; 12 female) were presented with the same actions from Exp. 1, except that the person performing the actions wore no gloves, further clarifying the contact relation between her hand and the object (Fig. 1, H2 and T2). Infants looked longer at the inefficient than the efficient reach of the bare hand, in the familiar context of a bare-handed reach ($\text{mean}_{\text{ineff}}$ = 9.715 s, mean_{eff} = 8.036 s, [0.008,0.331], β = 0.429, *B* = 0.170, SE = 0.078, *P* = 0.043, 2-tailed). Performance in Exp. 2 differed significantly from performance in the original study on which it was based (27) ([0.047,0.547], β = 0.539, *B* = 0.297, SE = 0.124, *P* = 0.022, 2-tailed). However, performance in Exps. 1 and 2 did not differ from each other ([−0.128,0.319], β = 0.167, *B* = 0.095, SE = 0.111 *P* = 0.396, 2-tailed). Collapsing across both Exps. 1 and 2, infants looked marginally longer at the inefficient than the efficient action ($\text{mean}_{\text{ineff}}$ = 13.872 s, mean_{eff} = 12.440 s, [−0.004,0.227], β = 0.185, *B* = 0.112, SE = 0.058, *P* = 0.060, 2-tailed) (Fig. 2*A*).

These experiments, together with past research (26, 27), suggest that untrained 3-month-old infants have weak and inconsistent looking preferences for direct versus indirect reaching and grasping actions. Nevertheless, the significant difference between Exp. 2 and the experiment presenting a mittened hand (27) calls into question the conclusion, from past research, that 3-month-old infants need action training in order to appreciate the physical costs of reaching actions. An exploratory analysis comparing the 3 experiments that used this method revealed that the magnitude of infants' looking preference for the indirect reach increased with increases in the visibility of the form of the reaching hand, from a mitten that obscured its shape and texture (27), to a glove that revealed its shape but obscured its color and texture (Exp. 1), to a fully visible hand (Exp. 2) ([0.007,0.053], β = 0.416, *B* = 0.03, SE = 0.011, *P* = 0.011, 2-tailed). *SI Appendix* presents a full report of this exploratory analysis, which raises the possibility that the use of mittens obscuring the hand in all past research with 3-month-old infants underestimates the infants' sensitivity to natural, bare-handed acts of reaching. Further research is needed to test this possibility.

What makes reaching for, grasping, and lifting objects problematic actions for 3-month-old infants to understand? Although

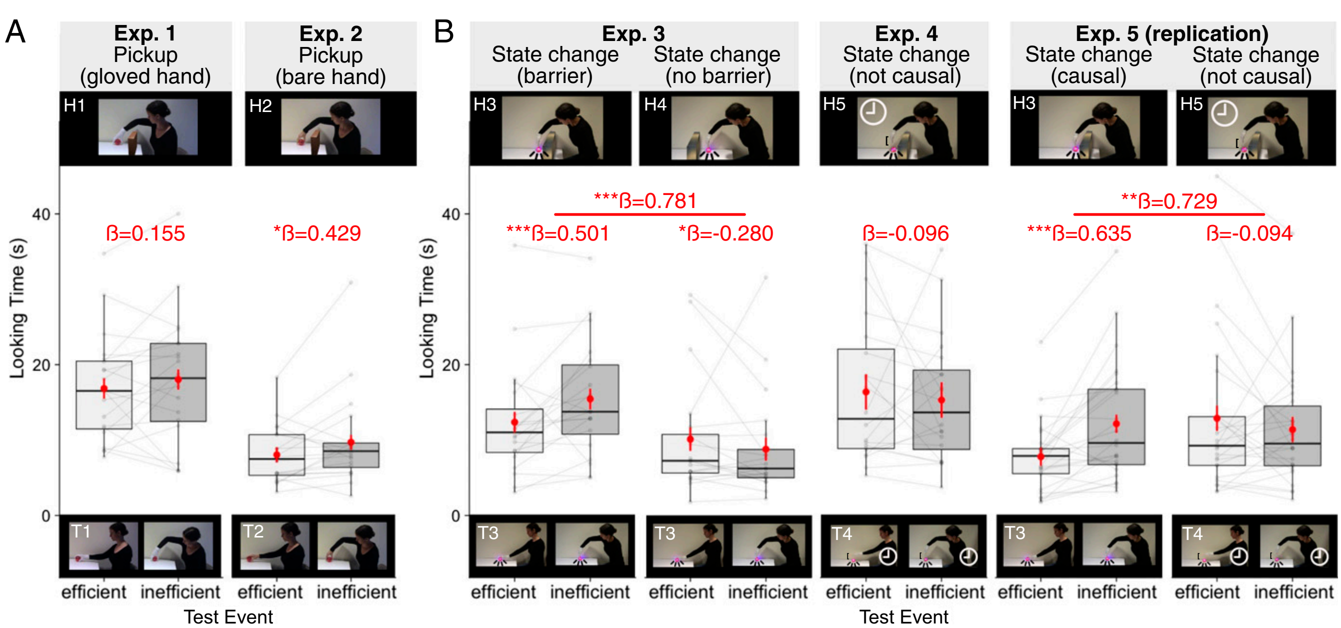

Fig. 2. Looking time in seconds toward the efficient versus inefficient reach at test across Exps. 1 to 5 (*n* = 152), for both (*A*) pick-up events (Exps. 1 and 2) and (*B*) state-change events (Exps. 3 to 5). Images indicate video displays used during the habituation phase (above each graph) and test phase (below each graph) for each experiment (Fig. 1). Red dots and error bars indicate means and within-subjects 95% CIs. Pairs of connected points indicate data from a single participant. Horizontal bars within boxes indicate medians, and boxes indicate the middle 2 quartiles of data. Upper whiskers indicate data up to 1.5 times the interquartile range above the third quartile, and lower whiskers indicate data up to 1.5 times the interquartile range below the first quartile. Beta coefficients (β) list effect sizes in SD units for each condition. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, 2-tailed, except for the causal condition in Exp. 5, which was preregistered as a 1-tailed test.

infants frequently see people lifting objects, the mechanism by which this action serves to displace an object depends on variables that are opaque to vision, such as the weight of the object and the force of the actor's grasp. Without understanding how the posture of the hand and the forces it exerts allow an actor to lift and move an object, infants may have difficulty distinguishing pick-up actions from hand movements that are guided by different intentions. If this is correct, then infants may more robustly represent the causal powers of other people who engage in simpler, albeit less familiar, efficient, object-directed actions. The next experiments test this possibility.

Experiments 3 to 5: Reaching Actions That Cause Objects to Change State

In Exps. 3 to 5, we explored whether prereaching infants view the act of reaching for and contacting an object as causally efficacious, when a simple but novel reaching action produces a change in the object on contact.

Experiment 3. Drawing inspiration from past studies of infants' and adults' causal perception (10, 11, 35, 36, 43), in Exp. 3 we tested infants' responses to displays similar to those of Exp. 1, except that the person reached for and touched the ball with the tips of her gloved fingers, causing it to illuminate and emit a soft sound on contact, and then withdrew her hand, causing the ball to return to its initial state (Fig. 1, H3-H4, T3). Because this event has not been used in previous research, infants were randomly assigned to 1 of 2 habituation conditions (n = 40; 20 per condition; mean age = 108 d; range = 91 to 122 d; 23 female). In the experimental condition, infants watched the person reach over a barrier that prevented direct access to the goal object (H3), as in Exps. 1 and 2. In the control condition, infants watched the person perform the same reaches with the barrier behind the goal object, out of the actor's way, as in the control condition of previous research with mitten-trained infants (H4) (27). Across both conditions, all barriers were added digitally to the same videos: Thus, the actor performed identical actions in the 2 conditions, but only in the first condition did the actor appear to reach efficiently on the habituation trials. After habituation, infants viewed the efficient, direct reach and the inefficient, indirect reach, as in Exps. 1 and 2, both of which activated the object (T3). These 2 conditions allow us to test whether infants differentiate efficient from inefficient reaches at test only when prior curved reaches were efficient.

In Exp. 3, infants responded differently to the test events across the 2 habituation conditions ([0.273,0.732], β = 0.781, B = 0.502, SE = 0.114, P < 0.001, 2-tailed) (Fig. 2B). When the actor's reaches were initially constrained by a barrier (H1) in the experimental condition, infants looked longer, at test, at the inefficient than the efficient action ($\text{mean}_{\text{ineff}}$ = 15.448 s, mean_{eff} = 12.368 s, [0.159, 0.486], β = 0.501, B = 0.322, SE = 0.081, P < 0.001, 2-tailed). Their preference for the inefficient test action cannot be attributed to low-level preferences for the curvilinear reach, because infants in the control condition (H2) showed a small preference in the opposite direction ($\text{mean}_{\text{ineff}}$ = 8.788 s, mean_{eff} = 10.104 s, [−0.343,−0.017], β = −0.28, B = −0.18, SE = 0.081, P = 0.032, 2-tailed). Infants' preference for the inefficient action was stronger in this experiment than in Exp. 1, which presented the same reaching trajectories ending in object pick-up ([0.029,0.467], β = 0.457, B = 0.248, SE = 0.112, P = 0.032, 2-tailed). Exp. 3 therefore provides evidence that infants are sensitive to the physical constraints on object-directed reaching when these reaches terminate in a simple, causally transparent contact event.

Experiment 4. In Exp. 4, preregistered at https://osf.io/a5byn/, we tested whether this sensitivity depends on infants' construal of the actor as a causal agent who changes the states of objects on contact. We introduced digital manipulations to the habituation and test events from Exp. 3 to create a small spatial and temporal gap between the termination of the actor's reach and the activation of the object, thereby removing the key condition that elicits causal perception in older infants and adults (10, 11, 35, 36, 43). Infants (n = 20; mean age = 107 d; range = 93 to 121 d; 12 female) saw videos identical to those from the experimental condition of Exp. 3, except the actor's hand never contacted the object (her fingers paused 50 pixels, or 2 cm, above it), and the object changed state 0.5 s after the hand came to rest in midair (Fig. 1, H5, T4). In contrast to Exp. 3, infants looked equally at test trials showing the inefficient and efficient actions ($\text{mean}_{\text{ineff}}$ = 15.306 s, mean_{eff} = 16.38 s, [−0.301,0.191], β = −0.096, B = −0.055, SE = 0.119, P = 0.649, 2-tailed) (Fig. 2B). Across Exp. 4 (H5, T4) and the experimental condition of Exp. 3 (H3, T3), infants responded differently to the test events, depending on whether or not the person acted on the object on contact ([0.003,0.623], β = 0.547, B = 0.313, SE = 0.154 P = 0.049, 2-tailed). Therefore, Exp. 3 provides initial evidence that infants appreciate the physical constraints on goal-directed reaching if this action causes a change in its goal object on contact, but not if the change in the object occurs after, and at a distance from, the end of the action.

