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Pomiechowska, Barbara
Csibra, Gergely

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Ten-month-olds infer relative costs of different goal-directed actions

Barbara Pomiechowska (pomiechowskab@ceu.edu)
Department of Cognitive Science, Central European University,
Október 6. u. 7, 1051 Budapest, Hungary

Gergely Csibra (csibrag@ceu.edu)
Department of Cognitive Science, Central European University,
Október 6. u. 7, 1051 Budapest, Hungary
Department of Psychological Sciences, Birkbeck, University of London,
Malet Street, London WC1E 7HX, UK

Abstract

While it is straightforward to compare the costs of different variants of the same action (e.g., walking to a coffeeshop at the end of the block will always be less costly than walking to a coffeeshop three blocks away), the relative costs of different actions are not directly comparable (e.g., would it be easier to jump over or walk around a fence?). Across two experiments we demonstrate that 10-month-old infants spontaneously encode the manner of different goal-directed actions (jumping over an obstacle vs. detouring around it, Experiment 1) and use the principle of cost-efficiency to infer their relative costs (jumping is less costly to bypass low walls, but detouring is less costly to bypass high walls, Experiment 2). By relating action choices to the physical parameters of the environment, infants identify the least costly actions given the circumstances, which allows them to make behavioral predictions in new environments and may also enable them to infer others' motor competence.

Keywords: cognitive development; action interpretation; rational action; infancy

Introduction

Walking up 108 stories to reach the top of the Eiffel tower on foot requires more stamina than climbing to its first-floor terrace. Taking a lift all the way up instead of taking the stairs seems definitely easier, while scaling the tower on the outside requires much more effort than either of the other choices. Different actions towards the same goal often vary dramatically in their energetic costs, and yet, people have no difficulty in comparing the prospective costs of these actions across a range of contexts.

The ease of performing these inferences conceals their complexity. In particular, there are no simple mappings of action parameters to energetic costs that would apply to all agents and situations. Thus, for an inexperienced or unknowledgeable observer the relative costs of various actions are not directly comparable. However, there is a way to infer relative costs by deploying the assumption of cost-efficiency (i.e., the idea that agents tend to go for the least costly of the available actions that gets them to their goal, Gergely & Csibra, 2003; Jara-Ettinger et al., 2016) while comparing an agent's actual actions to potential alternatives in a given physical environment. This way one can apply a backwards inference from the observed action to the underlying cost functions that the agent is minimizing. For example, witnessing someone jump over a low wall and then walk around a high wall would indicate that jumping is less costly than detouring for the particular dimensions of the first obstacle and, conversely, that detouring is less costly than jumping for the particular dimensions of the second obstacle. That is, from the assumption of cost-efficiency one can readily learn which action minimizes the cost function of the agent given the environmental constraints she faces.

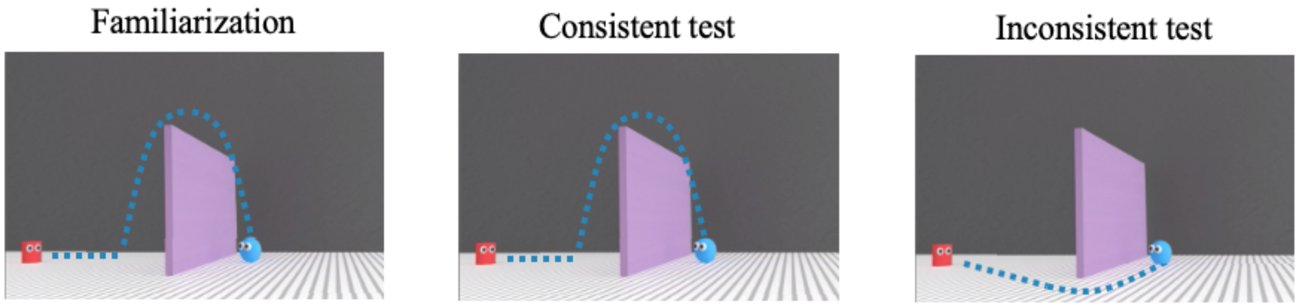
Computing relative cost functions by taking into account the co-variation between observed actions and environmental constraints allows us to assess an agent's cost profile (i.e., a set of relative costs associated with various actions for this agent) as a function of certain environmental variables. Such information is useful for two reasons. First, it supports behavioral predictions in novel environments (e.g., what will the agent do if the wall is lower?). Second, and relatedly, it enables us to find out the parameters defining one's motor competence (e.g., she can jump high).

