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

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Abstract: 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.

Significance statement: 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.

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As human adults, we view ourselves and others as *causal agents*, who choose to 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, on 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 4-5 months) (7) and manipulate them (at about 6-8 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 a character takes a long, circuitous route to a goal when a shorter route was available (14, 15), and they interpret actions as directed towards 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 multi-step 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 three-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 towards those goal objects, whereas untrained infant do not (26, 30). Nevertheless, two 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 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 again takes this circuitous route to the object, 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 pre-existing 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 three-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 Figure 1? In light of these challenges, sticky mittens experience 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 three-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 five experiments, we present 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 measure 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 on 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 current 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 1-2: Reaching and grasping actions

Experiment 1

We began by replicating the finding that 3-month-old infants, who have received no sticky mittens 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 Experiment 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 (Figure 1). Three-month-old infants (*N*=20; Mean age=108 days; range=92-122, 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 (Figure 1A, 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. 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 (Figure 1B, T1). On alternating test trials, she reached on the same curvilinear path towards 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 towards 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 two test events in Experiment 1. Consistent with this prediction, infants looked equally to the inefficient and the efficient reach of the gloved hand (M_{ineff}=18.029s, M_{eff}=16.844s, 95% confidence interval (CI) [-0.089,0.238], standardized beta coefficient (β)=0.155, unstandardized B coefficient (B)=0.074, standard error (SE)=0.079, p=0.359, two-tailed, replicating past findings (27). See Figure 2A. 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, two-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 Experiment 2, infants (N=20; M=108 days; range=93-120; 12 female) were presented with the same actions from Experiment 1, except that the person performing the actions wore no gloves, further clarifying the contact relation between her hand and the object (Figure 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 (M_{ineff}=9.715s, M_{eff}=8.036s, [0.008,0.331], β=0.429, B=0.170, SE=0.078, p=0.043, two-tailed). Performance in Experiment 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, two-tailed). However, performance in Experiments 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, two-tailed). Collapsing across both Experiments 1 and 2, infants looked marginally longer at the inefficient than the efficient action (M_{ineff}=13.872s, M_{eff}=12.440s, [-0.004,0.227], β=0.185, B=0.112, SE=0.058, p=0.060, two-tailed) (Figure 2A).

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 Experiment 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 three 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 (Experiment 1), to a fully visible hand (Experiment 2) ([0.007,0.053], ß=0.416, *B*=0.03, *SE*=0.011, *p*=0.011, two-tailed). The 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? Although 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 pickup 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 3-5: Reaching actions that cause state changes on contact

In Experiments 3-5, 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 Experiment 3 we tested infants' responses to displays similar to those of Experiment 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 (Figure 1, H3-H4, T3). Because this event has not been used in previous research, infants were randomly assigned to one of two habituation conditions (*N*=40; 20 per condition; Mean age=108 days; range=91-122, 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 Experiments 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 two 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 Experiments 1-2, both of which activated the object (T3). These two conditions allow us to test whether infants differentiate efficient from inefficient reaches at test only when prior curved reaches were efficient.

In Experiment 3, infants responded differently to the test events across the two habituation conditions ([0.273,0.732], β=0.781, *B*=0.502, *SE*=0.114, *p*<.001, two-tailed) (Figure 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 (M_{ineff}=15.448s, M_{eff}=12.368s, [0.159, 0.486], β=0.501, *B*=0.322, *SE*=0.081, *p*<.001, two-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 (M_{ineff}=8.788s, M_{eff}=10.104s, [-0.343,-0.017], β=-0.28, B=-0.18, SE=0.081, p=0.032, two-tailed). Infants' preference for the inefficient action was stronger in this experiment than in Experiment 1, which presented the same reaching trajectories ending in object pickup ([0.029,0.467], β=0.457, B=0.248, SE=0.112, p=0.032). Experiment 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 Experiment 4, pre-registered 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 Experiment 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 days; range=93-121; 12 female) saw videos identical to those from the *experimental* condition of Experiment 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 seconds after the hand came to rest in midair (H5, T4). In contrast to Experiment 3, infants looked equally at test trials showing the inefficient and efficient actions (M_{ineff}=15.306s, M_{eff}=16.38s, [-0.301,0.191], β=-0.096, B=-0.055, SE=0.119, p=0.649, two-tailed) (Figure 2B). Across Experiment 4 (H5, T4) and the *experimental* condition of Experiment 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, two-tailed). Therefore, Experiment 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 pre-registered direct replication of Experiments 3 and 4. In Experiment 5, pre-registered 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 days; range=92-121; 21 female). This design allowed us to compare infants' responses to causal (H3, T3) versus non-causal (H5, T4) actions, under testing conditions where all researchers were blind to condition as well as test events. We fully replicated the findings from Experiments 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, two-tailed) (Figure 2B). As in Experiment 3, infants looked longer at the inefficient than the efficient reach when the person appeared to cause a change in the object (M_{ineff}=12.166s, M_{eff}=7.791s, [0.211,0.66], β=0.635, B=0.436, SE=0.112 p<.001, one-tailed); as in Experiment 4, infants looked equally to the inefficient and efficient reaches when she did not appear to cause this outcome (M_{ineff}=11.395s, M_{eff}=12.888s, [-0.289,0.160], β=-0.094, B=-0.064, SE=0.112, p=0.567, two-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 Experiments 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 meta-analysis over these 5 experiments and 5 previous experiments using similar methods at the same age (27) and comparing 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 action *costs* and *goals.* 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 reach on a straight path in the absence of obstacles but to reach 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 pickup actions as intentional unless they see bare hands (Experiment 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 3-

month-old infants' understanding of action cost.[1]

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 one 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 non-agentic, 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 is rooted in 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 three post-natal months. Alternatively, these basic abilities may emerge over the course of fetal development and guide post-natal 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 show preferences for 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.

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

Materials and Methods

Participants. *N*=152 healthy, full-term infants (Mean age=107 days, range=91-122, 78 female) were included in our final sample across Experiments 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 Lab for Developmental Studies, and all study protocols were approved by the Committee on the Use of Human Subjects at Harvard University. See SI Appendix for inclusion information.

