Dangerous ground: Thirteen-month-old infants are sensitive to peril in other people's actions

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Abstract

Do infants appreciate that other people's actions may fail, and that the possibility of failure endows risky actions with variable amounts of negative utility (hereafter, "peril")? Three experiments addressed this question by presenting 10- and 13-month-old infants (N=124) with an agent who chose whether or not to jump over a trench of varying depth to reach two goals. At 13 months, infants expected the agent to minimize the potential negative consequences of actions, even though they never observed the agent fail to complete its action successfully. Moreover, they learned which goal the agent preferred by observing how much peril it risked to reach each goal. Although findings at 10 months were not clear, these findings provide evidence that 13-month-old infants represent danger as a kind of cost, possibly in an integrated utility calculus. They invite further study of infants' understanding of mental states and of counterfactual aspects of action.

Keywords: cognitive development; infancy; action understanding; open data; open materials; pre-registration

Introduction

Scaling *El Capitan*, a 3000-foot wall of sheer granite in Yosemite Park, is an effortful action. But scaling it without safety gear is fraught with peril. “Peril” describes the properties of a physical situation, and it is also informative about the mental states of an actor in that situation. When we see a parent chasing and retrieving a running child on the edge of a dangerous cliff, we may infer that the child is ignorant of her peril, whereas the parent is risking injury to save her highly valued child from harm. Such scenarios elicit reasoning not only about what happened (two people ran without mishap) but about what could have happened and didn’t. Here, we explore the early development of these abilities, by presenting infants with dangerous but consistently successful actions.

Intuitive psychology--the ability to turn observations of others’ behavior into information about their hidden mental lives--has been a focus of study for half a century (Dennett, 1987; Heider & Simmel, 1944; Perner, 1991; Premack & Woodruff, 1978; Wellman, 2002). Even infants appreciate that actions carry varying degrees of negative utility: for example, infants are sensitive to the physical effort that actors expend and expect them to act efficiently (Gergely & Csibra, 2003; Liu & Spelke, 2017), as do older children and adults (Baker, Jara-Ettinger, Saxe, & Tenenbaum, 2017; Baker, Saxe, & Tenenbaum, 2009; Jara-Ettinger, Gweon, Schulz, & Tenenbaum, 2016; Jara-Ettinger, Gweon, Tenenbaum, & Schulz, 2015; Liu & Spelke, 2017). Moreover, 10-month-old infants use the relative physical costs that an agent took to attain different goals (jumping higher walls, climbing steeper inclines, or clearing wider gaps for one goal than for another, Fig 1a) to infer the relative value of the two goals for the agent (Liu, Ullman, Tenenbaum, & Spelke, 2017). Because no single perceptual variable accounted for infants’ responses, they appear to represent the three actions in accord with a single variable of physical cost.