Experiment 5 (Direct Replication). To evaluate this suggestion further, we conducted a preregistered direct replication of Exps. 3 and 4. In Exp. 5, preregistered at https://osf.io/f2hvd/, we randomly assigned infants to events that differed only in spatiotemporal continuity: The object either activated on contact with the agent's hand, or after a small gap in space and time (n = 52, 26 per condition; mean age = 107 d; range = 92 to 121 d; 21 female). This design allowed us to compare infants' responses to causal (H3, T3) versus noncausal (H5, T4) actions, under testing conditions where all researchers were blind to condition as well as test events. We fully replicated the findings from Exps. 3 and 4: Infants again responded to the test events differently depending on whether or not the activation of the object occurred on contact with the hand ([0.184,0.815], β = 0.729, B = 0.5, SE = 0.158, P = 0.003, 2-tailed) (Fig. 2B). As in Exp. 3, infants looked longer at the inefficient than the efficient reach when the person appeared to cause a change in the object ($\text{mean}_{\text{ineff}}$ = 12.166 s, mean_{eff} = 7.791 s, [0.211,0.66], β = 0.635, B = 0.436, SE = 0.112 P < 0.001, 1-tailed); as in Exp. 4, infants looked equally to the inefficient and efficient reaches when she did not appear to cause this outcome ($\text{mean}_{\text{ineff}}$ = 11.395 s, mean_{eff} = 12.888 s, [−0.289,0.160], β = −0.094, B = −0.064, SE = 0.112, P = 0.567, 2-tailed). Although 3-month-old infants have limited experience acting on objects themselves, they understand that other people intend to cause changes in the world through their actions. Infants exhibited this ability in Exps. 3 and 5, both of which presented clear information that a change in the goal object occurred on contact with the actor's hand.

See *SI Appendix* for a metaanalysis over these 5 experiments and 5 previous experiments using similar methods at the same age (27), which compare different conditions of mittens-training, object manipulation (grasping and entraining vs. touching and activating an object), and causal information. Overall, we found that knowledge of the causal intentions behind and physical constraints on reaching actions arises without training, but it is more robust when infants view causally transparent actions or receive mittens-training.

Discussion

Since the birth of cognitive science and artificial intelligence, scholars have debated how human minds learn abstract, structured representations of objects, of other people, and of themselves (44–49). Do concepts like "cause," "cost," and "goal" emerge from sensorimotor associations formed during first-person experiences acting on objects? Alternatively, do some abstract, structured concepts emerge early and guide infants' analysis of the causal consequences of other people's actions, together with the goals and costs of those actions?

Our experiments provide evidence for the latter view. Across 5 experiments, we found that infants attended to changes in the physical constraints of other people's reaches if these actions give strong impressions of causal agency, involving contact with an object that immediately changes its state. Thus, before infants can reach for objects themselves, they represent other people's reaching actions in accord with the abstract concept of "cause," a concept that may function together with the associated concepts of "cost" and "goal." Three-month-old infants appreciate that agents act on the world in order to transform it in some way, that their actions occur on contact with objects, and that obstacles impose constraints on goal-directed action. First-person experiences of acting on and causing changes in objects are not prerequisites to the development of these concepts.

What Is the Nature of These Early Concepts? Although our experiments build on prior findings that purport to show that 3-month-old infants, trained with sticky mittens, view other people's actions as goal-directed (26, 30, 50, 51) and costly (27), neither our experiments nor their predecessors reveal how richly prereaching infants represent the costs and goals of other people's actions.

With respect to action cost, 6-month-old infants expect agents not only to move on a straight path in the absence of obstacles but on the least curved path available in the presence of obstacles (14). In contrast, neither the present studies nor past research reveals whether prereaching infants assess the continuous costs of different actions. Moreover, our experiments and their predecessors do not reveal whether 3-month-old infants expect causal actions to be efficient, or alternatively attend to path-relevant constraints on causal actions, looking longer at the disappearance of an object on a familiar reaching path than at a new, direct reach. Given that 3-month-old infants do not see pick-up actions as intentional unless they see bare hands (Exp. 2) or receive action-training (29), they may be only beginning to recognize which physical cues are relevant for analyzing the cost of causal, goal-directed actions. Future experiments that compare infants' responses to actions that vary in relative inefficiency, and that compare infants' responses to indirect reaching actions constrained by true obstacles (e.g., solid walls) from other objects (e.g., arches or shelves), could help reveal the nature of infants' early understanding of action cost.*

With respect to goal-directedness, 6-month-old infants attribute goals to purposeful actions but not accidental ones, and they represent acts of reaching by an agent, but not similar movements of an inanimate object, as goal-directed (16); our studies, like past studies of prereaching infants (26, 30, 50, 51), do not speak to these abilities. Finally, research reveals that 10-month-old infants form integrated representations of action costs and rewards (52): If an agent undertakes a more costly action to attain 1 goal object than another, infants infer that the agent values the former goal object more. Future research could investigate whether this ability is present in younger infants.

A further question that is raised but not answered by our studies concerns young infants' understanding of nonagentic, physical causes. It is possible that infants first attribute causal powers to agents who act on objects, and later generalize these attributions to inanimate objects that collide and interact (53, 54). Alternatively, 3-month-old infants may attribute causal powers to inanimate objects as well as to agents when they are presented with simple events like the present ones. Experiments that test these contrasting possibilities would speak to interventionist theories of causation (6, 55, 56), according to which our causal analysis of physical systems relies on our understanding of entities that stand outside those systems and have the power to intervene on them: A view with deep roots in cognitive and developmental science (4, 57, 58).

What Are the Developmental Origins of These Concepts? Our studies show that infants interpret actions they cannot perform as causally efficacious, but they do not reveal the cascading developmental processes that give rise to this understanding. It is possible that infants learn that agents cause changes in objects on contact, by observing the actions of other people over the first 3 postnatal months. Alternatively, these basic abilities may emerge over the course of fetal development and guide postnatal learning on infants' first encounter with people's actions. The latter possibility is compatible with a computational model of early visual development that leverages a primitive ability to identify agents ("movers") to support infants' learning of the visible boundaries of objects and the visible properties of human hands and gaze (49, 59). Experiments on precocial animals and newborn human infants provide suggestive support for the latter possibility, because newborn infants look preferentially to causal over noncausal physical events (39), and controlled-reared chicks preferentially imprint to objects that participated in causal events (60). Nevertheless, no newborn animal or human infant has been shown to attribute causal powers to agents.

Conclusion

Infants eventually learn to reach for objects, to plan actions around obstacles to achieve their goals, to reflect on their own intentions and skills, and even to act on the world at a distance. A skeletal understanding of people as causal agents may provide one foundation for this learning. Infants may enter the world with little knowledge of the actions or the goals of the people around them, and their own actions on objects are highly limited, but they may rapidly learn about people and objects by knowing that there are causes, agents, and actions to search for in the first place. The deep remaining question concerns the developmental mechanisms by which these concepts emerge in human brains, throughout fetal development and the first postnatal months, so as to generate abstract knowledge so early in life.

Materials and Methods

Participants. $n = 152$ healthy, full-term infants (mean age = 107 d; range = 91 to 122 d; 78 female) were included in our final sample across Exps. 1 through 5. Infants' legal guardians provided informed written consent for them to participate, and all families received a small gift (e.g., toy, T-shirt), and \$5 travel compensation. All data were collected at the Harvard Laboratory of Developmental Studies, and all study protocols were approved by the Committee on the Use of Human Subjects at Harvard University. See *SI Appendix* for participant exclusion information.

Materials and Procedure. Infants were tested in a dimly lit room, and seated in a car seat such that their faces were ~1 m away from a 70×40-m LCD screen. Prior to habituation, infants saw a 3-s video of an actress saying "Hi, baby!" in an infant-directed fashion. During habituation videos for all experiments, except for H4 in Exp. 3, she was seated at a table in front of an object, and then reached over a barrier for the object, and always adapted her action to the height of the barrier, which varied trial to trial. All videos were filmed using a metronome for consistency, and all barriers were added digitally to the videos after filming. To generate the videos for H4, we used the same videos as H3, moving the barrier beyond the goal object, out of her reach. To generate the noncausal videos for Exps. 4 and 5 (H5, T4), we manipulated the videos from the constrained condition of Exp. 3 (H3, T3) in Final Cut Pro to introduce a 50-pixel gap between the person's hand and the object, and a 0.5-s delay between the final position of the hand and the object's illumination. Prior to the test, infants saw an image of the scene including only the table and the object, without the person or the barrier. Then, at test, the person returned and alternatingly reached straight across the table for the object (efficient but novel path), or in the same curvilinear fashion that she did during habituation (inefficient but familiar path), order counterbalanced across participants. See *SI Appendix* for additional details.

*We thank an anonymous reviewer for suggesting this alternative interpretation for these and past experiments probing infants' understanding of goal-directed action.

Analysis Strategy. Infant looking times are often log-normally distributed (61), including in this dataset (*SI Appendix*, Fig. S3), and thus were log-transformed (main results) or transformed to proportions (supplemental and meta-analytic results; see *SI Appendix*) prior to analysis. Descriptive statistics and plots feature raw looking times for interpretability. We used linear mixed-effects models (42) in R (62) to analyze all looking-time data. In order to address potential outliers, we used the influence.ME package (63) to identify influential participants, and report effects in the main text excluding them, but see *SI Appendix* for primary results including these influential participants, information about data reliability, and analyses of attention during habituation. Fig. 2 and *SI Appendix*, Figs. S1 and S3–S5 were produced using the ggplot2 package (64). To explicitly model repeated measures and correlated data with experiments, all mixed models including multiple observations per participant included participant identity as a random intercept, and all models including observations from multiple experiments included experiment as a random intercept. The *Results* section of this paper was written in R Markdown (65) to enhance reproducibility and minimize error.

Open Science Practices. All stimuli, data, code, and preregistrations of this paper are open access at https://osf.io/rcsns/. Our laboratory began preregistering experiments on the Open Science Framework in the middle of this research; thus, Exps. 1 through 3 were not formally preregistered. The design, methods, and sample size of Exp. 3 were planned prior to data collection. In all other experiments, all details regarding the design, sample size, methods, exclusion criteria, and analyses were planned ahead of data collection, and were formally preregistered for Exps. 4 and 5.

ACKNOWLEDGMENTS. We thank the families who volunteered to participate; the Harvard Laboratory of Developmental Studies for helpful discussion; Tomer Ullman and the Cambridge Writing Group for feedback on an earlier draft of this paper; Amy Skerry for sharing data; Taylor Ladd and Alia Martin for help with filming stimuli; Aracely Aguirre for help with video manipulation; Alena Egner, Rosa Guzman, and Natasha Kalra for help with data collection; and Aracely Aguirre, Daisy Evariz, Nensi Gjata, Caroline Kerwin, and Bill Pepe for help with data coding. This material is based upon work supported by the Center for Brains, Minds and Machines, funded by National Science Foundation STC Award CCF-1231216, and by a National Science Foundation Graduate Research fellowship under Grant DGE-1144152.

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REPORT

COGNITIVE DEVELOPMENT

Ten-month-old infants infer the value of goals from the costs of actions

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Infants understand that people pursue goals, but how do they learn which goals people prefer? We tested whether infants solve this problem by inverting a mental model of action planning, trading off the costs of acting against the rewards actions bring. After seeing an agent attain two goals equally often at varying costs, infants expected the agent to prefer the goal it attained through costlier actions. These expectations held across three experiments that conveyed cost through different physical path features (height, width, and incline angle), suggesting that an abstract variable—such as "force," "work," or "effort"—supported infants' inferences. We modeled infants' expectations as Bayesian inferences over utility-theoretic calculations, providing a bridge to recent quantitative accounts of action understanding in older children and adults.