Materials and procedure. Infants were tested in a dimly lit room, and seated in a car seat such that their faces were approximately 1m away from a 70x40m LCD screen. Prior to habituation, infants saw a 3s video of an actress saying “Hi, baby!” in an infant-directed fashion. During habituation videos for all experiments, except for H4 in Experiment 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 non-causal videos for Experiments 4 and 5 (H5, T4), we manipulated the videos from the constrained condition of Experiment 3 (H3, T3) in Final Cut Pro to introduce a 50-pixel gap between the person’s hand and the object, and a 0.5s delay between the final position of the hand and the object’s illumination. Prior to 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.

Analysis Strategy. Infant looking times are often log-normally distributed (61), including in this dataset (see SI Appendix, Figure 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 both including these influential participants, information about data reliability, and analyses of attention during habituation. Figures 2, S1, and S3-5 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 pre-registrations of this paper are open access at https://osf.io/rcsns/. Our lab began pre-registering experiments on the Open Science Framework in the middle of this research; thus Experiments 1 through 3 were not formally pre-registered. The design, methods, and sample size of Experiment 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 pre-registered for Experiments 4 and 5.

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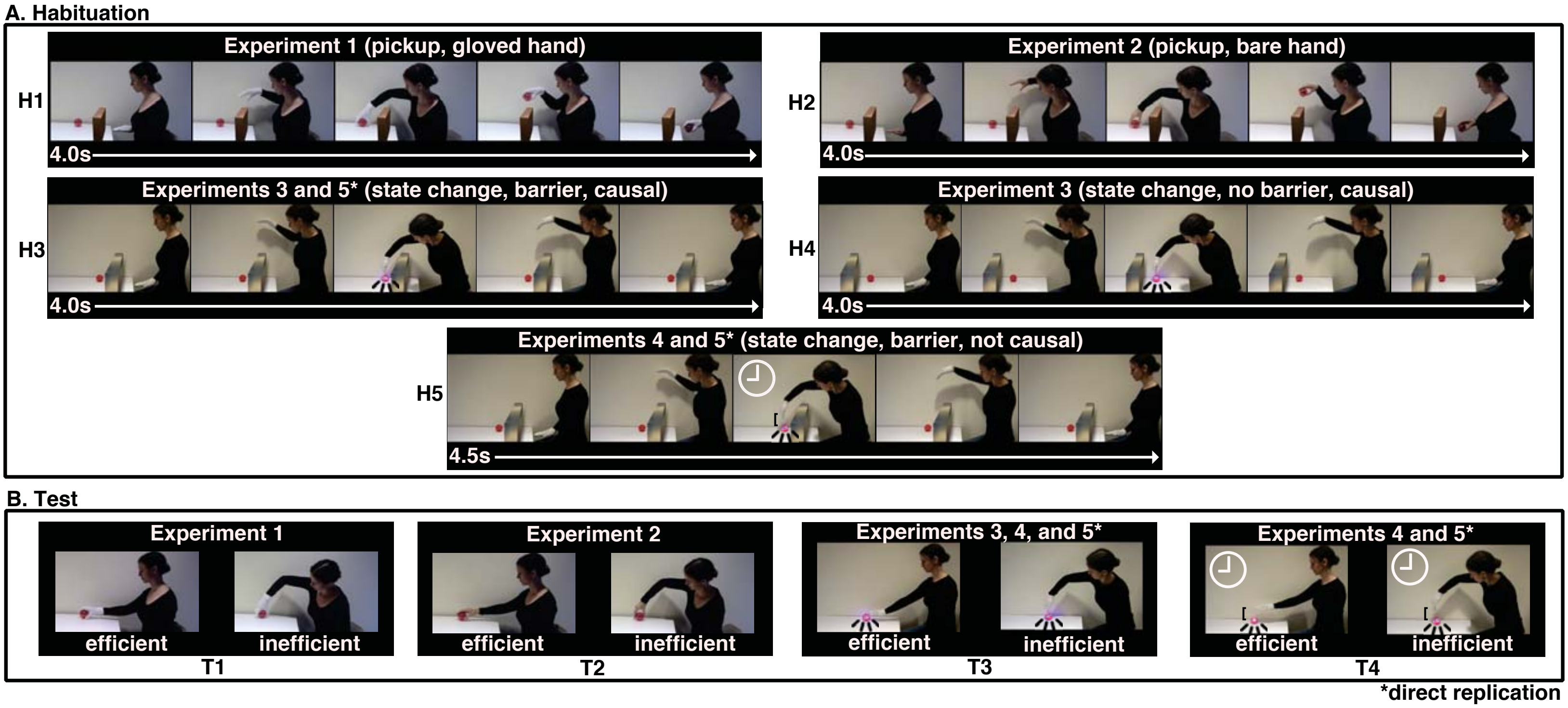
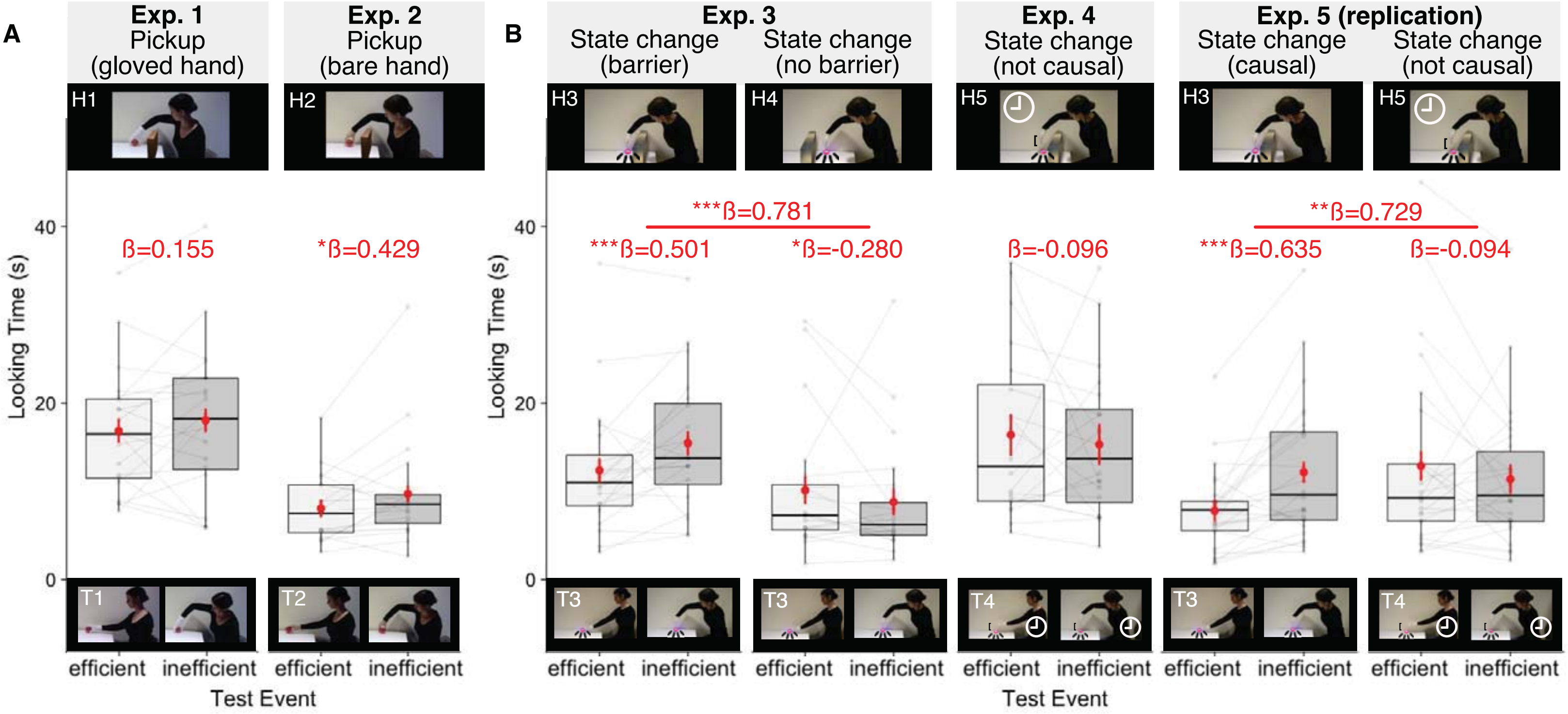
Figure Legends