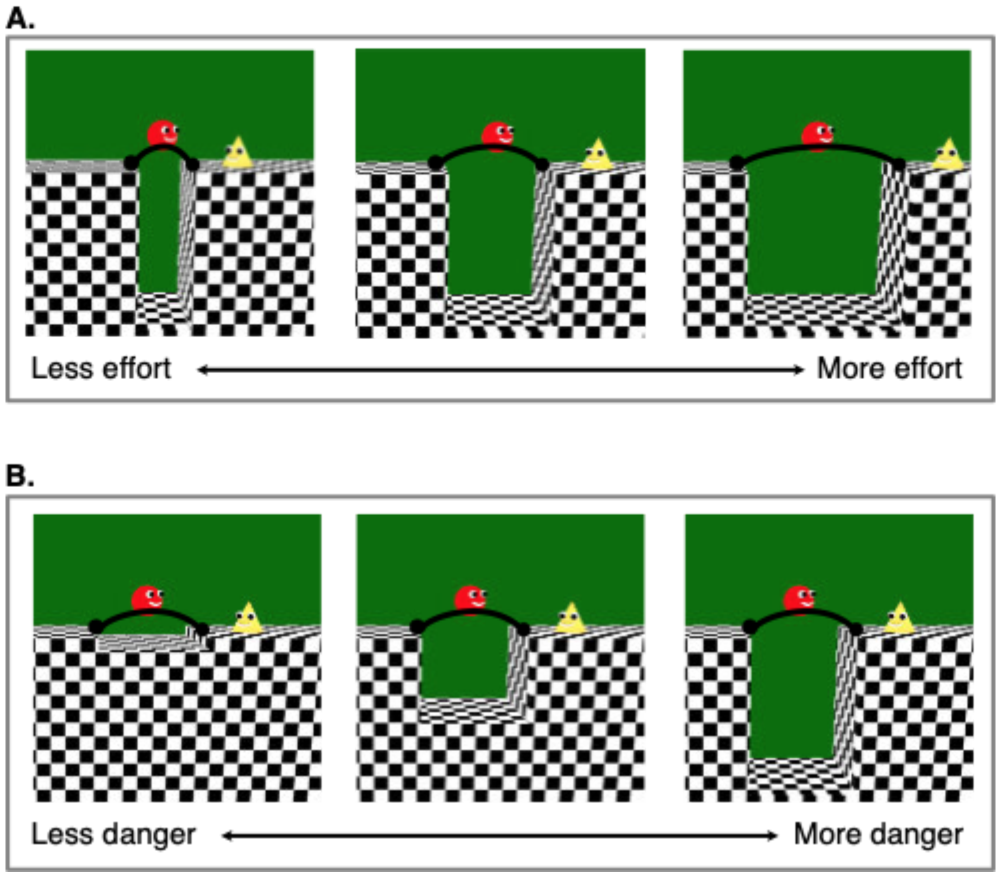

Figure 1. Actions that vary in (A) physical cost and risk or (b) peril.

Nevertheless, actions can carry negative utility in ways that past research on infants has not addressed. For example, consider the actions depicted in Figure 1. The jumps in (A) differ in physical effort but are equally perilous: failure to complete each jump will result in the same negative outcome. In contrast, the jumps in (B) are equal in effort but differ in peril, as the negative consequences of falling vary with the depth of the trench. Jumps over the latter trenches differ only in peril.

Inspired by research on depth perception and visuo-motor coordination in human and non-human animals (Adolph, 2000; Adolph & Kretch, 2012; Gibson & Walk, 1960; Walk, Gibson, & Tighe, 1957), we tested whether infants are sensitive to peril. We presented 10- and 13-month-old infants with an agent who performed identical jumps across the trenches in Figure 1b. Importantly, the agent always jumped successfully to its goal. Holding physical effort and the probability of failure[1] constant, we varied the negative utility that would have resulted had the action failed. Experiments 1 and 2 tested whether infants use the degree of peril of an action to infer the value of its goal for the actor. Experiment 3 tested whether infants expect actors to choose acts that minimize peril when goals are equal in value.