When we observe people's actions, we see more than bodies moving in space. A hand reaching for an apple is not just one object decreasing its distance from another; it can indicate hunger (in the person who is reaching), helpfulness (if the person is reaching on behalf of someone else), or compromise (if the person reaching would prefer a banana, but not enough to go buy one). This fast and automatic ability to interpret the behavior of others as intentional, goal-directed, and constrained by the physical environment is often termed "intuitive psychology" (*1*–*4*). We used behavioral experiments and computational models to probe the developmental origins and nature of this ability.

Over the past two decades, research has revealed that the building blocks of our intuitive psychology are present as early as the first year of life. Despite infants' limited experience, their interpretations of other people's actions are guided by assumptions about agents' physical properties (*5*), intentions and goals (*6*), mental states (*7*–*10*), causal powers (*11*), and dispositions to act efficiently (*7*, *12*, *13*). This wealth of findings does not reveal, however, whether infants' capacities depend on a host of distinct local abilities (*14*–*16*) or on a single coherent system supporting inference, prediction, and learning (*3*, *17*–*19*).

We tackled this question in a case study, based on a computationally precise proposal for a coherent, abstract, and productive system for action understanding (Fig. 1). Previous studies suggest that infants are sensitive to the costs of agents' actions (*3*, *7*, *12*, *13*) and can infer agents' preferences (*6*, *9*). Decision theorists for hundreds of years have recognized these as the two central factors guiding the decisions of rational agents (*20*–*22*). We asked whether infants can integrate these dimensions to infer agents' goals: Do infants use the cost that an agent expends to attain a goal state in order to infer the value of that goal state for the agent?

Such an inference has been proposed to rest on three nested assumptions that together constitute a "naïve utility calculus" (*23*), analogous to classical economic thinking. First, agents act

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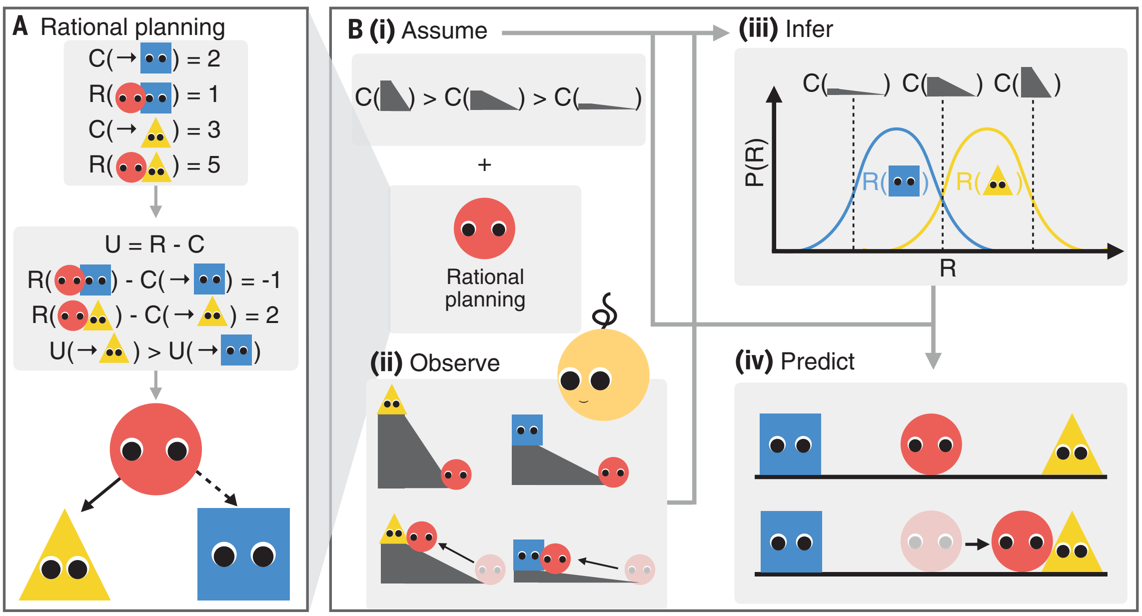

Fig. 1. A schematic of our computational model. (**A**) The forward direction defines the agent as a rational planner that calculates the utilities of different actions from their respective costs and rewards and then selects an action stochastically in proportion to its utility. In this case, the overall utility for approaching the triangle is higher than for approaching the square, so the central agent (circle) will likely choose triangle over square. (**B**) An observer (i) assuming this model and priors over the costs of different actions can (ii) observe a series of actions and then (iii) infer a posterior distribution over the hidden values of an agent's costs and rewards given its actions. (iv) These posteriors can then be used to predict the actions of the agent in a new situation, in which the same goal states can be reached with different actions.

to maximize their utility U, under constraints (2, 4, 24, 25). Second, this utility separates into rewards and costs, two distinct components that can be individual targets of inference (26). That is, if $R(S)$ is the reward of a goal state S, and $C(A)$ is the cost of an action, then an agent acts to maximize the following

$$U(A, S) = R(S) - C(A) \tag{1}$$

Third, the cost of an action is not arbitrary but depends on properties of both the agent and the situation: properties that jointly determine how much effort the agent might need to exert to carry out that action.

These assumptions can be formalized as generative models that successfully predict the quantitative and qualitative behavior of adults and older children (4, 23, 26). In these models, observers who reason that other agents are maximizing their expected utility according to Eq. 1 can use what they know about rewards and costs to predict the agents' future actions. Inverting this process, observers can use the agents' overt actions to infer their hidden rewards and costs, according to

$$P(R, C \mid A) \propto P(A \mid C, R) \cdot P(R, C) \tag{2}$$

where $P(R, C \mid A)$ is the posterior distribution over the rewards and costs of an agent. By Bayes' theorem, this distribution is proportional to the product of $P(A \mid C, R)$—the likelihood of the agent choosing action A given rewards R and costs C, given by a rational planning procedure (4, 23)—and $P(R, C)$, a prior distribution over costs and rewards.

Do infants apply the logic of cost-reward reasoning? Past research suggests that infants are sensitive to the relative value of different goal objects for an agent who chooses to approach one object over another (6, 27) as well as the relative efficiency of the actions taken by an agent who approaches a goal object (12, 13, 28). Past studies do not reveal, however, whether infants have a unified intuitive psychology in the form of a generative model, or separate representations for variables such as cost and reward that become unified only later in development, as children gain experience exerting themselves to achieve goals or communicating with others about their desires and actions. It is also an open question whether infants consider cost and reward in terms of abstract variables—such as work, effort, desire, or value—or whether their understanding is restricted to perceptual features of actions, such as the distance or duration an agent travels or the number of times it selects a particular goal. In physical action contexts, effort often covaries with perceptible properties such as the length or duration of a path traveled, but effort depends ultimately on the amount of force that the agent must exert over time and distance (the amount of work the agent must do). Likewise, value often covaries with the number of times an agent selects a goal but ultimately depends on how strongly the agent desires a goal relative to the cost of achieving it or its value relative to other options.

We designed and conducted three experiments to test whether infants learn about the reward agents place on goals from cost, working backward from the assumption that agents maximize utility and inferring relative rewards from observed actions under varying costs. We then used the data from these experiments, together with the findings from past experiments (6, 7, 13), to test a variety of computational models of infants' performance, including models with integrated versus isolated, and abstract versus cue-based, representations of costs and rewards (model description is provided in the supplementary materials). Our empirical and computational findings support the view that a productive system grounded in cost-reward trade-offs guides action understanding toward the end of the first year of life.

We tested n = 80 10-month-old infants in three experiments with prespecified designs, procedures, sample sizes, and analysis plans (29). In all experiments, infants first saw an agent move to and refuse to move to each of two target goals under conditions of varying cost. Then, infants watched test events in which the agent chose either the higher- or the lower-value target when both were present at equal cost. If infants infer the reward of the targets to the agent from the effort undertaken to reach them, then they should be more surprised when the agent chooses the lower-value target, looking longer at the test trials displaying that action (30).

In experiment 1 (n = 24 infants), we leveraged events widely used in studies of early action understanding, in which animated characters jump efficiently over barriers of variable heights to arrive at goal objects (3, 7, 13, 31) and indicate their preferences by selecting one goal over another (6, 9). During familiarization, infants watched six trials that consisted of four different events involving a central agent and one of two target individuals on a level surface (Fig. 2A and movie S1). In each event, the target jumped and made a noise, and the agent responded by turning to face and beginning to approach the target, whereupon a barrier fell onto the stage

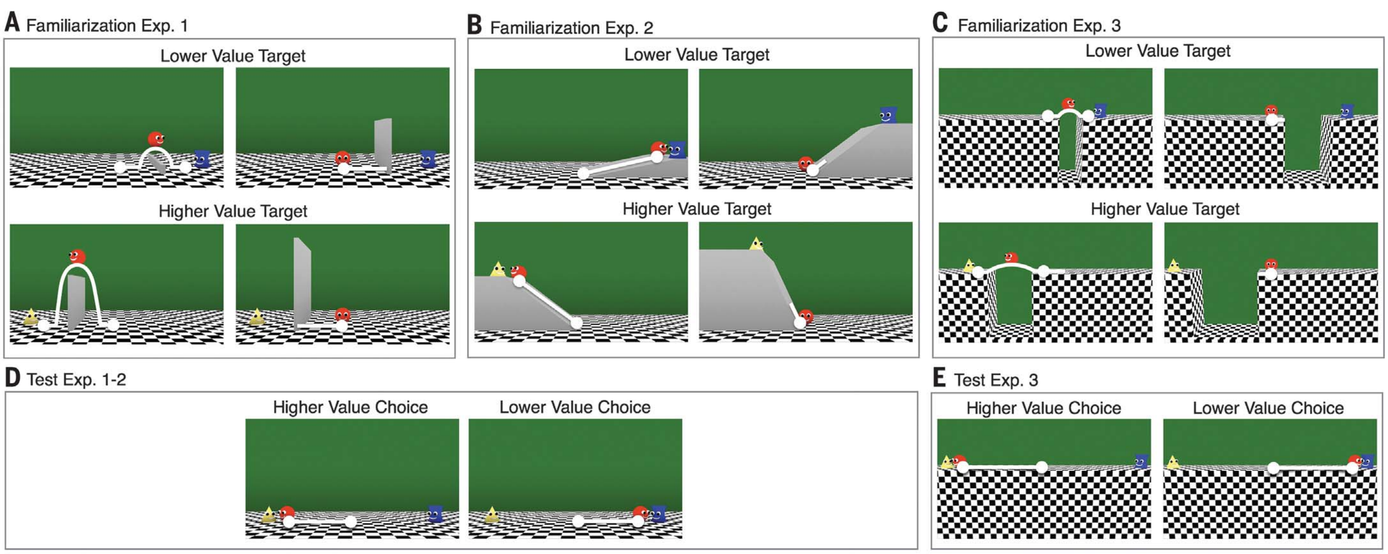

Fig. 2. Structure of experiments 1 through 3. (**A** to **C**) During familiarization, the central agent (circle) accepted a low cost and refused a medium cost for the lower-value target (square) and accepted a medium cost and refused a high cost for the higher-value target (triangle). Other than the sizes of the barriers, ramps, and trenches, and the consequent trajectories of motion, the pairs of events displaying approach or refusal of approach to the two targets were identical. (**D** and **E**) At test, the agent looked at each of the two targets and chose either the lower- or higher-value target. White circles indicate start- and end points of action, and white lines indicate trajectories.