Figure 1. Still frames from videos shown to participants in Experiments 1-5, 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 0.5s 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 test (B), the person either reached directly for the object on a novel but efficient trajectory (left panels), or in a curvilinear fashion on the familiar but inefficient trajectory (right panels). Clocks indicate temporal delays, black line segments indicate spatial gaps, and black line segments around the object indicate frames in which it illuminated. *indicates direct replication (Experiment 5).

Figure 2. Looking time in seconds towards the efficient versus inefficient reach at test across Experiments 1-5 (N=152), for both (A) pickup events (Experiments 1-2) and (B) state change events (Experiments 3-5). Images indicate video displays used during the habituation phase (above each graph) and test phase (below each graph) for each experiment (See Figure 1). Red dots and error bars indicate means and within-subjects 95% confidence intervals. 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 (ß) list effect sizes in standard deviation units for each condition. * < .05, **<.01, ***<.001, two-tailed, except for the causal condition in Experiment 5, which was pre-registered as a one-tailed test.


A. Habituation
Experiment 1 (pickup, gloved hand)
H1
4.0s
Experiment 2 (pickup, bare hand)
H2
4.0s
Experiments 3 and 5* (state change, barrier, causal)
H3
4.0s
Experiment 3 (state change, no barrier, causal)
H4
4.0s
Experiments 4 and 5* (state change, barrier, not causal)
H5
4.5s
B. Test
Experiment 1
efficient
inefficient
T1
Experiment 2
efficient
inefficient
T2
Experiments 3, 4, and 5*
efficient
inefficient
T3
Experiments 4 and 5*
efficient
inefficient
T4
*direct replication


A
Exp. 1
Pickup
(gloved hand)
Exp. 2
Pickup
(bare hand)
B
Exp. 3
State change
(barrier)
State change
(no barrier)
Exp. 4
State change
(not causal)
Exp. 5 (replication)
State change
(causal)
State change
(not causal)
H1
H2
H3
H4
H5
H3
H5
ß=0.155
*ß=0.429
***ß=0.781
***ß=0.501
*ß=-0.280
ß=-0.096
**ß=0.729
***ß=0.635
ß=-0.094
Looking Time (s)
0
20
40
T1
T2
T3
T3
T4
T3
T4
efficient
inefficient
efficient
inefficient
efficient
inefficient
efficient
inefficient
efficient
inefficient
efficient
inefficient
efficient
inefficient
Test Event
Test Event

Supplementary Information for

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

Shari Liu, Neon B. Brooks, & Elizabeth S. Spelke

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Procedures

Supplementary Results

Figs. S1 to S5

Tables S1 to S3

References

Procedures

Materials and Methods

Participants. *N*=152 healthy, full-term infants (Mean age=107 days, range=91-122, 78 female) were included in our final sample. An additional 50 infants participated but were excluded from our final sample due to fussiness (28 infants), inattentiveness (5 infants), caregiver interference (1 infant), experimenter or coding error (19 infants), or technical issues (5 infants). These exclusionary criteria were set prior to the start of data collection for all experiments and were pre-registered for Experiments 4 and 5. For exclusion information broken down by experiment, see Table S2.

Experimental Procedure. Caregivers were instructed to look away from the screen and not direct their infants' attention in any way for the entirety of the study. All videos were presented using Keynote. Prior to every trial, the experimenter played an attention-getting animation until infants looked towards the screen. Then, infants watched a ~4s video of an action, which paused on the last frame. All trials began on the first frame of the video, and ended when infants either looked for 45 cumulative seconds towards the screen or looked for 2 consecutive seconds away from the screen. Infants saw between 6 and 12 habituation videos followed by 3 pairs of efficient and inefficient test videos, order counterbalanced across participants. The experiment moved from habituation to test when infants' summed looking times towards the most recent 3 habituation trials fell to below half of their summed looking times towards the first 3 habituation trials, or after 12 habituation trials, whichever came first.

Data Coding and Reliability. Looking times were measured online using XHAB (1), and then coded offline in jhab (2) or Datavyu (3) with the same thresholds as online coding to check for coding errors and inattention, and these offline values entered the final analysis. To assess the reliability of our data, 50% of test trials from participants across Experiments 1-5 (76 participants, 456 trials) were randomly selected and coded by additional researchers who were unaware of experimental condition and test trial order. The intraclass correlation coefficient (ICC) between the original data, and this newly coded data, was 0.969 (95% CI [0.946, 0.982]), 0.969 (95% CI [0.943, 0.982]), 0.968 (95% CI [0.955, 0.978]), 0.963 (95% CI [0.938, 0.977]), and (95% CI 0.936 [0.911, 0.954]), for Experiments 1 through 5, respectively.