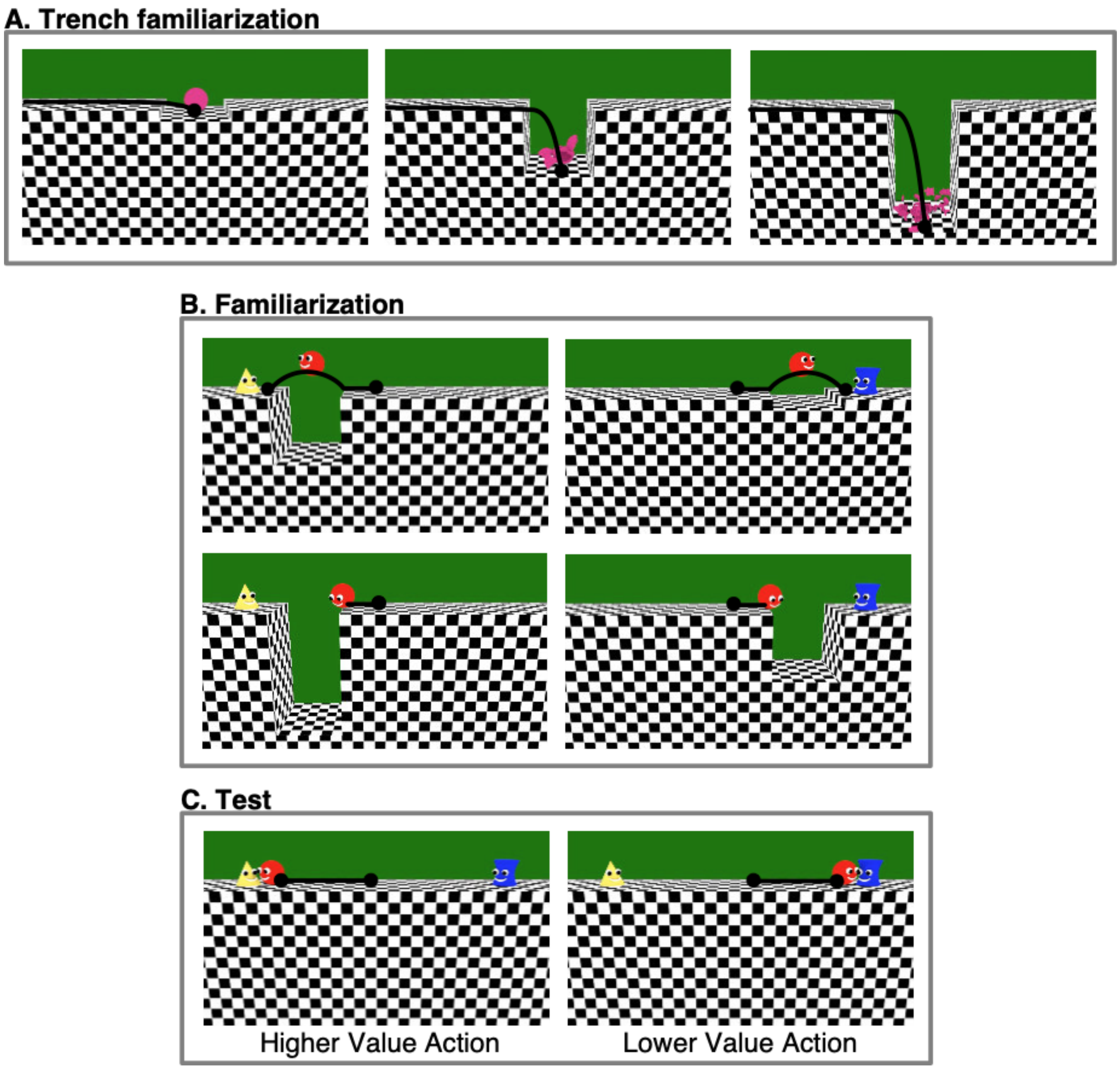

Figure 2. Still frames from videos shown to infants in Experiments 1 and 2. Black lines indicate trajectories of motion, and circles indicate start- and end-points of motion.

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[1] A third dimension of danger—the probability of failure—varies with trench width but not depth. Infants' understanding of action risks merits a separate investigation.

Experiment 1

Experiment 1 investigated whether 13-month-old infants infer the value of a goal to an agent from the peril of the action undertaken to achieve it. Infants viewed an agent jump a shallow but not a medium trench to attain one goal, and jump a medium but not a deep trench to attain another goal. All events were identical except for the depth of the trenches (Figure 2). Then infants were tested with events in which both goals were present with no trenches and the agent approached one or the other in alternation. We tested whether infants expected the agent to approach the goal for which it had risked greater peril.

Methods

Participants. Our final sample of participants included N=32 13-month-old infants (M=12.89 months, range=12.57-13.47, 17 female). Seven infants were excluded and replaced due to fussiness (3 infants) or inattentiveness during test trials (4 infants). All data were collected at the Harvard Lab for Developmental Studies with procedures approved by the Committee on the Protection of Human Subjects. The methods, sample size, hypotheses, and analyses were pre-registered at https://osf.io/bs3e7/. We chose to study 13-month-old infants in Experiment 1 because younger infants were not available at the time the study began, and because 13-month-old infants have more experience with standing, walking, and falling: experiences that may be important for the development of these abilities (Kretch & Adolph, 2013).