Here we asked whether the inferential apparatus responsible for calculating and comparing relative costs of different goal-directed actions is available in early ontogeny. A sophisticated understanding of others' actions within the first year of life seems to provide young infants with conceptual building blocks required for performing such computations. First, infants engage in action interpretation and attribute goals to the observed actions. For example, they recognize approach actions as means to seek proximity of, or getting access to, the approached objects (e.g., Woodward, 1998; Hernik & Southgate, 2012; Skerry, Carey, & Spelke, 2013). Second, their action interpretation is guided by the assumption of cost-efficiency, such that they expect agents to minimize the costs of their actions (e.g., by taking a straight path toward the goal, Gergely et al., 1995; Csibra et al., 1999; or by performing a jump aligned in height with an obstacle rather than leaping over it, Liu & Spelke, 2017). Finally, they treat action cost as a monotonic function of certain geometric features of the environment (e.g., height of a wall, length of a path, incline angle of a hill slope, Gergely & Csibra, 2003; Liu et al., 2017), interpreting, for instance, a higher jump as more costly to perform than a lower jump.

We hypothesized that the expectation of cost-efficiency should lead infants to perform cost comparisons even between alternative actions whose cost-relevant parameters are not on the same scale (i.e., the cost of detouring relates to the length of the obstacle, while the cost of jumping relates to its height and/or width). Under the efficiency assumption, the evidence of different behavioral choices in response to changes in the geometry of the environment allows one to map different monotonic cost functions onto each other. That is, just as in the example above, when the agent jumps over a low wall and detours around a high wall, one can identify the height interval containing the cross-over point at which the cost function of jumping starts to take higher values than that of detouring.

Building on this logic, we conducted two looking-time experiments to investigate whether 10-month-old infants appreciate the relative costs of two distinct goal-directed actions: jumping over versus detouring around obstacles towards a desired object. We proceeded in two steps. In Experiment 1, we tested whether infants spontaneously encode the manner of an efficient goal-directed action – even though such information is superfluous to goal attribution. More specifically, we sought to establish whether 10-month-olds would spontaneously differentiate between two approach actions varying in manner: *jumping* versus *detouring*. In Experiment 2, we tested whether infants

A Experiment 1



B Experiment 2

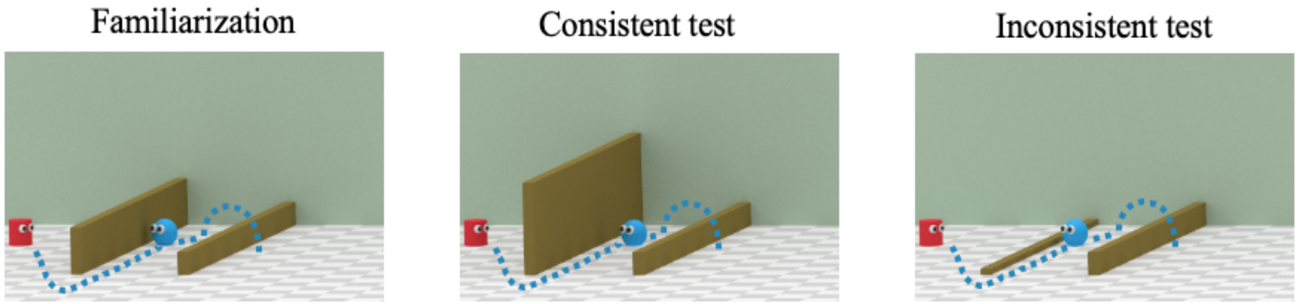


Figure 1 : **The stimuli used in Experiments 1 and 2.** The agent (blue sphere) moved always from the right to the left to approach its target (red cylinder). The dotted lines illustrate its trajectory. (**A**) In Experiment 1, during familiarization, the agent performed always one type of action (e.g., jumping) to bypass the obstacle blocking its way to the goal. Consistent test trials were identical to familiarization trials. On inconsistent test trials, the agent performed a novel action (e.g., detouring) to bypass the obstacle. (**B**) In Experiment 2, during familiarization the agent had to bypass two obstacles to reach its goal. It jumped over the first, low, obstacle and detoured around the second, high, obstacle. At test, the actions and their order were identical to familiarization (first jumping, then detouring), but the environment changed: the second, high, obstacle was replaced by a novel obstacle. On consistent test trials, the novel obstacle was higher than both familiarization obstacles, while on inconsistent test trials the novel obstacle was lower than both familiarization obstacles.

appreciate the fact that different actions varying in manner bear different relative costs, and are able to evaluate these costs for the sake of predicting the agent's future behaviors.