Supplementary Results

Comparing results including and excluding influential participants.

Across all of our experiments, we checked for influential participants in every model using Cook's Distance (4), as stated in the main text. This is a method for outlier detection: The purpose of this step in our analysis is to identify individuals whose inclusion in the analysis may have undue influence by either masking the effect, which is otherwise present across the rest of the sample, or by driving the effect, which is otherwise absent across the rest of the sample. Below are the results from the main text detailing how many influential participants were detected in each analysis, and report the results including these participants. Overall, none of the main conclusions reported in the main text differ depending on the inclusion or exclusion of these participants (though see below for minor differences in the findings from Experiment 2, the analysis collapsing across Experiment 1 and Skerry et al. (5), and the analysis collapsing across Experiments 1 and 2, none of which change the conclusions reported in the main text).

In the primary analysis for Experiment 1, we detected one influential participant. Including this participant in the analysis generates the same finding as reported in the main text: Infants looked equally at the efficient vs inefficient reach of a gloved hand ([-0.169,0.209], β=0.041, B=0.02, SE=0.092, p=0.831, two-tailed). In the analysis comparing Experiment 1 to Skerry et al. (5) Experiment 3, we detected 2 influential participants. Including them results in a null difference between these two experiments ([-0.086,0.415], β=0.07, B=0.165, SE=0.128, p=0.205, two-tailed), whereas excluding them results in a marginal difference across these two experiments (see main text). This difference does not change our interpretation of Experiment 1: Infants look equally to efficient and inefficient pickup actions when the person reaching wears a glove or a mitten.

In the primary analysis for Experiment 2, we detected 2 influential participants. Including them in the sample generates a marginal effect in the same direction as that reported in the main text: Infants looked longer at the inefficient than the efficient reach of a bare hand [-0.024,0.318], β=0.297, B=0.147, SE=0.083, p=0.091, two-tailed). In the analysis comparing Experiment 2 to Skerry et al. (5) Experiment 3, we detected 1 influential participant. Including them results in the same finding as reported in the main text: Infants' looking preferences significantly differed across these two experiments ([0.048,0.536], β=0.495, B=0.292, SE=0.121, p=0.021, two-tailed). These findings do not change our conclusion in the main text: Experiments 1 and 2 overall show that infants have inconsistent, fragile expectations about the efficiency of reaches that result in displacing objects.

In the analysis collapsing across Experiments 1 and 2, we found 1 influential participant. Inclusion of that participant generates a null effect ([-0.042,0.209], β=0.139, B=0.083, SE=0.063, p=0.191, two-tailed), whereas in the main text this effect was marginal, but our conclusion is the same: Infants look equally to efficient and inefficient reaches when these actions result in objects being displaced. In the analysis comparing infants' looking preferences across Experiments 1 and 2, we found 3 influential participants, and including them results in the same result as reported in the main text: Infants' looking preferences did not differ across the two experiments, ([-0.116,0.37], β=0.211, B=0.127, SE=0.124, p=0.311, two-tailed).

In the primary analysis for Experiment 3, we detected 2 influential participants. Including them in the sample generates the same finding as reported in the main text: Infants' looking preferences for the test events differed as a function of whether they were habituated to constrained action over a barrier (experimental group) or the same actions not over a barrier (control group) ([0.115,0.657], *ß*=0.596, *B*=0.502, *SE*=0.114, *p*<.001, two-tailed). In the experimental condition, infants looked longer at the inefficient action ([0.065,0.451], *ß*=0.398, *B*=0.258, *SE*=0.095, *p*=0.01, two-tailed). In the control condition, infants looked equally at the two test actions ([-0.321,0.065], *ß*=-0.198, *B*=-0.128, *SE*=0.095, *p*=0.186, two-tailed).

We did not detect any influential participants in the analyses for Experiments 4 and 5.

Comparing infants’ responses to mittens, gloves, and bare hands

Because Experiments 1 and 2 used the methods of Skerry et al. (5) (SCS), the primary difference between the events from Skerry et al. (5), and Experiments 1 and 2 from the main text concerned the presentation of the reaching hand, which was bare in Experiment 2, covered by tight-fitting gloves in Experiment 1, and covered by thick mittens in SCS, as in all the prior published research involving mittens training. Could infants' responses to the reaches from these experiments be explained, in part, by how easy it was to see the configuration of the hand (easy in Experiment 2, slightly harder in Experiment 1, and even harder in SCS)? To explore this question, we analyzed infants' proportion looking to the indirect, inefficient action in Experiment 1, Experiment 2, and the comparable experiment from SCS where infants had no mittens training (SCS Experiment 3), and asked whether the clarity of the person's hand in each of these experiments (2 in Experiment 2, 1 in Experiment 1, and 0 in SCS Experiment 3) predicted differences in looking preferences, controlling for correlated data within experiments. This analysis revealed that the magnitude of infants' looking preference for the inefficient over the efficient action increased with increasingly clear information about the form of the hand ([0.007,0.053], *ß*=0.416, *B*=0.03, *SE*=0.011, *p*=0.011, two-tailed, excluding 4 influential participants). This finding held regardless of whether the influential participants were excluded or included (in the latter case, [0.005,0.053], *ß*=0.359, *B*=0.029, *SE*=0.012, *p*=0.02, two-tailed).

Meta-analysis

To assess the effects of our experimental manipulations in Experiments 1-5 and in Skerry et al. (5), we performed an analysis over these two papers (total N=264, 12 conditions). Our analytic approach allows us to assess the independent effects of 5 manipulations: the type of or absence of motor training, the presence or absence of a barrier preventing a direct reach for the object during habituation, the nature of the goal (to change the state of an object or pick it up), the presence or absence of action on contact, and the presence or absence of mittens on the actor. The analysis also allows us to control for the participant variables of age and sex, and model the nested structure of the data (e.g. looks clustered within experiments and within papers). For ease of interpretation, we used average proportion looking to the inefficient action in this analysis, following Skerry et al (5)[1]. The findings below exclude 16 participants on the basis of Cook’s

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[1] Although this analysis condenses all the manipulations from these 10 experiments while taking into account data correlated within experiments and papers, only future experiments will give conclusive evidence for the independent contribution of each manipulation. For example, because no experiment in this analysis includes mittens training and state change events (only mittens training with pick up events or no mittens training with state change events), it is unclear whether the effects of these two manipulations are additive or redundant.

