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Infants infer motor competence from differences in agent-specific relative action costs

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Abstract

Determining others' motor competence is critical for action prediction and social decision making. One aspect of competence judgements involves assessing how costly a given action is for a particular agent (e.g., whether climbing 4 floors of stairs is a piece of cake or a tough physical exercise). Such information is not given away by the agents' physical appearance but can be inferred based on their behavior. Across two looking-time experiments, we show that 10-month-olds can infer and compare agent-specific costs of different actions. After being familiarized with agent A jumping over low obstacles and walking around high obstacles, and agent B jumping over both low and high obstacles, infants worked out that for B jumping bears little cost, while for A jumping high is more costly than detouring the obstacles by walking. Furthermore, they used this motor competence judgements to predict both agents' actions in a new environment. These findings suggest that basic building blocks competence evaluations are available in infancy and may be rooted in infants' action interpretation skills.

Keywords: infant cognition; action interpretation; competence; naïve utility calculus

Introduction

Reasoning about others' competence is a critical aspect of our social life. Knowing how competent a person is to carry out certain tasks guides not only action prediction (e.g., estimating whether someone will pass a math test or win a ping-pong match) but also social decision making (e.g., deciding whom to work with on a group assignment or pair up for a double game). Our concept of competence is versatile and can be applied to intellectual and physical characteristics of agents. However, whether we consider others' ability to write computer code, play the piano, or run a half-marathon, one aspect that competence judgements in very different domains have in common is the assessment of how costly (or effortful) a given action is for a particular individual. Generally, assuming the same outcome of a completed action, the person for whom the action was less costly (or easier) to carry out is likely to be judged as more competent than the person for whom it proved more costly (or difficult). Similarly, considering within-individual variations in competence, the person is likely more competent at actions that are less costly (or easier) for them than those that are more costly (or difficult).

Recent developmental work with young children suggests that this inferential strategy is operational early in human development: children seem to base their competence evaluations on how costly it is for an agent to complete a task. Already by 2 years of age, toddlers interpret the differences in two agents' relative efforts to activate a toy as indicative of differences in competence, judging a person who activated the toy with a fewer number of attempts as a better play partner than the person who needed to try more times before succeeding (Jara-Ettinger et al., 2015a; see also, Gweon & Schulz, 2011). Later, 4-year-olds use the time required to complete a task as a proxy of cost and select the person who was faster to assemble a block tower as more competent, i.e., better at building blocks (Leonard et al., 2019).

Here, expanding on the findings that complex inferences about action costs become operational in the first year of life (Liu et al., 2017; Liu & Spelke, 2017), we posited that human infants may have access to aspects of competence evaluations that rely on computing agent-specific costs. To test this hypothesis, we turned to approach scenarios, in which an agent overcomes obstacles on its way to a goal. This choice was motivated by the following empirical evidence. First, infants comprehend approach actions as means to seek proximity of, or getting access to, the approached objects or social partners, as early as 3 months of age (Skerry, Carey, & Spelke, 2013; Liu, Brooks, & Spelke, 2019.). Second, their action interpretation is guided by the assumptions of cost-efficiency, such that they expect agents to minimize their energetic expenditure (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). Third, infants treat action cost as a monotonic function of certain perceivable geometric parameters of the environment (e.g., the height of a wall, the length of a path, the 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.

Furthermore, by 10 months of age, infants apply the principle of cost efficiency to interpret the variability in an agent's behavior (e.g., sometimes jumping above obstacles, sometimes detouring them by walking) as linked to the

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environment in which the agent acts (e.g., some obstacles are high, some low) and indicative of differences in relative costs of distinct actions. For example, observing an agent detouring narrow obstacles by walking and jumping above long obstacles leads infants to think that making short but not long detours is less costly than jumping (Pomiechowska & Csibra, 2020). By assuming cost-minimizing action choices, they infer that the cost of jumping must be lower than the cost a long walk, while, conversely, the cost of a short walk must be lower than the cost of jumping. Critically, the ability to compute and compare the relative costs of different actions is a computational prerequisite for estimating agents' motor competences.

