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

Shari Liu[a,b,1], Neon B. Brooks[a,b], and Elizabeth S. Spelke[a,b]

[a]Department of Psychology, Harvard University, Cambridge, MA 02138; and [b]The Center for Brains, Minds, and Machines (CBMM), McGovern Institute for Brain Research, Massachusetts Institute of Technology, Cambridge, MA 02139

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/).

[1]To whom correspondence may be addressed. Email: shariliued@gmail.com.

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

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.,

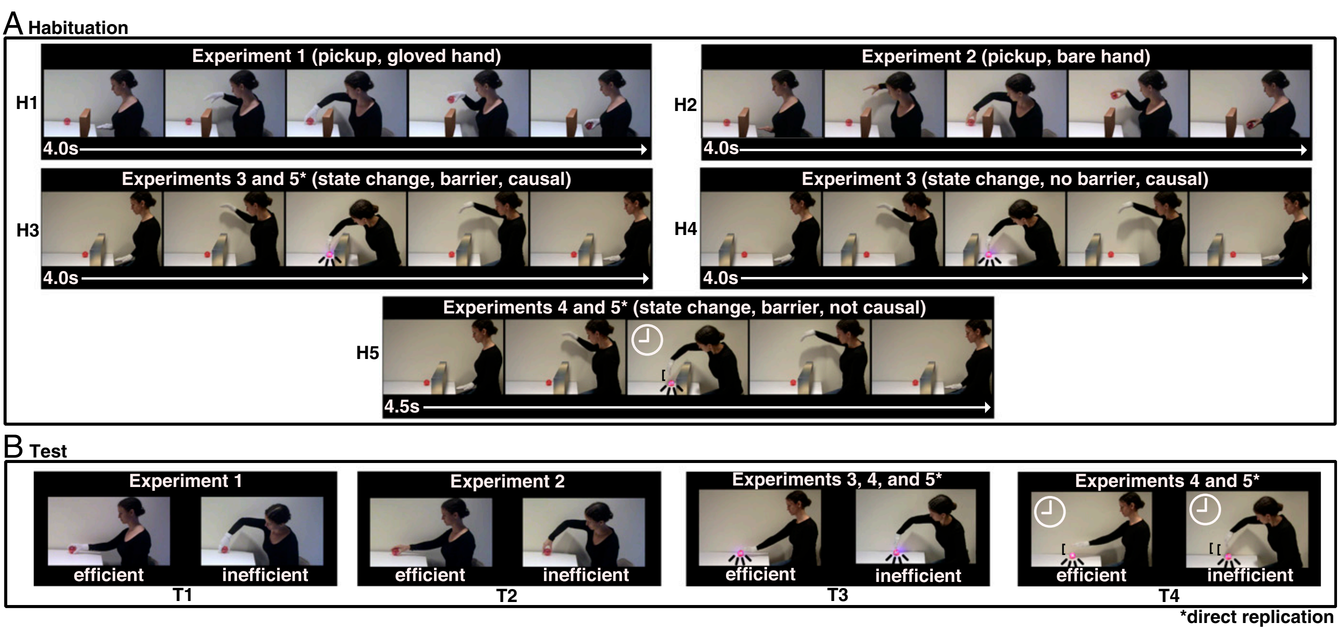

Fig. 1. Still frames from videos shown to participants in Exps. 1 to 5, including stimuli from habituation (*A*) and test (*B*). In each video, a person reached for and picked up the object (H1-H2, T1-H2), or caused it to illuminate (H3-H5, T3-T4), over a barrier (H1-H3, H5) or empty space (H4, T1-T4). 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 ($mean_{ineff}$ = 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 ($mean_{ineff}$ = 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 ($mean_{ineff}$ = 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