Distance, leaving 248 infants in the final sample. See Table S1 for results including all participants.

This analysis confirmed the findings from the individual experiments reported in the main text and in Skerry et al (5): Infants' looking preference for the inefficient action was stronger when the observed action was spatiotemporally continuous with its effect (i.e., appeared to be causal) ([0.025,0.058], β=0.467, B=0.041, SE=0.009, p<.001, two-tailed when infants received effective motor training (sticky mittens), relative to no training ([0.029,0.074], β=0.583, B=0.052, SE=0.011, p<.001, two-tailed); when the observed agent's actions were constrained by a barrier and were efficiently adapted to that barrier, relative to the same actions that were unconstrained by a barrier ([0.021,0.051], β=0.406, B=0.036, SE=0.008, p<.001, two-tailed); and when the agent pursued a state change goal, relative to a pickup goal ([0.011,0.042], β=0.302, B=0.027, SE=0.008, p=0.001, two-tailed). We also found that infants' looking preference for the inefficient reach was *smaller* when they received ineffective motor training (non-sticky mittens), relative to no training, ([-0.058,0], β=-0.33, B=-0.029, SE=0.015, p=0.051, two-tailed), and improved as the form of the hand became clearer ([0.003,0.056], β=0.333, B=0.03, SE=0.013, p=0.027, two-tailed), but neither of the latter two findings was present in the full analysis with all participants (see Table S1). These findings provide further evidence that action experience alters action interpretation, but so does causal information.

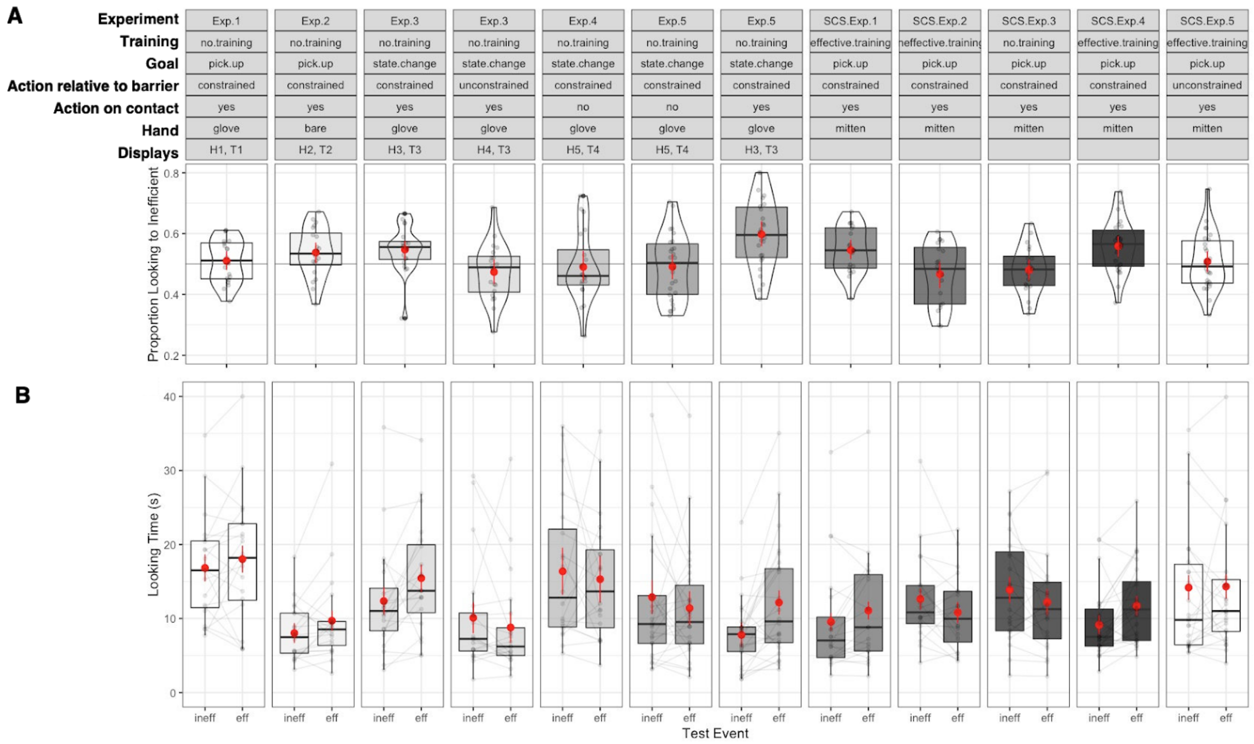

Figure S1. (A) Proportion looking towards the inefficient reach and (B) looking time in seconds towards the efficient versus inefficient reach, and at test across Experiments 1-5 (n=152) and across Experiments 1-5 in Skerry et al. (5) (SCS) (n=112). Labels above each panel list the experiment name (Exp. 1-5, SCS Exp. 1-5), type of motor training (none, ineffective non-sticky mittens, or effective sticky mittens), whether actions during habituation were constrained or unconstrained by a barrier, goal (state.change or pick.up), whether actions resulted in contact with the object, whether the actor reached with a bare, gloved, or mittened hand, and video displays listed in Figure 1. Error bars around means indicate within-subjects 95% confidence intervals (B) and bootstrapped 95% confidence intervals (A). Individual points (A) or pairs of connected points (B) indicate data from a single participant. Horizontal bars within boxes indicate medians, and boxes indicate the middle 2 quartiles of data. Violin plots (A) indicate distribution of data, area scaled proportionally to the number of observations. All data and analyses are open source and available at https://osf.io/rcsns/.