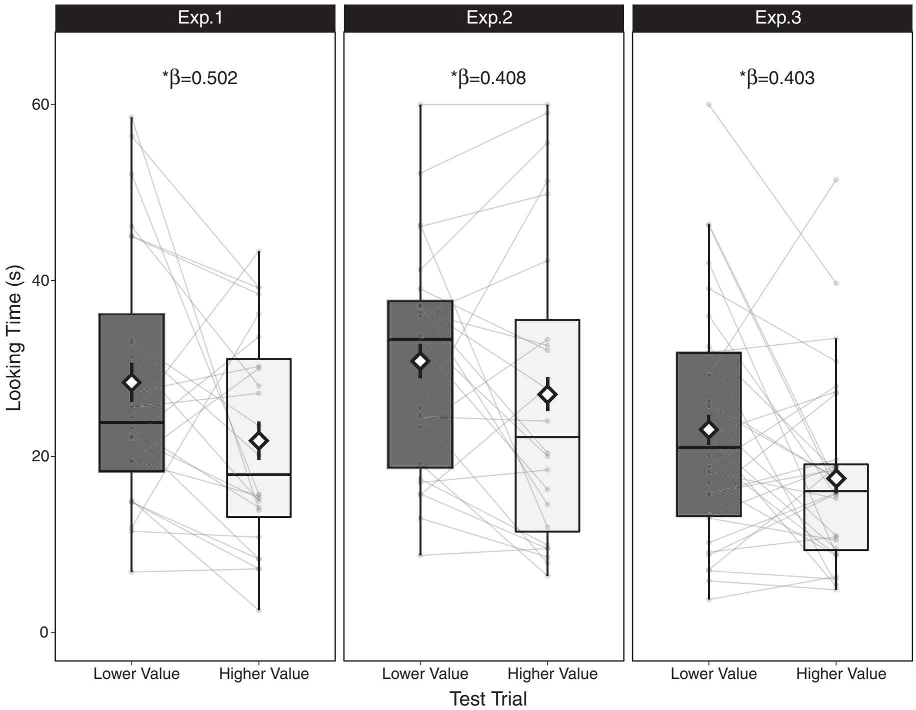

Fig. 3. Boxplots of average looking time toward the higher- and lower-value choice during test in experiments 1 through 3. White diamonds indicate means, with error bars indicating within-subjects standard errors. Horizontal lines indicate medians, boxes indicate middle quartiles, and whiskers indicate points within 1.5 times the interquartile range from the upper and lower edges of the middle quartiles. Light gray points connected across boxes indicate looking times from individual participants. Beta coefficients indicate effect sizes in standard deviations, and asterisks indicate significance relative to prespecified (experiments 1 and 2) and preregistered (experiment 3) alphas (*$P < 0.05$). Statistical analyses are provided in the text and supplementary materials.

directly in the agent's path. On two of these events (one for each target), the agent looked to the top of the barrier, made a positive "Mmmm!" sound, backed up, and then jumped over the barrier, landing next to the target. On the other two events, the agent looked to the top of the barrier, made a neutral "Hmmm…" sound, backed away, and returned to its initial position. The critical distinction between these events concerned the height of the barrier and therefore the length, height, and speed of the jump that the agent undertook so as to clear it (all jumps were equated for duration). For one target, the agent jumped over a low barrier and declined to jump a medium barrier; for the other target, the agent jumped the medium barrier and declined a tall barrier. After this familiarization, the agent appeared between the two equidistant targets on a level surface. Infants viewed two pairs of looped test events (Fig. 2D and movie S4), order counterbalanced, in which the agent looked at each of the targets and then repeatedly approached either the higher- or the lower-value target. Our prespecified dependent measure was average log-transformed looking time (*32*) across test trials. In experiment 1, we predicted differential looking at the test events but did not prespecify the direction of this difference.

Infants looked longer at test trials in which the agent chose the target for whom it had jumped a lower barrier (mean = 28.41 s, SD = 14.85), relative to the target for whom it had jumped a higher barrier (mean = 21.79 s, SD = 12.29) [95% confidence interval (CI) (0.062, 0.591), b coefficient (B) = 0.327, SE = 0.130, standardized β coefficient (β) = 0.502, $t(24) = 2.523$, $P = 0.019$, two-tailed, mixed effects model with random intercept for participant] (Fig. 3) (*30*). These findings suggest that infants inferred the rewards that the central agent placed over the targets from the cost the agent was willing to expend to reach these targets, and they therefore expected the agent to choose that target at test. Nevertheless, experiment 1 does not show whether infants used the physical effort undertaken by the agent, or variables that merely correlate with effort (such as distance or speed), in their predictions.

To control for distance and speed of travel, experiment 2 ($n = 24$ infants) used ramps of three different incline angles to convey cost (Fig. 2B and movie S2). On each familiarization trial, a target appeared on the top of one ramp, and the agent looked up the ramp and either climbed to the target or returned to its starting position. The agent climbed the shallow ramp and declined to climb the medium ramp for one target and climbed the medium ramp and declined the steep ramp for the other target. The methods were otherwise the same as in experiment 1. Consistent with our prespecified directional prediction, infants again looked longer at the test events in which the agent approached the lower-value target (mean = 30.94 s, SD = 13.31) than test events in which the agent approached the higher-value target (mean = 27.05 s, SD = 17.55) [95% CI (0.028, 0.472), B = 0.250, SE = 0.109, β = 0.408, $t(24) = 2.294$, $P = 0.015$, one-tailed, mixed effects model with random intercept for participant] (Fig. 3) (*30*). This finding further suggests that infants understand agents' actions in accord with abstract, general, and interconnected concepts of cost and reward, but narrower explanations remain. In experiments 1 and 2, the agent was confronted with an obstacle to its forward motion (a barrier or ramp), and the size of the obstacle covaried with the cost of the agent's action, requiring the agent to move further upward to attain the higher-value target. Because infants become sensitive to the effects of gravity on objects on inclined planes well before 10 months of age (*33*), they may learn that agents will move to greater heights or overcome higher obstacles for more rewarding targets, without invoking a more abstract representation of physical effort. Experiment 3 was undertaken to explore these interpretations.

In experiment 3 ($n = 32$ infants), the agent was separated from each of the two targets during familiarization not by an obstacle but by a horizontal gap in the supporting surface (Fig. 2C and movie S3). Infants first saw a ball roll off the edge of a narrow, medium, and wide gap and shatter (movie S6). During familiarization, these three trenches, requiring jumps of variable lengths and speeds but of equal durations and heights, were interposed between the agent and target; the agent moved to the edge of a trench, looked at the far side, and then jumped over a narrow trench for one target (and refused the medium trench) and a medium trench for the other target (and refused the widest trench). The methods were otherwise unchanged (Fig. 2E and movie S5). The methods and analyses for experiment 3 were preregistered at https://osf.io/k7yjt (*29*) and tested the same directional prediction as that in experiment 2. Infants again looked longer at the lower-value choice (mean = 23.05 s, SD = 13.58) relative to the higher-value choice (mean = 17.47 s, SD = 10.69) [95% CI (0.020, 0.501), B = 0.260, SE = 0.119, β = 0.403, $t(32) = 2.185$, $P = 0.018$, one-tailed, mixed effects model with random intercept for participant] (Fig. 3) (*30*).

Regardless of whether an agent cleared higher barriers (experiment 1), climbed steeper ramps (experiment 2), or jumped wider gaps (experiment 3) for one target over the other, infants expected the agent to choose that target at test. Across all experiments, infants looked longer at the lower-value action (mean = 26.99 s, SD = 14.13) than the higher-value action (mean = 21.64 s, SD = 13.94) [95% CI (0.139, 0.415), B = 0.277, SE = 0.070, β = 0.424, $t(80) = 3.975$, $P < 0.001$, one-tailed, mixed effects model with random intercepts for participant and experiment], supporting our general hypothesis that infants infer the values of agents' goals from the costs of their actions. Although past research had shown that infants represent the goal of an agent's action from observations of an agent's choices between two objects (*6*) and expect agents to give different emotional responses when agents complete versus fail to complete their goals (*31*), the present experiments provide evidence that infants develop ordinal representations of reward even when the number of choices and expressed emotions are equated across the actions and only the costs of the actions vary. Moreover, they show that infants do not simply attribute higher reward to goals that agents pursue for a longer duration or attain with greater frequency because these variables were equated as well. The findings also provide evidence for longstanding suggestions that infants represent physical cost as a continuous variable that agents seek to minimize (*3*, *13*): Infants make appropriate cost assessments even when the specific physical features that distinguished lower- from higher-cost actions—including the relative length, curvature, duration, or speed of motion trajectories—systematically varied. Together, experiments 1 through 3 suggest that infants represent cost and reward as interconnected, abstract variables that they apply to a wide range of events.

The discovery that infants infer the rewards of goals from the costs of achieving them provides empirical support for the thesis that an abstract and productive system guides infants' analysis of agents and their actions (*3*, *17*, *19*). Specifically, we suggest that the cognitive machinery supporting infants' intuitive psychology includes a mental model both of how agents plan actions in the forward direction, in accord with maximizing their utilities (Eq. 1 and Fig. 1A) (*23*), and a procedure for inverting this model, in accord with the computational framework of inverse planning (Eq. 2 and Fig. 1B) (*4*). Applying this general framework to our specific experiments, we posit that infants have developed a model of action planning before the experiment: They assume that agents value some goal objects more than others and that agents engage in costlier actions to achieve goals with higher reward. When infants see the agent take costlier actions to arrive at one target than to arrive at another, infants invert this model to infer the relative reward of the two targets to that agent. Then, when infants see the agent flanked by the two targets in a situation in which costs are equal, they apply their knowledge of the targets' relative value to the agent to run their planning model for that agent forward, predicting the target that it will approach. We have implemented this hypothesis in a computational model that accounts not only for the findings of the present experiments but also for a range of past studies of early action understanding (*6*, *7*, *13*). Furthermore, we compared this model with an array of simpler models that focus only on relative costs or rewards in isolation, or on particular cues to effort or value. We found that only the full model with abstract variables for costs and rewards can account for all of the findings (fig. S3 and supplementary materials).