Namely, estimating motor competence amounts to building an agent's cost profile, defined as a set of relative costs associated with different actions and indexed to a specific individual. While the past evidence discussed above indicates that infants compute relative actions costs, it remains unknown whether they appreciate that costs can vary across agents. It could be that infants initially assume that all agents have similar physical characteristics, and discover only later, through interacting with others, that action costs change across individuals. Alternatively, the appreciation that distinct individuals are characterized by different cost profiles may be part of the early-emerging action interpretation toolkit such as naïve teleology (Gergely & Csibra, 2003) or naïve utility calculus (Jara-Ettinger et al., 2016).

Across two looking time experiments, we examined whether 10-month-olds can estimate two agents' motor competences by computing agent-specific differences in relative costs of two different actions, jumping versus walking. Infants were first familiarized to agent A jumping over low obstacles and detouring high obstacles by walking, and agent B jumping over both low and high obstacles. Then, their ability to establish that the agent-specific cost profiles (i.e., for A walking around high obstacles is less costly than jumping, while for B jumping is always less costly) was probed via an action prediction test, in which both agents acted in a new environment. In Experiment 1, both agents were shown to jump over a new obstacle higher than those seen at familiarization: this action was consistent with the cost profile of agent B and inconsistent with the cost profile of agent A. In Experiment 2, both agents were shown to jump over a new obstacle whose height fell between the heights of the familiarization obstacles, making jumping consistent with the cost profiles of both agents. If infants compute agent-specific motor competences in jumping and walking, they should display longer looking to events inconsistent with the cost profile of agent A in Experiment 1 and look equally long to both test events in Experiment 2. We chose to test 10-month-olds for their ability to readily compute action costs based on the path characteristics (Liu et al., 2017) and extract relative costs of different approach actions (Pomiechowska & Csibra, 2020).

Experiment 1

Methods

Participants. The sample size was determined using a preregistered stopping rule, with $\log_{10}$ Bayes Factor ($\log_{10}$-BF) calculation to be performed after the collection of 16, 24 and, 32 valid samples (i.e., every 8th sample after reaching because 3 two-level factors were counterbalanced in the current design). The minimum and maximum sample sizes, of 16 and 32 respectively, were selected based on a meta-analysis of previous studies using frequentist statistics and within-participant designs (Csibra et al., 2016), and providing that 16 participants should be sufficient to demonstrate an effect with 0.75 probability, while 0.95 probability should be achieved by 32 participants ($\alpha = .05$, using paired-samples t tests, two-tailed).

The final sample included 24 10-month-olds (M = 10 months 7 days; R = 9 months 17 days to 10 months 25 days). A further 20 infants had to be excluded from the analysis (n = 2 due to an experimenter error; n = 3 due to parental interference at test; n = 5 cried; n = 2 reached a maximum looking time at both test trials; n = 5 fussed out; n = 3 leaned out of frame making the video coding impossible). Because the testing took part during the covid-19 pandemic some of the participants were tested after having completed another experiment, which likely increased the current task's attrition rate (i.e., 7/10 infants who cried or fussed out participated in another experiment before).

Stimuli and Design. The current stimuli and task were modelled on previous work (Pomiechowska & Csibra, 2020). The task consisted of 6 *familiarization* trials, followed by 2 *test* trials. Each trial involved a sequence of looped 3D animations depicting an agent bypassing two walls on its way to the target (Figure 1). The animations were created in Blender (https://www.blender.org/).

There were two active agents, A and B, presented separately on different familiarization trials. They differed in color and shape (blue sphere v. yellow cube) and exhibited different greeting behaviors at the beginning of the trial (the blue sphere agent made a small jump in place; the yellow cube agent wiggled sideways). The aim of these contrasts was to help the infant discriminate between the agents.

The agents moved in the same environment, but their action choices differed to reflect differences in their cost profiles. The familiarisation layout comprised two obstacles of different height (2 and 4 units high, respectively) but same length (20 units). The obstacles obstructed the agents 'way to the target by falling in front of them as they were moving across the stage.