Experiment 1

Our aim in Experiment 1 was to provide evidence that infants discriminate between goal-directed actions varying in manner: *jumping over an obstacle* and *detouring around it while remaining on the ground.* The ability to encode such information is a prerequisite for computing relative costs of different actions. Despite the abundant literature on infants' goal attribution, it remained unclear what information they encode about the action itself. Imagine an agent jumping over a barrier to get access to a desired object. Infants might conceptualize the observed action merely as an *efficient goal approach,* without representing the means via which it was achieved. Alternatively, infants might go for a more detailed description of the event, such as an *efficient goal approach via jumping.* Only this latter conceptualization, which specifies the manner of the performed action, would allow them to discriminate between jumping over an obstacle and other ways of making way around it (e.g., detouring it).

To assess whether 10-month-old infants encode the manner of efficient action carried out by an agent to achieve her goal, we familiarized them with an animated character approaching a target object separated from her by a wall. At familiarization, the agent always performed the same action to go past a wall (e.g., jumping). At test, infants saw the agent either perform the familiarized action (i.e., jumping) or a novel efficient approach action (e.g., detouring the obstacle while remaining on the ground). If infants represent the manner of the observed actions, they should look longer at the novel- than the familiarized-action test events.

Methods

Sample size The sample size in the current experiments was regulated using a prespecified preregistered stopping rule. Namely, the data collection was due to stop in one of following cases: either (i) after collecting 32 valid data sets or (ii) when the sequential $\log_{10}$-Bayes Factor ($\log_{10}$-BF) in the looking-time analysis assuming variable effect size (Csibra et al., 2016) becomes (ii.a) larger than +1 or (ii.b) smaller than -1. The BF calculation was fixed to be performed first after collecting 12 valid samples, and at every second sample thereafter. The $\log_{10}$-BF value larger than +1 would indicate a strong effect to the predicted or to the opposite direction, or the value smaller than -1 would indicate an absence of looking-time difference.

Participants Our final sample consisted of 12 healthy full-term 10-month-olds (M = 10 months 17 days, R = 9 months 25 days to 10 months 28 days). An additional 10 infants were excluded from the analysis as a result of parental interference ($n = 1$), not disengaging from the screen at either of test trials ($n = 2$), and failure to complete the task ($n = 7$). All parents gave written informed consent. Infants received a small gift for their participation. The study was approved by the local ethics committee.

Apparatus and procedure The visual stimuli were displayed on 24'' TFT wide screen monitor (sampling rate: 60 Hz, resolution: 1920 x 1200 px). The sound was delivered through stereo loudspeakers placed on both sides of the monitor. Matlab 2014b (MathWorks, MA, US) and Psychtoolbox 3.0 (Brainard, 1997) were used for stimuli presentation and on-line looking time measurement.

The experiment took place in a dimly lit soundproof laboratory room. Infants were seated on their caregivers' lap approximately 60 cm away from the monitor. Their behavior was monitored on-line by the experimenter using a digital video camera. The caregivers were instructed to remain silent throughout the task and wore opaque sunglasses to prevent them from watching the stimuli and biasing the infant's behavior toward the display.

Stimuli and design Stimuli were 3D animations depicting agent A bypassing a wall on her way to agent B (Figure 1A), either by jumping above it or detouring around it. Jumping and detouring actions were matched in duration. Each animation was 12 seconds long.

The task consisted of **6 familiarization trials** followed by **2 test trials**. In the familiarization trials, infants were exposed to one kind of approach action (e.g., jumping). The first test trial was identical to the familiarization trials. The second test trial depicted the novel action (e.g., detouring).

Trial structure and termination criteria. Each trial was participant controlled. That is, within each trial, the video stimulus was looped and displayed continuously unless the infant looked away for more than 2 seconds, in which case the trial was terminated. If the infant did not trigger the trial termination, the video stimulus was presented 5 times. Thus, the trail duration varied depending on the infant's looking behavior, with the maximum duration corresponding to 60 seconds per trial.

Attention getters. Before each familiarization trial, the infant's attention was drawn to the middle of the screen by a centrally displayed pulsing attention-getter consisting of two short animations. The display time of the first animation was fixed at 3 seconds, while the display time of the second gaze-contingent animation was regulated by the infant, as it remained on the screen until being fixated for 0.5 seconds. Each test trial was preceded by a novel attention-getter animation (15 seconds) and the same gaze-contingent animation as at familiarization.