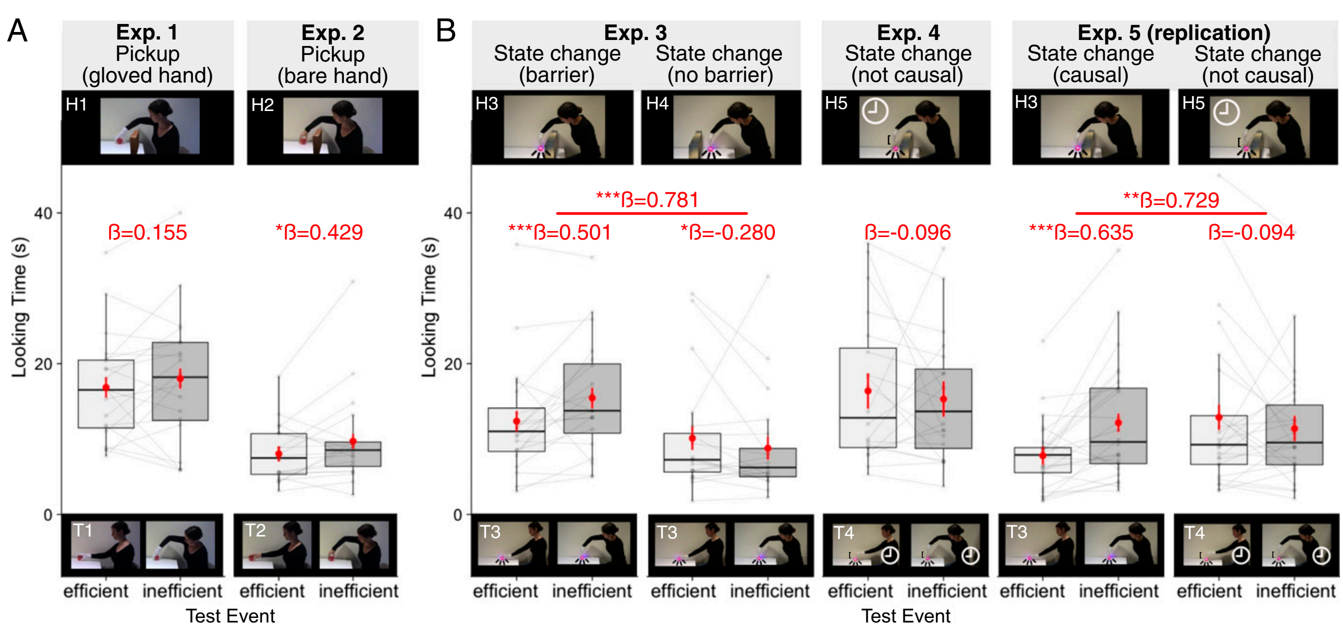

Fig. 2. Looking time in seconds toward the efficient versus inefficient reach at test across Exps. 1 to 5 (n = 152), for both (*A*) pick-up events (Exps. 1 and 2) and (*B*) state-change events (Exps. 3 to 5). Images indicate video displays used during the habituation phase (above each graph) and test 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], $\beta = 0.781$, $B = 0.502$, SE = 0.114, $P < 0.001$, 2-tailed) (Fig. 2*B*). 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], $\beta = 0.501$, $B = 0.322$, 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], $\beta = -0.28$, $B = -0.18$, 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], $\beta = 0.457$, $B = 0.248$, 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], $\beta = -0.096$, $B = -0.055$, SE = 0.119, $P = 0.649$, 2-tailed) (Fig. 2*B*). 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], $\beta = 0.547$, $B = 0.313$, 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], $\beta = 0.729$, $B = 0.5$, SE = 0.158, $P = 0.003$, 2-tailed) (Fig. 2*B*). 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], $\beta = 0.635$, $B = 0.436$, 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], $\beta = -0.094$, $B = -0.064$, 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.

PSYCHOLOGICAL AND COGNITIVE SCIENCES

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.