The present studies raise key questions for future research. First, the cognitive architecture underlying infants' assessment of cost remains to be explored. Our experiments suggest that infants are responding to an abstract notion of cost, rather than specific physical path features such as vertical motion (controlled for in experiment 3), horizontal motion (controlled for in experiment 1), or raw path length (controlled for in experiment 2). We do not know, however, whether infants represent the abstract costs of actions by drawing on a concept of experienced effort or exertion within the domain of naïve psychology, or by leveraging an intuitive concept of force or work done (the integral of force applied over a path) from the domain of naïve physics (*34*, *35*), or perhaps both. Also, our experiments investigated only one class of goal states and target-directed actions, leaving open the breadth and generality of infants' intuitive psychology. In particular, cost can be defined in terms of work or effort to produce physical forces, but there are other kinds of costs: Agents could consider variables such as the mental effort of planning (*36*, *37*) and the risks of choosing certain actions, neither of which involves applications of force. It is an open question whether these other variables trade off against reward in infants' intuitive psychology the way that physical work or effort does. Last, our studies do not speak to the origins of these abilities. Although 10-month-old infants cannot perform the actions from our experiments or communicate with others about them, their productive system for reasoning about costs and rewards may arise through their experiences observing the actions of other agents or performing actions within their repertoire, such as lifting their arms or balancing their bodies against the force of gravity. Alternatively, this system of intuitive psychology may guide infants' action understanding from the beginning. Testing these possibilities would address fundamental questions concerning the nature, origins, and interrelations between our intuitive psychology and intuitive physics.

However these questions are answered, the present study suggests that our propensity to understand the minds and actions of others in terms of abstract, general, and interrelated concepts begins early. Before human infants learn to walk, leap, and climb, they leverage mental models of agents and actions: forward models of how agents plan, and inverse models for working backward from agents' actions to the causes inside their minds.

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ACKNOWLEDGMENTS

All authors wrote the paper, S.L. designed the experiments and collected and analyzed the data under the direction of E.S.S., and T.D.U. built the computational models under the direction of J.B.T. This material is based on work supported by CBMM, funded by National Science Foundation Science and Technology Center award CCF-1231216, and by a National Science Foundation Graduate Research Fellowship under grant DGE-1144152. We thank the families who volunteered to participate and A. Aguirre, R. Guzman, C. Kerwin, N. Kalra, and H. Tarr for research assistance. All data, analyses, and materials from the experiments and models reported in this paper are archived on the Open Science Framework at https://osf.io/mykph.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/358/6366/1038/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S5
References (*38*–*54*)
Movies S1 to S6

22 May 2017; accepted 12 October 2017
10.1126/science.aag2132

Science

Ten-month-old infants infer the value of goals from the costs of actions

Shari Liu, Tomer D. Ullman, Joshua B. Tenenbaum and Elizabeth S. Spelke

Science **358** (6366), 1038-1041.
DOI: 10.1126/science.aag2132

Ranking valuations on the basis of observed choices

Obliged to make a choice between two goals, we evaluate the benefits of achieving the goals compared with the costs of the actions required before deciding what to do. This seems perfectly straightforward, and it is unsurprising to learn that we can also apply this reasoning to others; that is, someone that we see choosing a goal that requires a more costly action must value that goal more highly. What is remarkable, as Liu *et al.* report, is that preverbal children can reason in this same fashion.

Science, this issue p. 1038

Cognition 160 (2017) 35–42

Contents lists available at ScienceDirect

Cognition

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

Original Articles

Six-month-old infants expect agents to minimize the cost of their actions

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ARTICLE INFO

Article history:
Received 22 May 2016
Revised 9 December 2016
Accepted 20 December 2016

Keywords:
Cognitive development
Goal inference
Social cognition
Open data
Open materials

ABSTRACT

Substantial evidence indicates that infants expect agents to move directly to their goals when no obstacles block their paths, but the representations that articulate this expectation and its robustness have not been characterized. Across three experiments (total $N = 60$), 6-month-old infants responded to a novel, curvilinear action trajectory on the basis of its efficiency, in accord with the expectation that an agent will move to its goal on the least costly path that the environment affords. Infants expected minimally costly action when presented with a novel constraint, and extended this expectation to agents who had previously acted inefficiently. Infants' understanding of goal-directed action cannot be explained alone by sensitivity to specific features of agent's actions (e.g. agents tend to move on straight paths, along supporting surfaces, when facing their goals directly) or extrapolations of agents' past actions to their future ones (e.g. if an agent took the shortest path to an object in the past, it will continue to do so in the future). Instead, infants' reasoning about efficiency accords with the overhypothesis that agents minimize the cost of their actions.

1. Introduction

Action understanding is a fundamentally underdetermined problem: an infinite combination of causes could explain a given observed behavior, including the emotions, desires, and beliefs internal to agents, the goals and obstacles in the world, the physical forces that agents must overcome to achieve their goals, and the forces that their actions produce. In spite of this computational challenge, we solve this problem quickly and intuitively every day: Viewing a simple behavior, like a person walking into a building, licenses inferences about her desires to reach her destination, beliefs about what is there, and competence in planning this action. The building blocks of these capacities emerge early in human development: Infants interpret agents' actions by leveraging assumptions about their material properties (e.g. agents are solid and thus face physical constraints; Saxe, Tzelnic, & Carey, 2006), their causal powers (e.g., agents bring about changes in the motions and states of objects; Muentener & Carey, 2010; Saxe, Tenenbaum, & Carey, 2005) and their goals (e.g. agents face, perceive, and act on objects; Csibra & Volein, 2008; Gergely, Nádasdy, Csibra, & Bíró, 1995; Luo & Johnson, 2009; Woodward, 1998).

These findings raise two important questions about the cognitive infrastructure supporting early action understanding. First, what representations express infants' assumptions about agents and their actions? That is, what are the variables and functions that embody their knowledge? Second, is this content embedded in a coherent system of knowledge or does it reflect local learning about specific actions or physical contexts? In other words, to what extent does this knowledge capture the hidden causal structure of the world versus the statistical regularities in the immediately perceivable environment? The answers to these questions bear on theories of the form and content of mature intuitive psychology, as well as theories of its development.

1.1. Case study: Unpacking rational agency

The assumption that agents seek to maximize rewards and minimize costs, given their beliefs about state of the world, has long been proposed as a key principle in intuitive psychology (Baker, Saxe, & Tenenbaum, 2009; Dennett, 1987; Gergely & Csibra, 2003; Jara-Ettinger, Gweon, Schulz, & Tenenbaum, 2016). By 5 years of age, we attribute mental states, beliefs and desires, to agents (Bartsch & Wellman, 1989; Wellman, Cross, & Watson, 2001) by assuming that they have planned their actions so as to bring about maximum utility (Jara-Ettinger, Gweon, Tenenbaum, & Schulz, 2015). Nevertheless, questions about the origins of this capacity remain open. Does infants' earliest understanding of agents center on the assumption that their actions are guided by

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http://dx.doi.org/10.1016/j.cognition.2016.12.007
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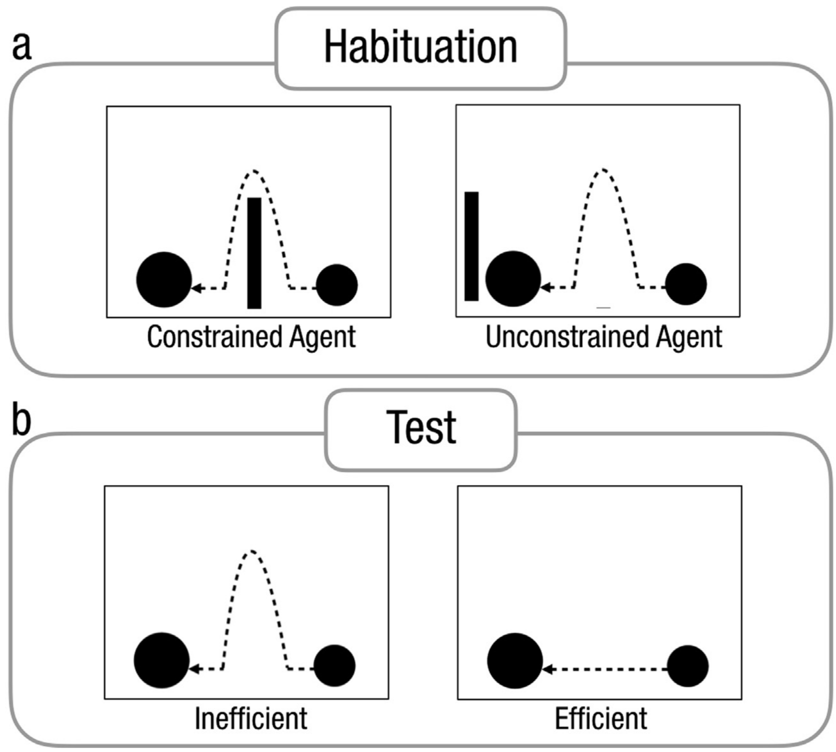

Fig. 1. Schematic of events used in past experiments (e.g. Csibra et al., 1999; Gergely et al., 1995) probing infants' sensitivity to action efficiency. Infants were (a) habituated to an agent leaping over an obstacle (left), or to an agent performing the same actions with the obstacle situated beyond its goal (right), and (b) then viewed test events where the obstacle was removed and the agent either performed an inefficient but perceptually familiar action (left) or efficient but perceptually novel action (right) towards its goal.

plans to maximize rewards and minimize costs? Or do infants first analyze actions using leaner assumptions, such as the assumption that goal-directed actions will have certain perceptual features (e.g. that they move across flat supporting surfaces while facing their goals) and later acquire the principles guiding rational action?

Many experimental findings are consistent with the thesis that infants expect agents to behave rationally. In these experiments, infants first view an agent who moves on an efficient, curvilinear path to reach an object that stands behind an obstacle. Then the obstacle is removed, and infants are tested with the path that the agent had previously taken and a new, direct path. Infants' looking preferences provide evidence that they expect the novel, direct trajectory (Csibra, 2008; Csibra, Gergely, Bíró, Koós, & Brockbank, 1999; Gergely & Csibra, 2003; Gergely et al., 1995; Phillips & Wellman, 2005; Skerry, Carey, & Spelke, 2013) (Fig. 1). This expectation is early emerging (Skerry et al., 2013) and is applied broadly to both human-like (Phillips & Wellman, 2005; see also Gergely, Bekkering, & Király, 2002; Schwier, van Maanen, Carpenter, & Tomasello, 2006) and unfamiliar (Csibra, 2008; Gergely et al., 1995) agents. It is also inferentially powerful, licensing predictions about the configuration of an occluded physical scene (Csibra, Bíró, Koós, & Gergely, 2003) and the outcomes of ongoing actions (Csibra et al., 2003; Southgate & Csibra, 2009; Wagner & Carey, 2005).

Nevertheless, this family of findings is open to several interpretations. The richest construal is consistent with utility theory, based on representations of the relative costs of different actions and the relative rewards that these actions bring. Under this interpretation, infants, given two alternative actions with equal rewards and varying costs, expect agents to minimize the cost of their actions. However, at least three leaner interpretations are equally consistent with these findings. First, infants could construe agents as rational planners without a minimum function over costs: Infants could jointly rely on their assumptions about the solidity of agents and objects (Saxe et al., 2006), plus a set of general rules concerning the trajectory of motion agents follow when pursuing an unobstructed goal (e.g. that agents tend to move smoothly across supporting surfaces, face their goals, and move to them on straight paths), to generate this prediction. These assumptions about the features of actions could be innate, or learned, based on infants' past experiences performing their own actions and observing the actions of others. Alternatively, infants may have no initial expectations about the efficiency of agents, but may develop such expectations over the course of the experiment (e.g. by generalizing an agent's efficient behavior across changes in an its physical constraints). Lastly, infants could lack any ability to represent the cost of actions, but succeed in these experiments by generalizing perceptual features of an agent's actions from habituation to test (e.g. by learning that agents jump just high enough to clear the barrier[1]). Under the latter three interpretations, the content supporting infants' responses need not appeal to continuous, rich representations of cost.