The agents differed in how they dealt with the obstacles. Agent A jumped over the low one and detoured the high one

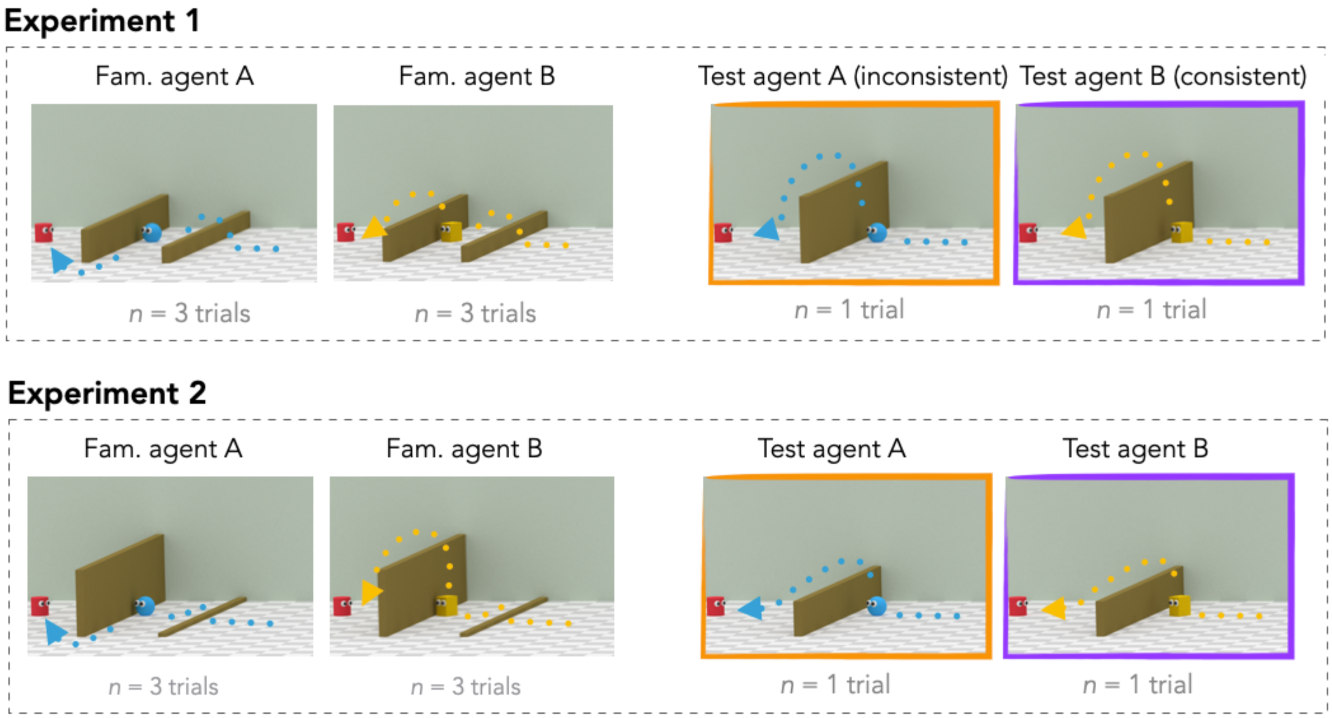

Figure 1 : Design and trial schematic across Experiments 1-2.

by moving around it on the ground, while agent B jumped over both of them. Thus, assuming cost-minimizing action choices, for B, the cost function of jumping always took lower values than the cost function of detouring. In contrast, for A, the cost function of jumping took lower values than the one of detouring only for the lower obstacle. The familiarisation trials were presented in an interleaved manner with respect to the agent's identity and cost profile: A B A B A B (counterbalanced).

In the test trials, infants were presented with a new environment, in which only one new obstacle blocked the agents 'way to the target. This obstacle was matched in length with the familiarization obstacles, but was higher (8 units high) than both of them. There were two test trials, one presenting agent A and the other presenting agent B jump above the new obstacle. Thus, both agents performed a perceptually novel action as neither of them was seen jump this high at familiarization. However, this new action was consistent with the underlying cost profile of only one of them (agent B), while being inconsistent with that of the other one (agent A).

We counterbalanced three factors: (1) the visual identity of the agent who acted first (blue sphere v. yellow cube), (2) test event order (consistent first v. consistent second), and (3) pairings between agent visual identity and cost profile (blue jumps twice v. blue jumps once and detours once).

Apparatus and Procedure. The visual stimuli were displayed on 24" wide screen monitor (sampling rate: 60 Hz, resolution: 1920 x 1200 px). The sound was delivered through built-in 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 sat on their caregivers 'lap approximately 60 cm away from the monitor. The caregivers were instructed to keep the babies by their hips not to obstruct their movement, and to remain silent and passive throughout the task. They wore opaque sunglasses to prevent them from watching the stimuli and bias the infant's behavior toward the display.