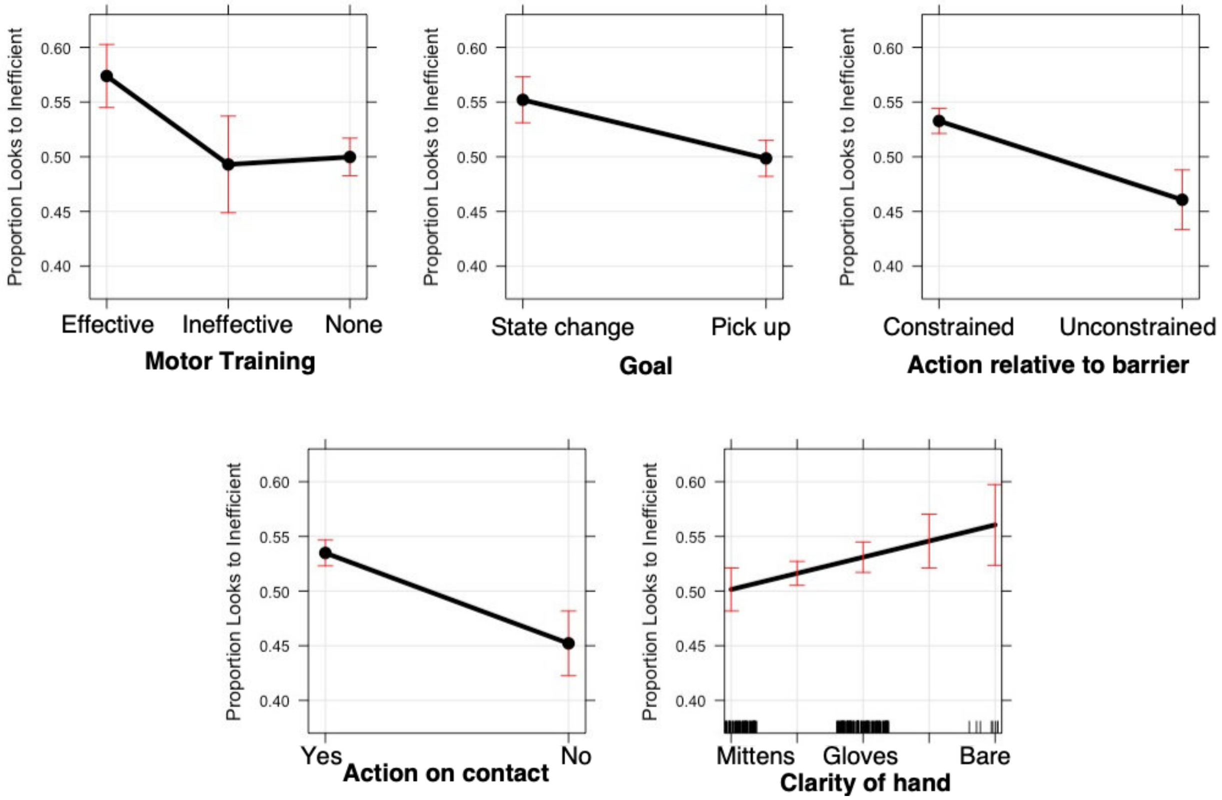

Figure S2. Effect plots for model investigating predictors of infants' looking preference for the inefficient versus efficient reach across Experiments 1-5 and Skerry et al. (5) (total N=264, 248 included in the final analysis, 16 excluded on the basis of Cook's Distance). Each point shows estimates of effects at each level of all predictors: Type of motor training (none, ineffective non-sticky mittens, or effective sticky mittens), the goal of the actor (state change vs pick up), action during habituation (constrained or unconstrained by a barrier), whether actions resulted in contact with the object (yes or no), and the clarity of the form of the hand (0=mittens, 1=gloves, 2=bare hand). Error bars indicate 95% confidence intervals. See Table S1 for full results.

Table S1. (A) Regression table for model investigating predictors of infants' looking preference for the inefficient over the inefficient reach across Experiment 1-5 and all experiments from Skerry et al. (5) (total N=264, 248 included in the final analysis, 16 excluded on the basis of Cook's Distance). (B) Regression table for the same analysis, including all participants. Dependent measure is proportion looking towards the inefficient reach, averaged across 3 test trials during test. Categorical predictors were coded using sum contrasts, and fixed effects from the model should therefore be interpreted with respect to the grand mean. Model formula: `prop.ineff.all ~ training + goal + hab + causal + clarity + (1|experiment) + (1|ageday) + (1|sex) + (1|paper).`

A	**Standardized Estimate (ß)**	**Estimate (B)**	**Standard Error (SE)**	**df**	**t**	**p**	**95% CI (Lower)**	**95% CI (Upper)**
(Intercept)	-0.716	0.457	0.012	241	37.17	<0.001	0.433	0.481
Effective training	0.583	0.052	0.011	241	4.50	0.000	0.029	0.074
Ineffective training	-0.330	-0.029	0.015	241	-1.96	0.051	-0.058	0.000
State change goal	0.302	0.027	0.008	241	3.39	0.001	0.011	0.042
Reach constrained by barrier	0.406	0.036	0.008	241	4.67	<0.001	0.021	0.051
Action on contact	0.467	0.041	0.009	241	4.86	<0.001	0.025	0.058
Clarity of hand	0.333	0.030	0.013	241	2.22	0.027	0.003	0.056

B	**Standardized Estimate (ß)**	**Estimate (B)**	**Standard Error (SE)**	**df**	**t**	**p**	**95% CI (Lower)**	**95% CI (Upper)**
(Intercept)	-0.640	0.455	0.016	10.73	28.34	<0.010	0.424	0.487
Effective training	0.578	0.058	0.015	7.55	3.79	0.006	0.028	0.088
Ineffective training	-0.355	-0.035	0.019	7.58	-1.86	0.102	-0.073	0.002
State change goal	0.301	0.030	0.011	6.75	2.79	0.028	0.009	0.051
Reach constrained by barrier	0.350	0.035	0.010	17.43	3.61	0.002	0.016	0.054

Action on contact	0.423	0.042	0.010	37.41	4.11	<0.001	0.022	0.062
Clarity of hand	0.294	0.029	0.018	7.48	1.66	0.137	-0.005	0.064

Exclusion info

Table S2. Tally of infants who participated in Experiments 1-5 but were excluded in our final sample. These exclusion criteria vary slightly across experiments (e.g. we relaxed our definition of inattentiveness from excluding all data from a participant if they missed a test trial, or if that trial was miscoded, in Experiment 3, to excluding data from just that trial in all other experiments).