1.2. Current experiments

Here, we test whether infants expect agents to minimize the cost of their actions against these alternatives. As reviewed above, the extant evidence for continuous representations of cost is consistent both with the broad and general principles of utility theory

[1] The last three interpretations could in principle explain findings from the control condition of past experiments (e.g. Csibra, 2008; Csibra et al., 1999; Gergely & Csibra, 2003; Gergely et al., 1995; Skerry et al., 2013), where the agent performs the same actions during habituation that are unconstrained by a barrier. This could (a) cause infants to suspend their predictions about an ostensibly irrational agent or (b) place a more difficult demand on them to learn the relation between the height of the jump and the height of the barrier (c.f. Csibra et al., 1999).

but also with narrower and more limited expectations, including the expectation that goal-directed agents travel to unobstructed goals by facing them and moving on straight paths, that agents who act rationally tend to continue to do so in the future, and that the path of an agent's action is predictable by the features of its environment.

To ask whether infants represent cost as a continuous variable, we present 3 experiments wherein infants' action predictions cannot be explained using rule-like assumptions about cost, learned from an agent's past efficiency, or learned from perceptual features of its past actions. We begin by testing infants for sensitivity to curved trajectories of motion that vary in efficiency. Whereas a system that represents the cost of actions as a set of local assumptions (e.g. agents move directly to their goals) would not distinguish between more or less efficient actions, a system that represents efficiency as a continuous variable would expect agents to minimize it. In Experiments 1 and 2, we test the hypothesis that 6-month-old infants expect agents to perform minimally costly actions when faced with a novel obstacle. In Experiment 3, we explore whether learning alone can account for this expectation by asking whether infants expect minimally costly action from an agent who previously engaged in inefficient actions.

2. Experiment 1

Experiment 1 tests whether infants discriminate between goal-directed actions over obstacles that vary in length and degree of curvature. When a barrier blocks an agent's direct path to a goal, do infants expect the agent to circumvent the barrier as efficiently as possible? If continuous representations of cost support expectations for efficient action, then infants should discriminate between the low and high trajectory of motion over the test barrier, and selectively recover attention when an agent takes a novel degree of cost given its new constraints.

2.1. Methods

2.1.1. Participants

Our sample included 20 full-term, healthy infants (10 female, M_{age} = 5.95 months, range = 5.57–6.63 months), comparable to studies of similar format and focus (e.g. Csibra, 2008; Csibra et al., 1999; Skerry et al., 2013). Seven more infants were tested, excluded and replaced (2 for fussiness that prevented study completion, 1 for failure to habituate, 1 for online coding error, 2 for technical failure, and 1 for parental interference). Sample size and exclusion criteria were fixed prior to the start of data collection, and decisions to exclude infants were made by researchers who were unaware of the order of events viewed by the infants. All participants were recruited from the greater Boston area and tested at the Laboratory for Developmental Studies at Harvard University with parental informed consent. Families received a small thank-you gift (e.g. a t-shirt or toy) for participating.

2.1.2. Materials

The animated events were created in Blender (Stichting Blender Foundation, 2016), synchronized with a custom audio track in iMovie, and presented using Keynote on an LCD projector screen 40″ in height and 52″ in width. Two speakers located on either side of the screen played all stimuli-related sounds. Infants' looking time data were coded online using Xhab64 (Pinto, 1995) software and offline using jHab (Casstevens, 2007).

2.1.3. Design

We used a habituation paradigm to probe infants' preferential looking towards two kinds of test events after reaching a predetermined habituation criterion (Fig. 2). All habituation and test trials began with an attention-getting star animation (2.0 s), and subsequently consisted of looped sequences of an animated event (5.0 s), which paused on the last frame (0.5 s) and was followed by a blank screen (0.5 s) before the next animation. Each animation featured a red spherical agent with eyes and a smiling mouth that began to move directly toward an unobstructed goal object (a blue cone), only to be impeded by a grey barrier that fell to rest with an audible thud between the agent and its goal. The agent then backed away, approached the obstacle, and leapt over it while making a popping sound, coming to rest next to the goal object. The timing of the jump was held constant across all habituation and test trials (0.9 s); thus, taller jumps were executed more rapidly.

In the *habituation events*, the height of the barrier varied across 3 levels (6, 5, and 3 Blender units) within each trial. The agent's jump height always aligned with that of the barrier (9.5, 8.5, and 6.5 units, respectively). Barriers and jumps of different heights were presented in a consistent pseudorandom order across trials.

The *test events* featured the same basic event structure with one critical change: a very short barrier (1 unit) obstructed the trajectory of the agent. To assess whether infants discriminate curved action trajectories on the basis of their efficiency with respect to this novel barrier, infants' attention was measured for two test trial types. On alternating test trials, the agent backed away from the barrier and performed either a low, efficient jump or a high, inefficient leap over it (4.5 and 9.5 units, respectively).

2.1.4. Procedure

Infants were seated on their caregivers' laps approximately 60″ away from the screen. Caregivers were instructed to keep their eyes closed and to refrain from interacting with their infants throughout the experiment, and were monitored for compliance.

After calibrating the infant to the screen using a squeaky toy, the researcher began the experiment. The researcher had access to a video feed of the infant's face, a computer screen indicating the current trial, and a third screen indicating when to conclude a trial and move from habituation to test. The researcher ran the experiment and coded looking time online while remaining unaware of the events displayed and test pair order, but could determine the precise start of each trial as well as the timing of the obstacle falling and the agent jumping over it based on auditory cues, which were identical in timing across all habituation and test trials.

Across both phases of the experiment, the experimenter began coding a trial immediately following the attention getter, and ended a trial once the infant had looked at the screen for 60 cumulative seconds or looked away for 2 consecutive seconds. The test phase began after infants' summed looking time from the most recent 3 habituation trials fell to below half their looking time in the first 3 trials (6–12 habituation trials total) and consisted of 3 pairs of test trials, order counterbalanced across subjects. These criteria were fixed prior to the start of data collection.

2.1.5. Coding and analyses

Videos of all test sessions were coded offline by observers without access to the events infants viewed, using the same thresholds as online coding, and reviewed for the predetermined subject exclusion criteria (fussiness that prevented study completion, online coding error, experimenter error, technical failure, parental interference, and failure to habituate). Further, if infants were determined to have missed a critical part of the test trial (i.e., never saw the agent jump over the test barrier), that test pair was marked and excluded from subsequent analyses. To assess the reliability of the offline-coded data, 100% of the test events were recoded independently by an additional researcher who was unaware of test pair order. The two coders agreed on the trial cutoffs

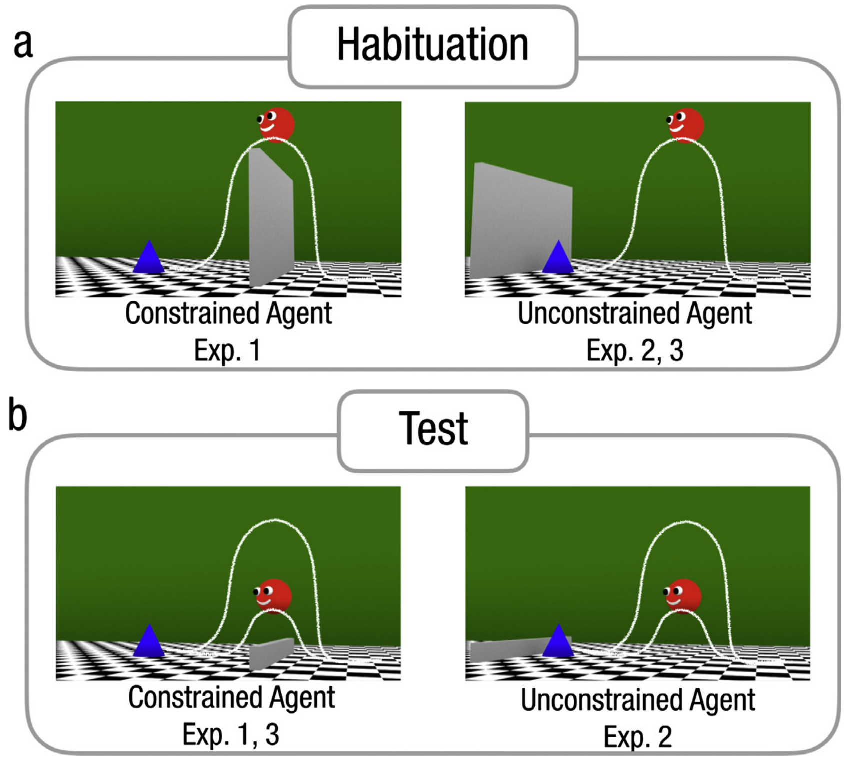

Fig. 2. Trial structure for Experiments 1–3, including (a) habituation to an agent leaping over tall barriers efficiently (left, Experiment 1) or performing identical motions without a physical constraint (right, Experiments 2 and 3) and (b) test, with the agent performing low and high jumps over a novel barrier (left, Experiments 1 and 3) or no barrier (right, Experiment 2). White lines indicate trajectories of motion.

for 94.17% of the test trials, and the intraclass correlation (ICC) between them was 0.969, 95% CI [0.957, 0.979]. Thus, the highly reliable primary offline coding data were used in our analyses.

Across all experiments, inferential statistics (e.g. model estimates, CIs) were fit to log-transformed looking time[2] (Csibra et al., 2016) averaged across all three test pairs, but plots and descriptive statistics feature raw looking times for ease of interpretation.

All analyses leveraged both traditional paired *t*-tests and linear mixed effects models in R (version 3.2.3; R Development Core Team, 2015). Linear mixed models were fit using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015). Detection of influential observations was conducted using the influence. ME package (Nieuwenhuis, te Grotenhuis, & Pelzer, 2012), a suite of methods for determining whether individual cases—in our models, participants—influenced the results such that their inclusion or exclusion could impact interpretation. Plots were produced using the ggplot2 package (Wickham, 2009). To explicitly take into account repeated measures, all mixed models included subject identity as a random intercept. Three classes of models were fit: (1) null models, featuring subject identity as the only predictor, (2) hypothesis-driven models, which included additional manipulated factor(s), and (3) exploratory models, which included additional non-hypothesis driven factors. We leveraged likelihood ratio tests (LRTs) to evaluate model fit by assessing whether the inclusion of certain predictors significantly reduced residual variance. All model-produced degrees of freedom were calculated using the Satterthwaite approximation method.

2.2. Results

2.2.1. Hypothesis-driven results

A hypothesis-driven model, including test action height (high versus low) as a fixed effect and subject identity as a random intercept, revealed that infants looked longer to the high test actions ($M = 16.24$ s, $SD = 12.54$) relative to the low test actions, ($M = 11.35$ s, $SD = 7.41$), 95% CI [0.106, 0.491], $B = 0.298$, $SE = 0.093$, $\beta = 0.462$, $t(20) = 3.191$, $p = 0.005$, two-tailed. A paired *t*-test supported this finding, 95% CI [0.098, 0.499], $t(19) = 3.110$, $d = 0.695$, achieved power = 0.838, $p = 0.006$, two-tailed. See Fig. 2. The hypothesis-driven model provided a better fit than a null model by a LRT, $\chi^2(1) = 8.229$, $p = 0.004$.