We used an infant-controlled procedure, in which the duration of all experimental trials was contingent on infants' attendance to the screen. The experimenter coded online whether the infant looked at the screen, beginning at the onset of the trial, and terminated the trial when (i) the infant looked away from the screen for more than 2 s or (ii) after all stimuli planned for a given trial were delivered (for a total trial duration of 60 s). We used an infant-controlled instead of fixed-length familiarisation to adapt the amount of exposure to individual participants.

Measure, Coding, and Analysis. Our main measure was total looking time toward the screen during the test events. The looking time data for the analysis were coded offline using the same criteria as online coding. Offline coders were unaware of the condition infants viewed.

We used a set of preregistered trial and participant inclusion criteria. To be included in the final analysis, infants had to contribute a minimum of 4 valid familiarisation trials and 2 valid test trials. A trial was valid, when the participant attended to both actions performed by the agent; that is, looked at the screen between 4 and 10.5 seconds of at least one action animation. Additionally, we excluded participants who did not display familiarization to the presented stimuli and who did not not disengage from the screen (i.e., looking for 60 s / trial) during 5 out of 6 familiarisation trials or during both test trials and those whose caregivers intervened during test.

The test data were base-10 log-transformed. Our primary statistical analysis computed log$_{10}$ Bayes Factors (log$_{10}$-BF) assuming variable effect size (Csibra et al., 2016). We compared a null model to an alternative model that assumes a change in looking times between conditions. 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 strong evidence for the lack of a looking-time difference. Additionally, we conducted frequentist statistical analyses: paired two-tailed t tests to assess differences between the test events (consistent v. inconsistent), and multi-model ANOVAs with test event and order (consistent 1st v. consistent 2nd) to test for order effects.

In addition, we explored infants' looking during familiarization. To assess whether infants displayed habituation to the familiarisation stimuli, we averaged and compared looking times in the first versus second half of familiarisation (i.e., trials 1-3 v. trials 4-6). As for the test data, the average looking times were base-10 log-transformed to approximate a normal distribution.

Results and discussion

Familiarization. Infants' looking times decreased significantly by the end of familiarisation (trials 1-3: *M* = 39.85 s, *SD* = 12.97 s; trials 4-5: M = 22.52 s, SD = 12.76 s; t(23) = 5.768, *p* < .001, 95% CI = [.18, 39]). There was no evidence that infants' looking at familiarisation was influenced by the agent's cost profile or its appearance, as assessed using two separate repeated-measures ANOVAs with familiarisation half (trials 1-3 v. trials 4-5) and cost profile (agent A vs. agent B) or appearance (blue sphere v. yellow cube) as within-subject factors.

Test. At test, infants looked significantly longer to the events in which agent A jumped over the high wall (*M* = 27.73 s, SD = 14.41 s) relative to events in which the same action was performed by agent B (*M* = 21.02 s, *SD* = 14.26 s), log$_{10}$-BF = 2.123, *t*(23) = 2.281, *p* = .032, 95% CI = [.01, .28]. This pattern of response was present in 20/24 infants. Exploratory ANOVAs using test event as a within-subject factor and order (consistent 1st v. consistent 2nd) or competent agent's appearance (blue sphere v. yellow cube) as between-subject factors provided no support for the influence of order, *p*s > .262, or features of the tested agent, *p*s > .837.

These results show that 10-month-olds displayed surprise when an agent who previously detoured *high* familiarisation obstacles was shown to jump over the test obstacle that was even higher. This effect supports the idea that infants extracted motor competence profiles of the two agents presented at familiarization and used this information to form expectations about their behavior in a new test environment. We propose that infants assumed both agents to be minimizing their costs and linked the dimensions of the obstacles to their action choices, which in turn allowed them by positing cost functions that were both individual- and action-specific. In particular, infants have established that for agent A the cost function of jumping took higher values than the one of detouring for high obstacles. In contrast, for agent B jumping appeared to be consistently less costly in the depicted environment.