1. D. C. Dennett, *The Intentional Stance* (The MIT Press, London, 1987).
2. J. Jara-Ettinger, H. Gweon, L. E. Schulz, J. B. Tenenbaum, The naïve utility calculus: Computational principles underlying commonsense psychology. *Trends Cogn. Sci.* **20**, 589–604 (2016).
3. A. Gopnik, H. M. Wellman, Why the child's theory of mind really is a theory. *Mind Lang.* **7**, 145–171 (1992).
4. L. Schulz, The origins of inquiry: Inductive inference and exploration in early childhood. *Trends Cogn. Sci.* **16**, 382–389 (2012).
5. A. Gopnik, L. Schulz, L. E. Schulz, *Causal Learning: Psychology, Philosophy, and Computation* (Oxford University Press, New York, 2007).
6. J. Woodward, *Making Things Happen: A Theory of Causal Explanation* (Oxford University Press, New York, 2005).
7. C. von Hofsten, "Mastering reaching and grasping: The development of manual skills in infancy" in *Advances in Psychology*, S. A. Wallace, Ed. (North-Holland, 1989), pp. 223–258.
8. C. F. Palmer, The discriminating nature of infants' exploratory actions. *Dev. Psychol.* **25**, 885–893 (1989).
9. H. A. Ruff, Infants' manipulative exploration of objects: Effects of age and object characteristics. *Dev. Psychol.* **20**, 9–20 (1984).
10. P. Muentener, S. Carey, Infants' causal representations of state change events. *Cognit. Psychol.* **61**, 63–86 (2010).
11. A. M. Leslie, Infant perception of a manual pick-up event. *Br. J. Dev. Psychol.* **2**, 19–32 (1984).
12. S. Pauen, B. Träuble, How 7-month-olds interpret ambiguous motion events: Category-based reasoning in infancy. *Cognit. Psychol.* **59**, 275–295 (2009).
13. R. Saxe, J. B. Tenenbaum, S. Carey, Secret agents: Inferences about hidden causes by 10- and 12-month-old infants. *Psychol. Sci.* **16**, 995–1001 (2005).
14. S. Liu, E. S. Spelke, Six-month-old infants expect agents to minimize the cost of their actions. *Cognition* **160**, 35–42 (2017).
15. G. Gergely, G. Csibra, Teleological reasoning in infancy: The naive theory of rational action. *Trends Cogn. Sci.* **7**, 287–292 (2003).
16. A. L. Woodward, Infants selectively encode the goal object of an actor's reach. *Cognition* **69**, 1–34 (1998).
17. J. Piaget, M. Cook, *The Origins of Intelligence in Children* (International Universities Press, New York, 1952).
18. J. Loucks, J. A. Sommerville, The role of motor experience in understanding action function: The case of the precision grasp. *Child Dev.* **83**, 801–809 (2012).
19. S. A. Gerson, N. Mahajan, J. A. Sommerville, L. Matz, A. L. Woodward, Shifting goals: Effects of active and observational experience on infants' understanding of higher order goals. *Front. Psychol.* **6**, 310 (2015).
20. C. Press, C. Heyes, J. M. Kilner, Learning to understand others' actions. *Biol. Lett.* **7**, 457–460 (2011).
21. V. Gallese, A. Goldman, Mirror neurons and the simulation theory of mind-reading. *Trends Cogn. Sci.* **2**, 493–501 (1998).
22. C. Heyes, Where do mirror neurons come from? *Neurosci. Biobehav. Rev.* **34**, 575–583 (2010).
23. C. Keysers, D. I. Perrett, Demystifying social cognition: A Hebbian perspective. *Trends Cogn. Sci.* **8**, 501–507 (2004).
24. A. N. Meltzoff, P. K. Kuhl, J. Movellan, T. J. Sejnowski, Foundations for a new science of learning. *Science* **325**, 284–288 (2009).
25. G. Rizzolatti, L. Fogassi, V. Gallese, Neurophysiological mechanisms underlying the understanding and imitation of action. *Nat. Rev. Neurosci.* **2**, 661–670 (2001).
26. J. A. Sommerville, A. L. Woodward, A. Needham, Action experience alters 3-month-old infants' perception of others' actions. *Cognition* **96**, B1–B11 (2005).
27. A. E. Skerry, S. E. Carey, E. S. Spelke, First-person action experience reveals sensitivity to action efficiency in prereaching infants. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 18728–18733 (2013).
28. J. A. Sommerville, A. L. Woodward, Pulling out the intentional structure of action: The relation between action processing and action production in infancy. *Cognition* **95**, 1–30 (2005).
29. M. Bakker, J. A. Sommerville, G. Gredebäck, Enhanced neural processing of goal-directed actions after active training in 4-month-old infants. *J. Cogn. Neurosci.* **28**, 472–482 (2016).
30. S. A. Gerson, A. L. Woodward, Learning from their own actions: The unique effect of producing actions on infants' action understanding. *Child Dev.* **85**, 264–277 (2014).
31. S. A. Gerson, A. L. Woodward, The joint role of trained, untrained, and observed actions at the origins of goal recognition. *Infant Behav. Dev.* **37**, 94–104 (2014).