Experiment	Fussy	Inattentive	Caregiver Interference	Experimenter/ Coding Error	Technical Failure	Total
Exp.1	7	0	0	2	0	7
Exp.2	6	0	0	1	2	9
Exp.3	9	5	1	12	3	30
Exp.4	0	0	0	2	0	2
Exp.5	6	0	0	2	0	8
Total	28	5	1	19	5	50

Distribution of Looking Times, Experiments 1-5

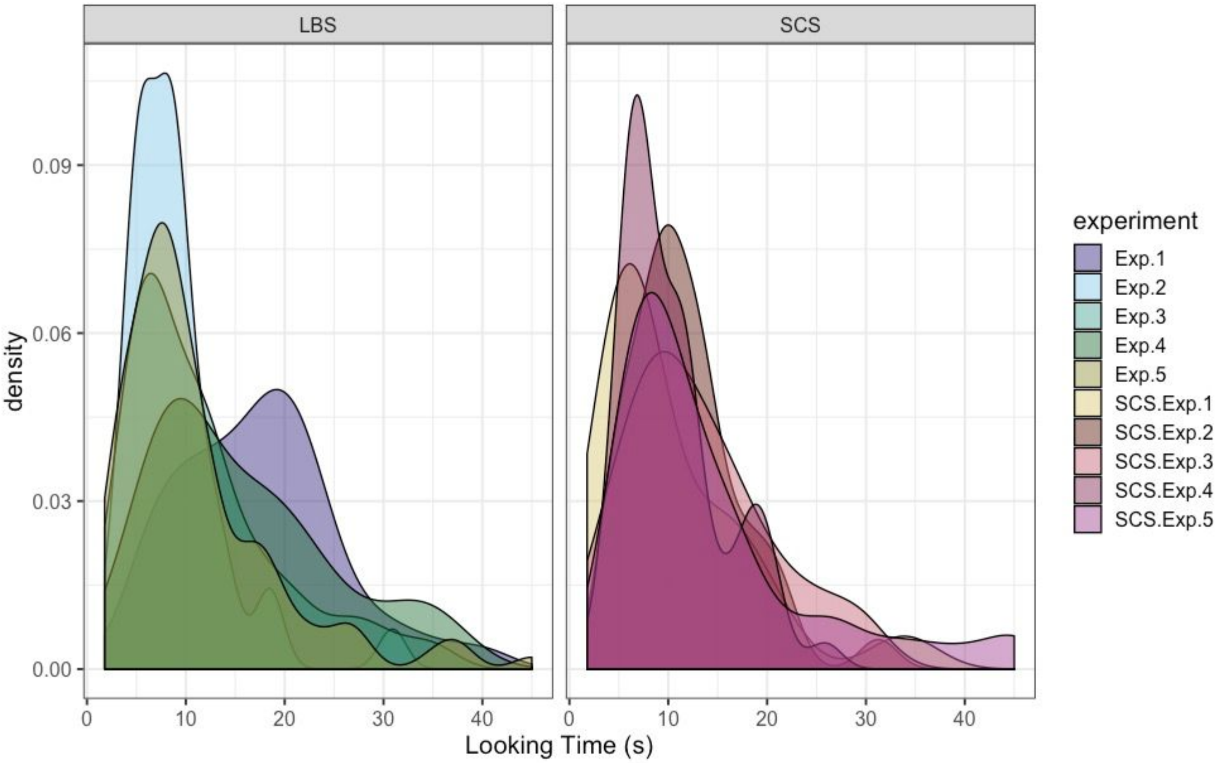

Figure S3. Density plot of looking times during test across Experiments 1-5 from the current paper (Liu, Brooks & Spelke, LBS, left panel), and Experiments 1-5 from Skerry et al. (5) (SCS, right panel) (N=264). Maximum-likelihood fitting revealed that the lognormal distribution (log likelihood=-1720.509) provides a better fit to these data than the normal distribution (log likelihood=-1842.196).

Attention to actions during habituation trials in Experiments 1-5

To ask whether infants' total attention during habituation was affected by experimental manipulations across Experiments 1-5 (action constrained vs unconstrained by a barrier, state change vs pickup goal, mittened, gloved, or bare-handed actor, and action with vs without contact with the object), and varied by gender and age, we fit a mixed effects model on these fixed effects and experiment (1-5) as a random intercept. We found that the only robust predictor of attention during habituation was age, [-3.4,-0.714], ß=-0.233, B(SE)=-2.058(0.68), p=0.003, two-tailed, such that older infants looked for a shorter time overall than younger infants.