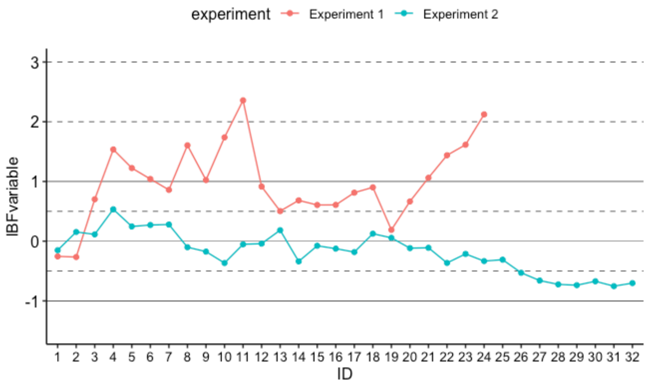

Figure 2 : Evolution of log$_{10}$ Bayes Factor across participants.

However, an alternative interpretation of the current results is that the observed looking pattern might have been independent from cost computations. Instead, it might have resulted from the changes of agent-specific action statistics: at familiarization, agent B jumped 100% of the time, while agent A split his actions equally between jumping and detouring, performing each 50% of the time. At test, both agents jumped 100% of time. Merely tracking the changes in agent-specific action frequency would also lead to longer looking at agent A who started to jump more often than it used to. This possibility was addressed in Experiment 2.

Experiment 2

The aim of Experiment 2 was to adjudicate what processing strategy infants adopted in Experiment 1. One possibility is that they tracked motor competence of two distinct agents based on the differences in their individual cost profiles. Alternatively, they might have only extracted the frequency of each agent's actions (e.g., A jumping 100% v. B jumping 50% of the time).

A new group of infants participated in a modified version of the task used in Experiment 1, in which we changed the height of the obstacles while keeping the action sequences and action frequency the same. As previously, infants were familiarized to two agents, one jumping above low walls while detouring high walls (agent A), and another one jumping above low and high walls (agent B). Unlike in Experiment 1, however, the height of the test wall fell in between the heights of familiarisation walls. Therefore, if infants solve the current task, using an agent-specific attribution of motor cost profiles, they should be agnostic about how the agent who previously detoured the highest wall would behave. This is because they were not given evidence about the precise cut-off height at which jumping becomes more costly than detouring for that agent. This account would predict no differentiation between the two test events, and a support for the null hypothesis in the BF analysis. On the other hand, if infants interpret the current events by tracking the frequency of actions for each agent, they should display the same pattern of results as observed in Experiment 1: looking longer at the agent who detoured the familiarisation obstacles by walking 50% of the time and changed his strategy at test to jumping 100% of the time.

Methods

The methods were the same as in Experiment 1, except the details described below.

Participants. The final sample size was determined following the same procedure as in Experiment 1 and consisted of 32 10-month-olds infants (*M* = 10 months 9 days, *R* = 9 months 18 days to 10 months 28 days). An additional 20 infants were tested and excluded from the analysis (*n* = 2 due to parental interference at test; *n* = 6 cried; *n* = 2 leaned out of frame; *n* = 3 reached the maximum looking on all familiarization trials; *n* = 1 reached the maximum looking at both test trials; *n* = 6 fussed out; 6/12 infants who cried or fussed out participated in another experiment before).