32. C. von Hofsten, Predictive reaching for moving objects by human infants. *J. Exp. Child Psychol.* **30**, 369–382 (1980).
33. A. Woodward, "Infants' learning about intentional action" in *Learning and the Infant Mind*, A. Woodward, A. Needham, Eds. (Oxford University Press, New York, 2008).
34. M. R. Cutkosky, On grasp choice, grasp models, and the design of hands for manufacturing tasks. *IEEE Trans. Robot. Autom.* **5**, 269–279 (1989).
35. A. Michotte, *The Perception of Causality* (Routledge, 1963).
36. A. M. Leslie, The perception of causality in infants. *Perception* **11**, 173–186 (1982).
37. R. Saxe, S. Carey, The perception of causality in infancy. *Acta Psychol. (Amst.)* **123**, 144–165 (2006).
38. G. Gergely, Z. Nádasdy, G. Csibra, S. Bíró, Taking the intentional stance at 12 months of age. *Cognition* **56**, 165–193 (1995).
39. E. Mascalzoni, L. Regolin, G. Vallortigara, F. Simion, The cradle of causal reasoning: Newborns' preference for physical causality. *Dev. Sci.* **16**, 327–335 (2013).
40. L. B. Cohen, G. Amsel, Precursors to infants' perception of the causality of a simple event. *Infant Behav. Dev.* **21**, 713–731 (1998).
41. S. Desrochers, Infants' processing of causal and noncausal events at 3.5 months of age. *J. Genet. Psychol.* **160**, 294–302 (1999).
42. D. Bates, M. Mächler, B. Bolker, S. Walker, Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **67**, 10.18637/jss.v067.i01. (2015).
43. B. J. Scholl, P. D. Tremoulet, Perceptual causality and animacy. *Trends Cognit. Sci.* **4**, 299–309 (2000).
44. S. Carey, *The Origin of Concepts* (Oxford University Press, 2009).
45. D. Hassabis, D. Kumaran, C. Summerfield, M. Botvinick, Neuroscience-inspired artificial intelligence. *Neuron* **95**, 245–258 (2017).
46. B. M. Lake, T. D. Ullman, J. B. Tenenbaum, S. J. Gershman, Building machines that learn and think like people. *Behav. Brain Sci.* **40**, e253 (2017).
47. Y. LeCun, Y. Bengio, G. Hinton, Deep learning. *Nature* **521**, 436–444 (2015).
48. A. M. Turing, Computing machinery and intelligence. *Mind* **59**, 433–460 (1950).
49. S. Ullman, Using neuroscience to develop artificial intelligence. *Science* **363**, 692–693 (2019).
50. Y.-J. Choi, Y. Mou, Y. Luo, How do 3-month-old infants attribute preferences to a human agent? *J. Exp. Child Psychol.* **172**, 96–106 (2018).
51. Y. Luo, Three-month-old infants attribute goals to a non-human agent. *Dev. Sci.* **14**, 453–460 (2011).
52. S. Liu, T. D. Ullman, J. B. Tenenbaum, E. S. Spelke, Ten-month-old infants infer the value of goals from the costs of actions. *Science* **358**, 1038–1041 (2017).
53. L. Lakusta, P. Muentener, L. Petrillo, N. Mullanaphy, L. Muniz, Does making something move matter? Representations of goals and sources in motion events with causal sources. *Cogn. Sci.* **41**, 814–826 (2017).
54. P. Muentener, L. Schulz, What doesn't go without saying: Communication, induction, and exploration. *Lang. Learn. Dev.* **8**, 61–85 (2012).
55. P. Menzies, H. Price, Causation as a secondary quality. *Br. J. Philos. Sci.* **44**, 187–203 (1993).
56. J. Pearl, *Causality: Models, Reasoning, and Inference* (Cambridge University Press, 2000).
57. J. Piaget, The child's conception of physical causality. *Am. J. Psychol.* **44**, 612 (1932).
58. H. von Helmholtz, *Treatise on Physiological Optics* (Dover Publications, 1867), vol. III.
59. S. Ullman, D. Harari, N. Dorfman, From simple innate biases to complex visual concepts. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 18215–18220 (2012).
60. E. Mascalzoni, L. Regolin, G. Vallortigara, Innate sensitivity for self-propelled causal agency in newly hatched chicks. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 4483–4485 (2010).
61. G. Csibra, M. Hernik, O. Mascaro, D. Tatone, M. Lengyel, Statistical treatment of looking-time data. *Dev. Psychol.* **52**, 521–536 (2016).
62. R Core Team, R: A language and environment for statistical computing, Version 3.4.1. https://www.R-project.org/. Accessed 30 June 2017.
63. R. Nieuwenhuis, M. te Grotenhuis, B. Pelzer, Influence.ME: Tools for detecting influential data in mixed effects models. *R J.* **4**, 38–47 (2012).
64. H. Wickham, ggplot2: Elegant graphics for data analysis (Springer, New York, 2016), Version 3.1.1.
65. J. J. Allaire *et al*., rmarkdown: Dynamic documents for R. R package, Version 1.12. https://rmarkdown.rstudio.com. Accessed 14 March 2019.