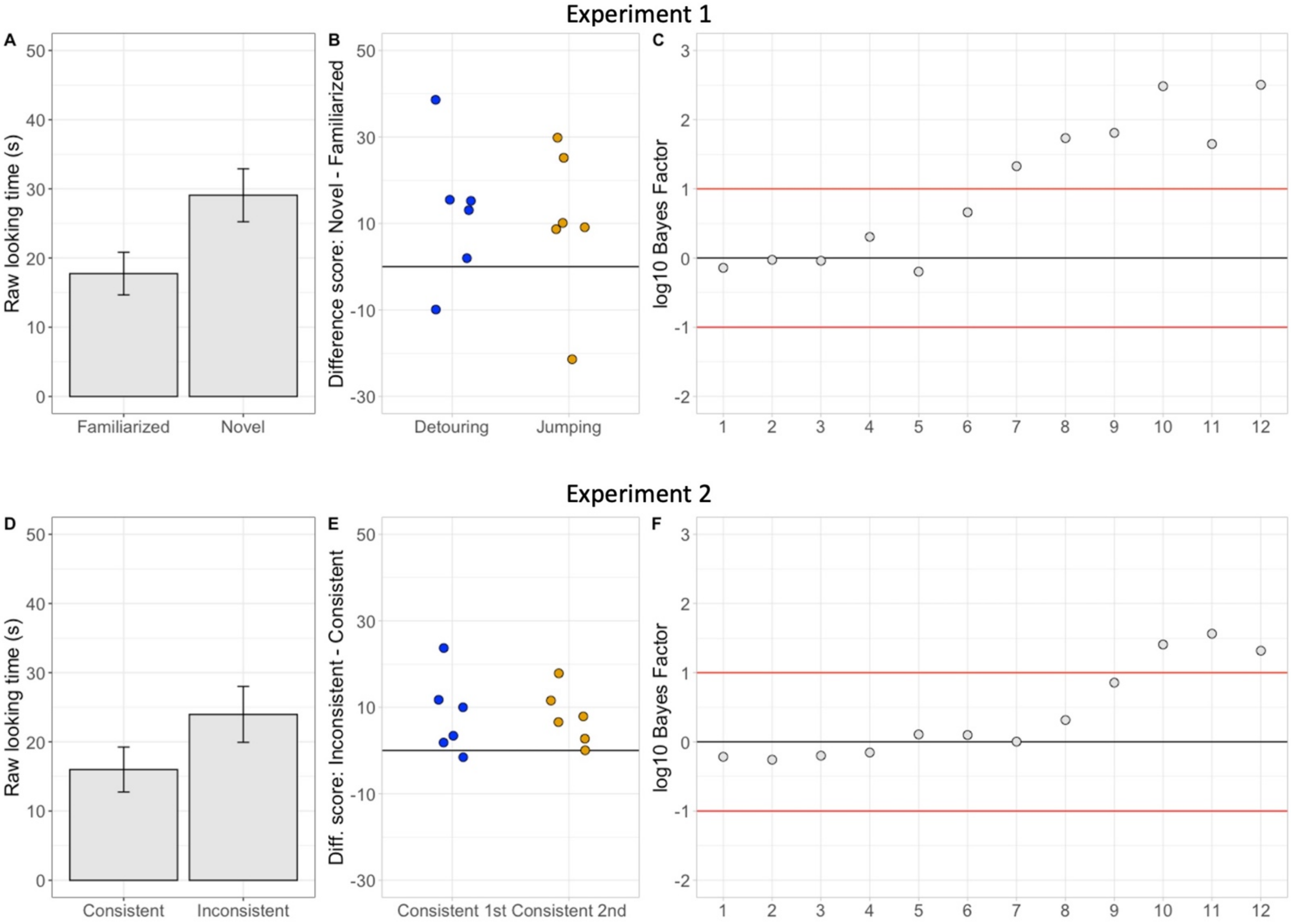


Figure 2 : **Results of Experiment 1 and 2.** (**A,D**) Bar plots represent the average raw looking times across consistent versus inconsistent test trials. Error bars represent +/- 1 standard error. (**B,E**) Dots represent individual differences scores calculated by subtracting raw looking time at the consistent test trial from the raw looking time at the inconsistent test trial. Positive values indicate longer looking to the inconsistent test trials, while negative values indicate longer looking to the consistent test trials. (**C,F**) Evolution of $\log_{10}$-Bayes Factor over the course of data collection. Values larger than +1 indicate a strong effect in the predicted direction.