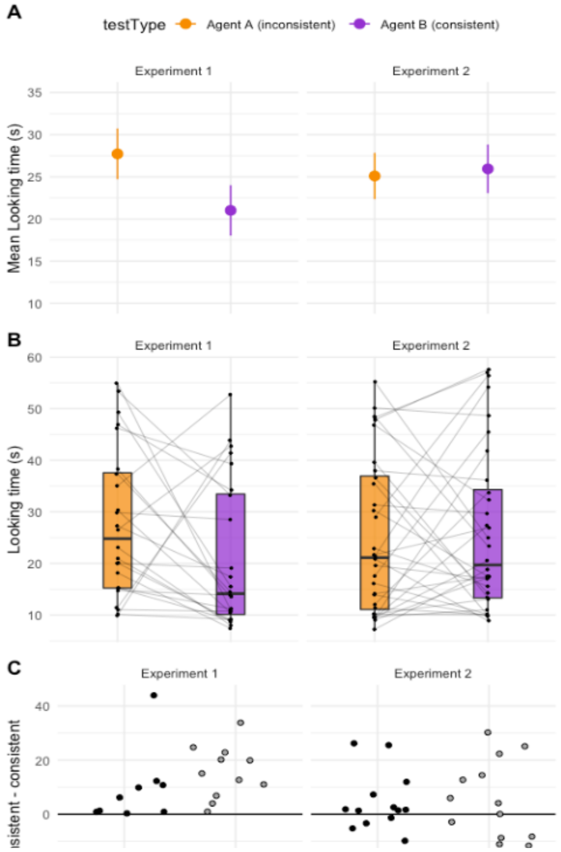

Figure 3 : Looking times across Experiments 1-2**.** (A) Dots represent the average raw looking times across test trials. Error bars represent +/- 1 standard error. (B) Dots represent individual participants' data points. (C) Dots (jittered) represent individual differences scores calculated by subtracting 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.

Stimuli and design. All aspects of task design were identical as in Experiment 2. We introduced only one modification regarding the height of the obstacles, both at familiarisation and test, to ensure that the height of test obstacle is numerically equidistant from the heights of both familiarization obstacles. We lowered the first familiarisation obstacle (to 0.5 units high from 2 units high in Experiment 1) and heightened the second one (to 8 units high form 4 units high in Experiment 1). One agent jumped above the first low obstacle and detoured by walking the second high obstacle (agent A), while the other jumped above both obstacles (agent B). The test wall was 4.25 units high (i.e., lowered from 8 units in Experiment 1), a height selected to be equidistant (by 3.75 units) from both familiarisation obstacles. Note that, as before, all obstacles were matched in length (20 units) and width (0.5 units). There were two test trials: the consistent test trial presented agent B jumping, while the inconsistent test trial presented agent A jumping.

Results and discussion

Familiarization. Infants' looking significantly decreased over the course of familiarisation trials (trials 1-3: *M* = 37.29 s, *SD* = 14.92 s; trials 4-6: *M* = 26.39; *SD* = 12.45 s, t(31) = 3.672, *p* = .001, 95% CI = [.07, .25], replicating the pattern of habituation to the familiarisation stimuli observed before. There was no evidence that the agent's cost profile (A vs B) influenced their looking behavior, by a repeated-measures ANOVA with familiarisation half (trials 1-3 v. 4-6) and agent as within-subject factors, *p*s > .18. Another repeated-measures ANOVA with familiarisation half and agent appearance (blue sphere v. yellow cube) yielded significant main effects of familiarisation half, *F*(1,31) = 10.715, *p* = .002, and agent appearance, *F*(1,31) = 15.173, *p* < .001. This effect reflected the fact that infants looked overall longer at the blue agent (*M* = 36.73 s) than at the yellow one (*M* = 26.71 s). Note, however, that for both agents there was evidence of habituation: looking times decreased significantly from the first to the second half of familiarisation for both the blue spherical agent (trials 1-3: *M* = 43.61 s, trials 4-6: 29.85 s, *t*(31) = 3.622, *p* = .001, 95% CI = [.09, .33]) and the yellow cubic one (trials 1-3: *M* = 30.63 s, trials 4-6: *M* = 22.80 s, t(31) = 2.077, *p* = .046, 95% CI = [.002, .25]).

Test. Infants looked equally long to both test events (consistent event featuring agent B: *M* = 25.195 s, *SD* = 15.86; inconsistent event featuring agent A: *M* = 25.10 s, *SD* = 15.14 s). The $\log_{10}$-BF reached -0.702, thus indicating substantial support for the null hypothesis that there was no difference in looking times across conditions. The auxiliary frequentist analysis yielded no significant effect: *t*(31) = .365, *p* = .717, 95% CI =[-.09, .13]. Seventeen out of 32 infants looked longer at agent A relative to agent B. Furthermore, exploratory analyses provided no evidence that infants' looking was influenced by the order of test event delivery (consistent 1st v. consistent 2nd, by a mixed-model ANOVA with test event as a within-subject factor and order as a between-subject factor, *p*s > .44), or agents 'appearance (blue sphere v. yellow cube, by a repeated measures ANOVA test event and agent appearance within-subject factors, *p*s > .10).