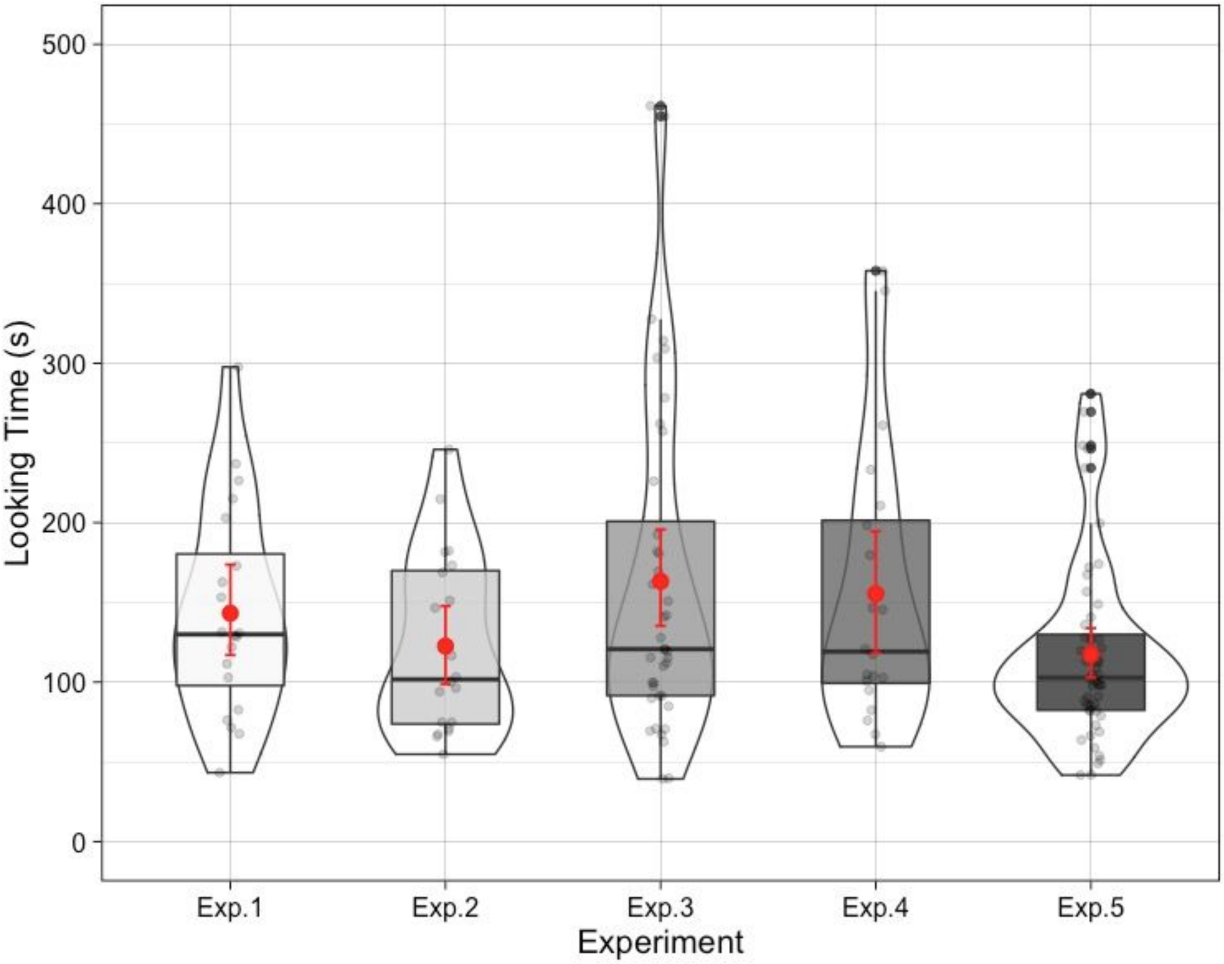

Figure S4. Total looking time in seconds during habituation across Experiments 1-5. Error bars around means indicate bootstrapped 95% confidence intervals (CIs). Individual points indicate data from a single participant. Horizontal bars within boxes indicate medians, and boxes indicate the middle 2 quartiles of data. Violin plots in indicate distribution of data, area scaled proportionally to the number of observations.

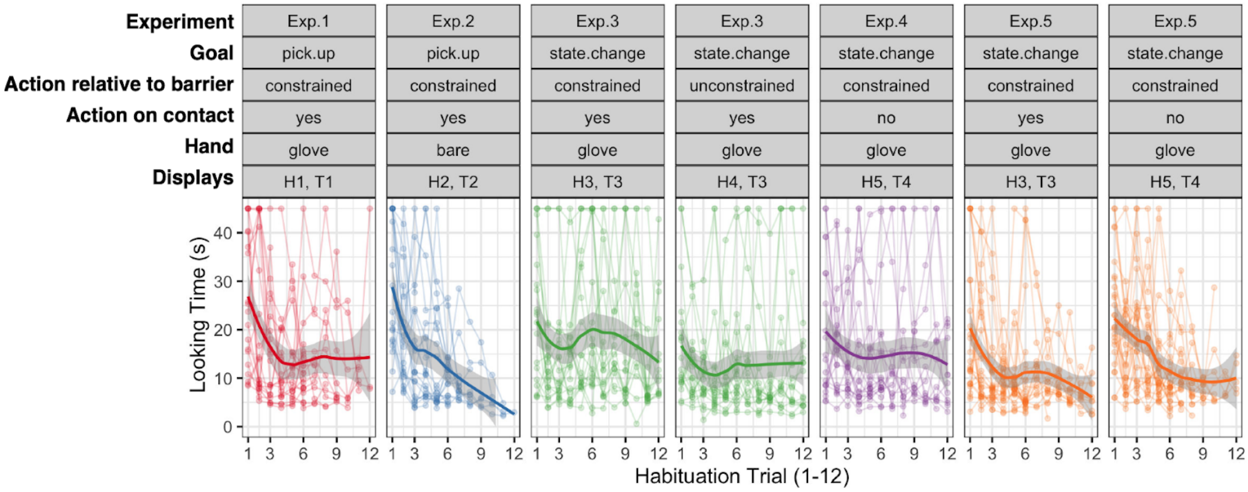

Figure S5. Looking time in seconds during each habituation trial across Experiments 1-5. Curves with 95% confidence interval ribbons indicate smoothed conditional means, generated using the loess method. Connected points indicate data from a single participant. Labels above each panel list the experiment name (Exp. 1-5), whether actions during habituation were constrained or unconstrained by a barrier, goal (state.change or pick.up), whether actions resulted in contact with the object, whether the actor reached with a mittened, gloved, or bare hand, and video displays listed in Figure 1.

Table S3. Regression table for mixed effects model analyzing the effect of age, sex, order of test events, habituation condition, goal, coverage of the hand, and causal information on total looking time habituation, controlling for other variations across Experiments 1-5. Model formula: total_hab ~ ageday + sex + first.test + hab + goal + clarity + causal + (1|experiment)

	Standardized Estimate (ß)	**Estimate (B)**	**Standard Error (SE)**	**df**	**t**	**p**	**95% CI (Lower)**	**95% CI (Upper)**
(Intercept)	0.171	373.160	89.49	51.41	4.170	0.000	194.14	553.006
Age in days	-0.233	-2.058	0.68	147.54	-3.026	0.003	-3.40	-0.714
Sex	0.066	5.203	6.11	148.65	0.852	0.396	-6.92	17.274
First test event	-0.006	-0.439	6.00	146.65	-0.073	0.942	-12.27	11.393
Action over a barrier	0.222	17.590	11.03	131.57	1.595	0.113	-6.44	41.220
Goal	0.007	0.589	16.02	6.18	0.037	0.972	-37.44	37.615
Clarity of hand	-0.253	-19.993	38.05	5.73	-0.525	0.619	-110.17	70.275
Action on contact	-0.055	-4.379	9.08	75.38	-0.482	0.631	-23.75	13.935

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5. Skerry AE, Carey SE, Spelke ES (2013) First-person action experience reveals sensitivity to action efficiency in prereaching infants. *Proc Natl Acad Sci U S A* 110(46):18728–18733.