We randomized which action the infants were familiarized to. Half of the participants was randomly assigned to the jumping action and the other half to the detouring action. Because one of our test trials was identical to the familiarization trials, we fixed the order of test trials such that the familiarized action was always presented first the novel action second. This is a typical procedure for testing infants' ability to discriminate between to two stimuli (Colombo & Mitchell, 2009).

Measure, coding, and analysis

Our main measure of interest was infants' looking time toward the screen during the test phase. The looking times were measured from the beginning of the trial (i) until the infant looked away from the screen for more than 2 s or (ii) until the end of the test trial. The looking time data was coded offline.

The data were base-10 log-transformed and our primary statistical analysis computed Bayes factors assuming variable effect size (Csibra et al., 2016). We calculated a $\log_{10}$-BF to compare a null model to an alternative model that assumes a change in looking times between conditions (i.e., familiarized goal-directed action v. novel goal-direct action targeting the same goal as the familiarized action). Additionally, we conducted frequentist statistical analyses.

Results and discussion

Novel-action test trials elicited longer looking (*M* = 29.08 s, *SD* = 13.27 s) than familiarized-action trials (*M* = 17.75 s, *SD* = 10.66 s), providing strong evidence that infants discriminated between two kinds of actions performed by an agent to bypass an obstacle, jumping versus detouring ($\log_{10}$-BF = 2.504; $t(11) = 2.722$, $p = .020$, $d = 0.79$, 95% CI = [0.04, 0.41] (Figure 2A-C). Ten out of 12 infants displayed this looking pattern. Their looking time was not affected by the type of action they were familiarized to. This was confirmed by the absence of significant main effect of familiarized action (*jumping v. detouring),* or significant interaction between this factor and test action (*familiarized v. novel*) in an ANOVA using these contrasts as a between- and a within-subject factors, respectively (*p*s > .249). These results indicate that 10-month-olds spontaneously encoded the type of action performed by the agent to reach her goal object even though such information was not necessary for action interpretation and goal attribution.

Experiment 2

In Experiment 1 we established that infants differentiate goal-directed jumping from detouring. In Experiment 2, we investigated whether they compute and compare relative costs of these actions. To this aim, we presented 10-month-olds with events depicting an agent encountering two obstacles, O1 and O2, on the way to her goal. The obstacles had the same length (20 units), but O1 was lower than O2 (O1: 2 units, O2: 4 units). The agent jumped over the lower obstacle, O1, and detoured the higher one, O2, by detouring it. Relating the kind of performed action to the size of the obstacle would allow infants to evaluate the costs of jumping and detouring relative to the height parameter and, more specifically, to infer that jumping over O1 was less costly than detouring it and the opposite held for O2. If infants compute costs of jumping as a monotonic function of the height of the obstacle, and expect efficient actions in a novel situation, they should look longer to an event in which the agent detours an obstacle lower than O1 than to another event in which the agent detours an obstacle higher than O1 and O2.

Methods

Participants Twelve healthy full-term 10-month-olds (M = 10 months 13 days, R = 9 months 20 days to 10 months 28 days) were included in the analysis. An additional 6 infants were excluded from the analysis as a result of failure to complete the task ($n = 5$) and preterm birth ($n = 1$). The rule to determine the sample size was identical to Experiment 1.

Apparatus and procedure We used the same apparatus and followed the same procedure as in Experiment 1.

Stimuli and design Stimuli were 3D animations depicting agent A bypassing two walls (one by jumping above it and the other one by detouring it) on her way to agent B (Figure 1B). The obstacles fell from above as the agent advanced towards her target such that when its way was blocked, it was located at the midpoint of the obstacle.

As in Experiment 1, the task consisted of 6 familiarization trials, followed by 2 test trials. In each **familiarization** trial, infants were exposed to a sequence of two actions: jumping over a low obstacle O1 (2 units) and detouring a high obstacle O2 (4 units). The obstacles had the same length (20 units). The order in which actions were performed was fixed.

At **test**, the agent jumped over O1 and detoured a new obstacle, O3 or O4, that replaced O2. All obstacles were matched in length but differed in height: one obstacle, O3, higher (8 units) than both O1 and O2 was presented on consistent test trials, and another one, O4, which was lower (0.5 unit) than both O1 and O2, appeared on inconsistent test trials. Both O3 and O4 differed by a factor of 4 from O1, such that the relative change in height between O1 and the new obstacle was the same across consistent and inconsistent test trials. The kinematics and trajectory of both actions were kept constant across familiarization and test.