Unlike in Experiment 1, infants did not differentiate between the test events, looking equally long regardless of which agent was shown jumping above the test wall. This lack of differentiation rules out the possibility that infants in Experiment 1 simply relied on internal statistics of action sequences. In Experiment 2, this strategy would have brought about longer looking to the test events featuring agent A who detoured approximately 50% of the time during familiarisation and switched to 100% jumping at test.

Rather, infants appeared to have computed agent-specific relative costs of jumping and detouring, allowing them to estimate the individual agents' motor competence across different actions. As the height of the test wall fell in between the heights of the familiarisation walls, infants could not know whether it was below or above the cut off height that had made jumping more costly than detouring for agent A during familiarization. Therefore, jumping remained consistent with agent A's motor competence profile.

Comparison across Experiments

Familiarization. To compare familiarisation looking behavior across Experiments 1 and 2, we conducted two multi-model ANOVAs with experiment (1 v. 2) as a between-subject factor and either cost profile or agent appearance as a within-subject factor. Only the latter analysis yielded significant effects: a main effect of color, $F(1,54) = 8.217$, $p = .006$, and an interaction between experiment and color, $F(1,54) = 7.583$, $p = .008$. This interaction can be explained by the fact that while in the familiarisation of Experiment 1 infants attended equally whether blue or yellow agent was presented, in Experiment 2 they tended to spend overall more time watching the blue agent. Such difference was likely due to random inter-group differences in infants 'color and/or shape preferences and could not account for the null result observed at test.

Test. A mixed-model ANOVA with test event (consistent v. inconsistent) as a within-subject factor and experiment (1 v. 2) as a between-subject factor yielded as a significant interaction between these two factors, $F(1,54) = 4.063$, $p = .048$, other *p*s > .13. This result confirms that the observed looking patterns differed across experiments.

General Discussion

The results of the present experiments suggest that motor competence judgements emerge early in life and are supplied by the computations of agent-specific action costs of different actions. More specifically, 10-month-olds appreciate that relative action costs vary across agents and compute agent-specific cost profiles that summarize the information about agents' motor competence (i.e., which actions are more costly than others given the environmental constraints). Infants expect that individual cost profiles remain stable over time and have an influence on the agents' behavioral choices. In Experiment 1, infants looked longer to an agent who navigated a new environment in a manner inconsistent with the cost profile it displayed at familiarization than to an agent who acted consistently with its familiarized cost profile. Experiment 2 confirmed that this looking pattern resulted from inferences about motor competence to jump versus detour obstacles by walking, and not from tracking action frequency.

What inferences are involved in the infants' judgements of motor competence? We propose that the assumption cost-efficiency leads infants to seek explanation for the variability of the observed behavior at two levels: within-agent as well as across-agent. This can be achieved by drawing backward inferences from action choices and the environment characteristics to the underlying action costs. For instance, here, upon observing that one agent's (A) actions varied between jumping and detouring, while the other agent (B) consistently jumped, infants worked out that (1) for A the costs of jumping and detouring varied as a function of obstacle height, such that below a certain obstacle height jumping was less costly than detouring, and (2) for B jumping was the cost-optimal action regardless of the obstacle height.

The present work is in line with recent studies showing that toddlers and preschoolers accurately judge third-party competence based on considerations about action cost and efficiency (Leonard et al., 2019; Jara-Ettinger et al., 2015a, 2015b) or emotional expressions (Asaba et al., 2020). Jointly, these findings speak against the long-held view that children struggle to evaluate competence, being overly optimistic in their evaluations (e.g., holding that they will perform better in the future than they did in the past, e.g., Nicholls & Miller, 1984; Ruble et al., 1980; Harter, 2012). As pointed by Cimpian (2017), the view that early judgements of competence are deficient was based on experiments investigating predominantly children's predictions about their own performance, which may have led to wishful thinking masking the underlying inferences about competence.

In conclusion, our research provides early evidence of motor competence judgements in human infants and uncovers the action-interpretation mechanisms that subserves them. It remains open, however, whether infants have an abstract concept of competence that extends beyond physical abilities. The adult understanding of competence encompasses vastly different domains of actions, and different ensuing costs. Determining the scope of infants' competence judgements is an exciting avenue for future research.

Preregistration & Materials

The preregistration can be accessed here: https://osf.io/8hnkj The materials, data, and analysis scripts can be accessed here: https://osf.io/dx9zs/

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