An analysis detecting influential cases using Cook's Distance (4/*n*, where *n* refers to the number of groups in the grouping factor in question; Van der Meer, te Grotenhuis, & Pelzer, 2010) revealed one influential subject (D = 0.201, cutoff = 0.2). Removal of this subject from the hypothesis-driven model produced an inferentially equivalent result, 95% CI [0.074, 0.448], $B = 0.261$, $SE = 0.097$, $\beta = 0.439$, $t(19) = 2.878$, $p = 0.010$, two-tailed.

2.2.2. Exploratory results

An exploratory model, testing for an fixed interactive effect of test presentation order and test action height, a fixed effect of sex, and subject identity as a random intercept, revealed no strong order effect, 95% CI [−0.185, 0.564], $B = 0.189$, $SE = 0.182$, $\beta = 0.239$, $t(20) = 1.039$, $p = 0.311$, two-tailed, or gender effects, 95% CI [−0.624, 0.429], $B = -0.097$, $SE = 0.256$, $\beta = -0.151$, $t(20) = -0.380$, $p = 0.708$, two-tailed. A LRT indicated that the exploratory model

[2] The log-normal distribution provided a better fit for raw LTs (log-likelihood = −376.95) across Exp. 1–3 than did the normal distribution (−416.10), maximum-likelihood fitting. We find inferentially equivalent results on hypothesis-driven tests by comparing the average proportion of time infants looked at the high test action against chance ($\mu = 0.5$), our original outcome measure, and using non-parametric analyses of raw looking times (see Supplemental Material available online). Our decision to present results using the dependent measure in the main text followed the recommendation of Csibra, Hernik, Mascaro, Tatone, and Lengyel (2016).

did not provide a better fit than the hypothesis-driven model, $X^2(3) = 1.863$, $p = 0.601$. No influential cases were detected.

2.3. Discussion

Experiment 1 provides evidence that is consistent with the hypothesis that infants leverage continuous representations rather than narrower assumptions about motion directness when reasoning about goal-directed action. Given a perceptually novel but efficient low jump and a perceptually familiar but inefficient high jump, infants recovered their attention to the inefficient jump, over and above the perceptual familiarity of this action. However, Experiment 1 alone cannot establish whether infants have a baseline looking preference for higher or faster motion, which could explain this finding in part or in whole. Experiment 2 explores this possibility.

3. Experiment 2

In Experiment 2, we followed the logic of past experiments (e.g. Gergely et al., 1995) to test for baseline looking preferences for higher or faster motion. We repeated Experiment 1 except for one critical change: All barriers fell *beyond* the goal object, such that the agent's actions were no longer physically constrained. If infants merely prefer faster or higher motion, then results should resemble those from Experiment 1, because the agent moved in identical ways across the two experiments. In contrast, if infants' responses in Experiment 1 are driven by representations of efficiency, their responses in Experiment 2 should differ, because all the actions in Experiment 2 were unconstrained and inefficient.

3.1. Methods

3.1.1. Participants

Our planned sample consisted of 20 full-term, healthy infants (10 female, $M_{age} = 6.10$ months, range = 5.70–6.67 months). An additional two infants were tested, excluded, and replaced due to online coding error.

3.1.2. Materials, design, and procedure

All aspects of the materials, design and procedure were identical to those from Experiment 1, except for the critical change in the location of the barrier from in between the agent and goal object to just beyond the goal object (Fig. 2).

3.1.3. Coding and analyses

The coding procedure was identical to that from Experiment 1. To test the reliability of the offline-coded data, 100% of the test events were recoded by an additional researcher who was unaware to the order of test trials. The two coders agreed on the trial cutoffs for 95.83% of the test trials, and the intraclass correlation (ICC) between them was 0.993, 95% CI [0.991, 0.995]. Thus, the highly reliable primary offline coding data were used in our analyses.

3.2. Results

3.2.1. Hypothesis-driven results

A hypothesis-driven model, including test action height (high versus low) as a fixed effect and subject identity as a random intercept, revealed that infants did not look longer to the high test event ($M = 11.21$ s, $SD = 6.04$) relative to the low test events ($M = 12.76$ s, $SD = 8.37$), 95% CI [−0.358, 0.235], $B = -0.071$, $SE = 0.149$, $\beta = -0.131$, $t(20) = -0.479$, $p = 0.637$, two-tailed. A paired t-test supported this finding, 95% CI [−0.390, 0.248], $t(19) = -0.466$, $d = 0.104$, achieved power = 0.073, $p = 0.646$, two-tailed. See Fig. 3. This model provided a fit no better than a null model by a LRT, $\chi^2(1) = 0.228$, $p = 0.633$.

An analysis detecting influential cases using Cook's Distance revealed one influential subject (D = 0.260, cutoff = 0.2). Removal of this subject from the hypothesis-driven model produced an inferentially equivalent result, 95% CI [−0.246, 0.280], $B = 0.017$, $SE = 0.128$, $\beta = 0.034$, $t(19) = 0.135$, $p = 0.894$, two-tailed.

3.2.2. Exploratory results

An exploratory model, testing for an fixed interactive effect of test presentation order and test action height, a fixed effect of sex, and subject identity as a random intercept revealed an order effect, 95% CI [0.232, 1.037], $B = 0.608$, $SE = 0.265$, $\beta = 1.122$, $t(20) = -2.297$, $p = 0.033$, two-tailed, and no gender effect, 95% CI [−0.354, 0.067], $B = -0.148$, $SE = 0.187$, $\beta = -0.273$, $t(20) = -0.789$, $p = 0.439$, two-tailed. A LRT indicated that the exploratory model did not provide a significantly better fit than the hypothesis-driven model, $\chi^2(3) = 5.315$, $p = 0.150$. Removal of one influential case (D = 0.382, cutoff = 0.2) produced an inferentially equivalent result, and this subject was removed from the following paired contrasts.

To probe the interactive effect between test order and test trial type, paired contrasts averaged across gender were extracted from the exploratory model and revealed that infants tended to look longer at whichever test event they first saw. Infants assigned to watch the high test event first looked longer at it ($M = 13.16$ s, $SD = 6.96$) than the low test event ($M = 10.39$ s, $SD = 5.16$), 95% CI [−0.120, 0.585], $t(21.24) = 1.371$, $p = 0.185$, two-tailed, and infants assigned to watch the low test event first looked longer at it ($M = 12.84$, $SD = 7.94$) than the high test event ($M = 9.606$, $SD = 4.63$), 95% CI [−0.594, 0.149], $t(21.24) = -1.242$, $p = 0.228$, two-tailed.

3.2.3. Comparing Experiments 1 and 2

To investigate the effect of barrier location (behind the goal object in Experiment 2, in front of it in Experiment 1) on the direction and extent to which infants discriminated between the test events, we fit a linear mixed effects model including an interactive fixed effect of action height (high versus low) and experiment (1 versus 2), plus a random intercept on subject identity. This analysis revealed that infants in Experiment 1 displayed a stronger looking preference than those in Experiment 2, 95% CI [0.017, 0.722,], $B = 0.369$, $SE = 0.176$, $\beta = 0.623$, $t(40) = 2.103$, $p = 0.042$, two-tailed. Removal of one influential case (D = 0.161, cutoff = 0.1) produced an inferentially equivalent result, 95% CI [−0.060, 1.026], $B = 0.281$, $SE = 0.157$, $\beta = 0.483$, $t(39) = 1.790$, $p = 0.081$, two-tailed.

3.3. Discussion

The findings of Experiment 2 are consistent with many previous reports that infants do not expect efficient action from an agent previously observed to move inefficiently (Csibra, 2008; Csibra et al., 1999; Gergely et al., 1995; Skerry et al., 2013; Southgate, Johnson, & Csibra, 2008). Infants who viewed events identical to those from Experiment 1, except for the position of the barrier, did not differentiate between the test events, indicating that infants in the previous experiment did not look longer at the inefficient action merely because it was higher or faster than the efficient one. So far, our findings are consistent with the hypothesis that infants expect agents to minimize the cost of their actions, rather than move smoothly and directly across supporting surfaces towards their goals.

Nevertheless, the interpretation of the above findings, including our own, is not clear. Two alternative construals remain: First, infants may learn over the course of the experiment that the agent will jump just high enough to clear the barrier and generalize this

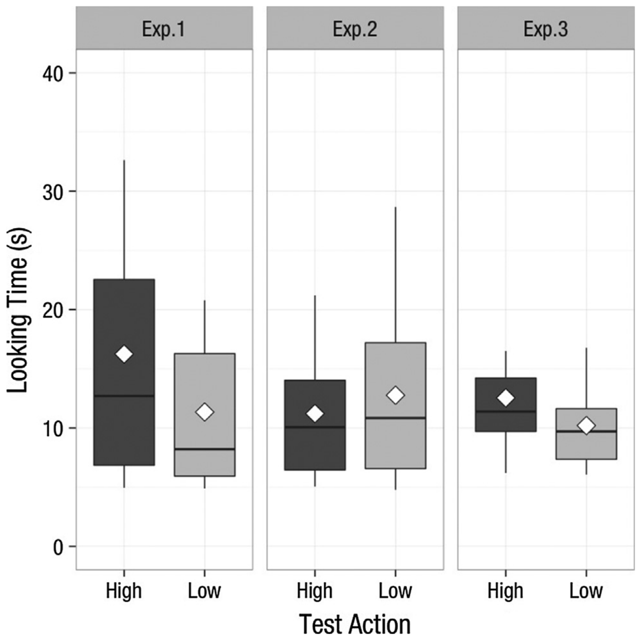

Fig. 3. Boxplots for raw looking times in seconds to test events in Experiments 1–3 ($N = 20$ per experiment). Boxes indicate interquartile ranges, bold horizontal lines indicate medians, and white diamonds indicate means.

relation at test, but fail to learn a similar relation when the barrier is away from the agent's path. Second, infants may not *a priori* expect agents to minimize the cost of their actions: they may expect previously efficient agents to continue acting efficiently, but when shown an agent behaving inefficiently in one context, suspend all predictions about its subsequent actions (Csibra, 2003; Csibra et al., 1999; Gergely et al., 1995; Southgate et al., 2008). In summary, a key remaining question is whether infants have an overhypothesis (Goodman, 1983) that agents minimize the cost of their actions. Experiment 3 was undertaken to address this question.

4. Experiment 3

Experiment 3 investigates whether infants expect minimally costly action given no prior evidence of an agent's rational action or opportunity to learn about the trajectory of the action given the barrier as a point of reference. If infants assume an overhypothesis on observing minimally costly actions, then observing inefficient action may suspend the expectations of efficiency only in the narrow context in which the agent is acting: infants may continue to expect the agent to act efficiently in new situations. To test for this possibility, we paired the habituation events from Experiment 2, in which the agent acts efficiently, with the test events of Experiment 1, in which the agent confronts a new obstacle. If infants expect agents to act efficiently only when they have prior evidence of its efficiency, or if infants are merely adept at learning that an agent will jump just as high as necessary to clear the barrier, then they should hold no expectations here. In contrast, if infants represent the principle of efficiency as an overhypothesis, then they may expect a previously non-goal-directed agent to minimize the cost of its action the very first time it faces a physical obstacle.