Note that, unlike in Experiment 1, both test trials differed from the familiarization trials. Hence, the order in which the test events were presented was counterbalanced across participants: half of the infants saw the consistent test first, while the other half saw the inconsistent test first.

Measure, coding, and analysis Infants' looking times at test remained our main measure. We employed the same coding and analysis schemes as in Experiment 1.

Results and discussion

Infants looked significantly longer to the inconsistent test event ($M = 23.97$ s, $SD = 14.01$ s), in which the agent detoured the lowest obstacle, than to the consistent test ($M = 16.00$ s, $SD = 11.24$ s), in which the agent detoured the highest obstacle, $\log_{10}$-BF = 1.319; $t(11) = 4.06$, $p = .002$, $d = 1.17$, 95% CI = [0.08, 0.27], (Figure 2D-F). Eleven out of 12 infants displayed this looking pattern. A mixed-model ANOVA with test event (consistent v. inconsistent) and order (consistent 1st v. consistent 2nd) did not reveal a significant main effect of order nor interaction with this factor, *p*s > .317.

These results provide evidence that 10-month-olds interpreted the variability of action choices of the agent by the principle of cost-efficiency, and computed relative costs of jumping and detouring accordingly. Namely, they identified jumping as more costly than detouring for the high obstacle O2 (4 units), while remaining less costly than detouring for the low obstacle O1 (2 units). This inference allowed them to use the height of the novel obstacles at test to establish which action would minimize the agent's cost: detouring when the novel obstacle was higher than O1 (i.e., O3 8-unit high) and jumping when the novel obstacle was lower than O1 (i.e., O4 0.5-unit high).

To corroborate the above interpretation and rule out the use of simpler heuristics (e.g., jump whenever the wall is higher than 2 units), in follow-up work, we are testing whether infants are surprised to see the agent jump over an obstacle that would be less costly to detour.

General discussion

Our experiments establish initial evidence that 10-month-olds encode the manner of distinct goal-directed actions performed by others and are sensitive to how the relative costs of these actions vary as function of environmental constraints. In Experiment 1, infants increased their looking when the agent changed the way it approached its target from jumping over an obstacle to detouring around it (or vice versa). This indicates that infants spontaneously encode not only the goal of the action but also how it is performed. This information is required to estimate the cost functions that may differ across actions and govern agents' behavioral choices. Indeed, in Experiment 2, infants were able to infer that distinct actions had different relative costs for the observed agent. Namely, they appreciated that jumping over a wall was less costly than detouring around it unless the wall exceeded a particular height. Furthermore, they used this inference productively to predict an agent's behavior in a new environment, expecting her to detour novel obstacles lower, but not higher, than the cut-off height.

How did the infants infer the relative costs of jumping and detouring in Experiment 2? We propose that the assumption of cost-efficiency led to them to seek explanation for the variability of the agent's behavior. To do so, infants drew backward inferences from action choices and the environment characteristics to the underlying action costs. That is, upon observing that an agent's actions varied between jumping and detouring, they worked out that (1) the costs of these actions were not equal at the obstacles with particular dimensions, and that (2) below a certain obstacle height jumping was less costly than detouring. The properties of cost functions posited by the infants (beyond being monotonic) remain a question for the future research.

The ability to compare cost functions of different actions can be used not only to predict how others will behave in the future, but also to learn about their motor competence. People vary in how fit and how skilled they are. However, the information about their fitness and competencies is not directly available to others. Behavioral dispositions can be either conveyed verbally (e.g., "Malvin is a great climber") or inferred from their performance. Computing relative cost functions of an agent provides a way to learn about her motor competence (e.g., she can climb higher than she would be able to jump). Furthermore, identifying relative cost functions of several agents enables the observer to take a step further and compare motor competence across agents (e.g., Malvin can climb higher than Mike). The experiments reported here are not sufficient to assess whether infants' inferences to cost functions were agent-specific. Further research should address this question by contrasting the behavior of multiple agents (e.g., one who detours a high wall and one who jumps over it).

To conclude, our findings suggest that young infants apply the principle of cost-efficiency to make sense of variability in the behavior of others. By linking others' action choices to the physical parameters of the environment, they are able to compute and compare cost functions of different actions. Such computations are inferentially powerful, supporting not only behavioral predictions but also providing a foundation for reasoning about others' motor competence.

Preregistrations

The preregistrations and materials can be found under the following links: Experiment 1 (https://osf.io/wuxp3), Experiment 2 (https://osf.io/w329v).

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