4.1. Methods

4.1.1. Participants

Our planned sample included 20 full-term, healthy infants (10 female, $M_{age} = 5.84$ months, range = 5.40–6.13 months). An additional 5 infants were tested, excluded and replaced (2 for fussiness and 2 for online coding error, and 1 for missing a critical portion of the events for all 3 test pairs).

4.1.2. Materials, design, and procedure

All aspects of the materials, design and procedure were identical to those from Experiment 1 and 2 except for the configuration of the habituation and test events. To test whether infants expect an agent to navigate over a low constraint efficiently without ever having seen the agent act in a goal-directed manner, we paired the habituation events from Experiment 2 with the test events from Experiment 1. That is, infants were habituated to an agent that performed unconstrained actions, and then were tested on events in which a constraint was in the agent's way for the very first time. See Fig. 2.

4.1.3. Coding and analyses

The coding procedure was identical to that from Experiments 1 and 2. To assess the reliability of the offline-coded data, 100% of the test events were recoded by an additional researcher who was unaware of test pair order. The two coders agreed on the trial cutoffs for 94.17% of the test trials, and the intraclass correlation (ICC) between them was 0.972, 95% CI [0.960, 0.980]. Thus, the highly reliable primary offline coding data were used in our analyses.

4.2. Results

4.2.1. Hypothesis-driven results

A hypothesis-driven model, including test action height (high versus low) as a fixed effect and subject identity as a random intercept, revealed that infants looked longer to the high test event ($M = 12.54$ s, $SD = 5.01$) relative to the low test event ($M = 10.20$ s, $SD = 3.56$), 95% CI [0.056, 0.325], $B = 0.190$, $SE = 0.066$, $\beta = 0.522$, $t(20) = 2.906$, $p = 0.009$, two-tailed. A paired t-test supported this finding, 95% CI [0.050, 0.331], $t(19) = 2.833$, $d = 0.633$, achieved power = 0.766, $p = 0.011$, two-tailed. This model outperformed a null model by a LRT, $X^2(1) = 7.046$, $p = 0.008$.

An analysis detecting influential cases using Cook's Distance revealed one influential subject (D = 0.256, cutoff = 0.2). Removal of this subject from the hypothesis-driven model produced an inferentially equivalent result, 95% CI [0.034, 0.275], $B = 0.155$, $SE = 0.058$, $\beta = 0.452$, $t(19) = 2.649$, $p = 0.016$, two-tailed.

4.2.2. Exploratory results

An exploratory model testing for order and sex effects included fixed interactive effect of test presentation order and test action height, a fixed effect of sex, and subject identity as a random intercept. This analysis revealed neither an order effect, 95% CI [−0.207, 0.239], $B = 0.061$, $SE = 0.130$, $\beta = 0.167$, $t(20) = 0.468$, $p = 0.645$, two-tailed, nor an effect of sex, 95% CI [−0.169, 0.401], $B = 0.116$, $SE = 0.138$, $\beta = 0.318$, $t(20) = 0.838$, $p = 0.412$, two-tailed. A LRT indicated that the exploratory model did not provide a significantly better fit than the hypothesis-driven model, $\chi^2(3) = 0.910$, $p = 0.823$. Removal of one influential case (D = 0.218, cutoff = 0.2) produced an inferentially equivalent result.

4.2.3. Comparing Experiments 1 and 3

To investigate the effect of the initial behavior of the agent during habituation (efficient in Experiment 1 and inefficient in Experiment 3) on infants' responses to subsequent constrained actions during test, we fit a model including interactive fixed effect between study (Experiment 1 versus 3) and test action height (high versus low) and a random intercept for subject identity. This analysis revealed no consistent difference in looking preference across the 2 experiments, 95% CI [−0.337, 0.121], $B = -0.108$, $SE = 0.114$, $\beta = -0.207$, $t(40) = -0.945$, $p = 0.350$, two-tailed. Removal of two influential cases (D = 0.143 and 0.101, cutoff = 0.1) produced an inferentially equivalent result, 95% CI [−0.328, 0.095], $B = -0.117$, $SE = 0.105$, $\beta = -0.240$, $t(38) = -1.110$, $p = 0.274$, two-tailed. An additional model removing this interaction revealed that infants looked longer to the high test action collapsing across both experiments, 95% CI [0.128, 0.360], $B = 0.244$, $SE = 0.058$, $\beta = 0.468$, $t(40) = 4.234$, $p < 0.001$, two-tailed, but not differently across Experiments 1 and 3 collapsing across trial type, 95% CI [-0.340, 0.256], $B = -0.042$, $SE = 0.148$, $\beta = -0.080$, $t(40) = -0.283$, $p = 0.779$, two-tailed. Removal of influential cases in the second model (D = 0.158 and 0.108, cutoff = 0.1) produced inferentially equivalent results: Infants selectively recovered attention to an inefficient action performed over a novel barrier, 95% CI [0.116, 0.0.345], $B = 0.231$, $SE = 0.057$, $\beta = 0.504$, $t(38) = 4.045$, $p < 0.001$, two-tailed, and did so regardless of whether they previously saw it act efficiently, 95% CI [−0.181, 0.342], $B = 0.081$, $SE = 0.130$, $\beta = 0.176$, $t(38) = 0.618$, $p = 0.540$, two-tailed. See Supplemental Material available online for additional analyses across experiments.

4.3. Discussion

After an action-relevant change in the location of an obstacle, infants expected a previously inefficient agent to minimize cost in Experiment 3, as in Experiment 1. This result contrasts with the findings of previous studies (Csibra, 2008; Csibra et al., 1999; Gergely et al., 1995; Phillips & Wellman, 2005; Skerry et al., 2013) as well as Experiment 2, in which infants saw no change in the physical constraints of the agent between habituation and test. This finding shows that by 6 months of age, infants expect agents to minimize the cost of their actions under conditions where learning about the efficiency of or perceptual regularities found its actions was not possible. Thus, infants appear to assume an overhypothesis on observing minimally costly action given a change in an agent's constraints (Experiment 1) or the first time a constraint is introduced (Experiment 3).

5. General discussion

Three experiments provided evidence that by 6 months of age, infants represent the principle of efficiency as an expectation that agents minimize the cost of their actions. When presented with action trajectories differing in curvature, infants differentiated between these actions on the basis of their efficiency, over and above perceptual differences in height or velocity. This finding indicates that the principle of efficiency is not articulated only by local assumptions about agents and their actions, such as the assumption that agents move in straight lines or directly towards their goals. Its activation also does not depend on prior observation of efficient action: infants even applied this expectation to an agent whose previous actions were all inefficient, indicating that their responses cannot be explained by learning, during the experiment, either that an agent acts efficiently or that the height of its jumps bears a consistent geometric relationship to the height of the barrier that it jumps over. We suggest that this expectation is carried in an overhypothesis (Goodman, 1983) on minimal costs. That is, infants have an inductive bias to expect maximally efficient action from agents situated in new physical contexts, even if they never acted efficiently in past contexts. This assumption may guide their analysis and learning about the social world by biasing their expectations towards observing rational behavior.

Though our experiments only address representations of cost, their results are consistent with the thesis that early action understanding is expressed as a richer system of reasoning about how hidden variables like effort, desire, and belief guide action planning. Nevertheless, it is still an empirical question how richly utility theory articulates early understanding of action. We conclude by describing three future lines of research that bear on this question.

First, although we argue that infants hold an overhypothesis on minimal costs, it is not clear how rich and abstract the variables are that enter into these computations. It is possible, for example, that infants' understanding of cost is restricted to one or a few dimensions of action: In Experiments 1 and 3, infants may have leveraged a minimum function on the length or indirectness of the agent's actions without considering the psychological cost of planning and the physical cost executing them. Further research could reveal whether infants' intuitions about cost are best described in terms of these leaner assumptions, or instead in terms of the physical work required to execute actions and the mental effort required to plan them. If infants have a general, abstract assumption that agents minimize cost, then they might expect agents to choose an action that requires less force or less planning under conditions where features like path length are held equal.

Second, the present research raises questions concerning the inferential role of costs within a broader schema of action understanding. Do infants, like older children, expect agents to plan utility-maximizing actions, considering not only the costs of different actions but also the rewards that these actions bring (Jara-Ettinger et al., 2015)? To our knowledge, no research reveals whether infants reason about costs and rewards by representing a function that subsumes both roles. Future experiments could test, for example, whether infants can infer an agent's desires and beliefs about the world given the degree of effort it expends.

Finally, these results do not reveal how this knowledge is acquired and how it develops over the first six months. How does a cognitive system come to represent functions over abstract costs and identify the range of events to which such functions apply? According to one theoretical stance, concepts like goals are constructed from sensorimotor mappings between observed and experienced actions (Paulus, 2012; Paulus, Hunnius, Vissers, & Bekkering, 2011; Woodward, 2009). According to a second account, these concepts are embedded in an innate, fully productive schema for action understanding that supports representations of the actions we experience and observe in the world (Carey, 2009; Gergely & Csibra, 2003). Recent evidence suggests that sensitivity to the costs of actions does not rely on action experience alone (Skerry et al., 2013), but the precise role of experience in action understanding is not known. A third possibility is that infants begin with a skeletal set of assumptions about agents and their actions, which is then enriched in in the first years of life, in line with their developing knowledge about the physical world (Baillargeon, 2002). Under this account, infants begin with some assumptions about costs and rewards, but face the challenges of learning the specific costs and rewards of actions and states in the world and constructing the form of knowledge that best captures how agents plan behavior. Research documenting the ontogeny and phylogeny of action understanding could distinguish these possibilities.

5.1. Conclusion

Our intuitive psychology is supported by the assumption that agents plan actions so as to maximize desired states of the world (rewards) while minimizing effort (costs). Characterizing the functions, variables, and procedures that articulate these assumptions not only constrains our theories of mature social cognition but also provides a framework under which we investigate its changes over development. Here, we applied this approach to probe the representations that support expectations for efficient action in the first year of life. We discovered that 6-month-old infants use a minimum function over costs to guide their expectation for rational action, and that they apply this expectation even to agents whose previous actions were inefficient. Our case study provides a step toward characterizing the early cognitive substrates on which humans build a rich, abstract, and productive system for action understanding.

Acknowledgements

The authors thank the families who volunteered to participate, A. Aguirre, C. Kerwin, and T. Ladd for research assistance, R. Guzman and N. Kalra for administrative assistance, and to S. Carey, J. Tenenbaum, T. Ullman, and two anonymous reviewers for comments and advice. This material is based upon work supported by the Center for Brains, Minds and Machines (CBMM) funded by National Science Foundation STC award CCF-1231216, and by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1144152.

Appendix A. Supplementary material

All data and materials have been made publicly available via the Open Science Framework, and can be accessed at http://osf.io/sxdtg/ and http://osf.io/4qw45/, respectively. Supplementary data associated with this article can also be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.12.007.

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