Materials and Design. The displays (Figures 1A and 2) are based on those of Liu et al. 2017 (Figure 1A). Using Blender (Foundation, 2016), we created animated videos featuring a central red agent jumping to two goals differing in color and shape. All stimuli were projected to a 1.02x1.32m screen and displayed using Keynote. Infant looking times were coded online using XHAB (Pinto, 1995), and offline using Datavyu (Datavyu Team, 2014).

To familiarize infants with the trenches (*trench familiarization,* Figure 2A), infants first viewed a ball emerging from one side of the screen (side counterbalanced across participants), rolling into a shallow, medium, or deep trench at the center of the screen, and either remaining unbroken (5.8s), breaking into 5 pieces (5.8s), or shattering into 100 pieces (5.0s), respectively.

Infants then were shown an agent taking more dangerous actions for one goal than another (*familiarization*, Figure 2B). The red agent began at the center of the screen, and one of the targets appeared to its left or right beyond a shallow (1 unit in Blender space), medium (8 units), or deep (15 units) trench. The target jumped up and down twice, making a noise, the agent turned and moved to the edge of the cliff, and either jumped over it (making a positive “Mmmm!” sound) (9.4s), or declined, backing away from its edge (making a reluctant “Hmmm...” sound) (7.7s). The agent jumped a shallow but not medium trench for one target, and a medium but not deep trench for the other. Each infant watched the four events in two orders: from low to high peril and the reverse. The location of the more dangerous trenches (left vs. right) and therefore of the more valued goal object (blue vs. yellow) and which familiarization video infants saw first (low to high peril, or the reverse), were counterbalanced across participants. Thus, infants saw the agent accept and refuse equally effortful actions towards each target with equal frequency and affect. Indeed, all the actions were physically identical except for their direction (left vs. right, counterbalanced across infants), with relative cliff depth (i.e. relative danger) as the only variable that distinguished actions toward the two targets.

To test infants’ expectations about the targets’ relative value, they were shown test events (*test*, Figure 2C) in which the central agent appeared equidistant from the targets with no intervening trenches. The agent looked between the targets, making an uncertain ‘Hmmmm…’ sound, and then moved on alternating trials to the target for which it had jumped deeper trenches (hereafter, the Higher Value Goal), and to the other target (the Lower Value Goal) (5.2s). Both *familiarization* and *test* trials looped with 0.5s blank screens interspersed between videos until infants spent a total of 60s attending to the screen or looked away for 2s; all infants saw 6 familiarization and 4 test trials. During *trench familiarization*, the three videos played once each in a constant order for all infants (total duration 23.5s, with pauses and intertrial blank screens), without infant-controlled timing.

If infants are sensitive to danger in other people's actions and view more dangerous actions as carrying more negative utility, even when the actions are successful, then they should expect agents to trade off peril and reward: Infants should infer that people who take more dangerous actions towards certain goals value those goals more highly, as they do for people who take more effortful actions toward those goals (Liu et al., 2017). Under this hypothesis, we expected infants to look longer when the agent, at test, chose the goal for which it had taken the less dangerous action. Alternatively, if infants are sensitive to effort but not peril, then they should attribute equal value to the two goals and look equally at the two test events, since the physical costs of all the actions were equal.

Procedure. Infants were seated on their caregiver’s lap, approximately 1.5m from the screen. Prior to the experiment, an experimenter attracted the baby’s attention to the left, right, top, and bottom edges of the screen, generating calibration images to guide human coders. Caregivers were asked to keep their eyes closed and to refrain from interacting with their infants during the experiment.

Data Coding and Analysis Strategy. All experimenters and coders were naive to the nature and the order of the test events and were unable to see what the babies saw during the experiment (they relied on trial-neutral sound cues to start each trial). To check for exclusions and coding errors, all test trial data were re-coded in Datavyu and excluded as necessary: If an infant looked away from a test event without ever having seen the agent jump, or if the trial ended too early or late, that trial was marked and excluded from subsequent analysis (14 out of 128 total test trials). We used these offline coded looking times for our final analyses. To assess the reliability of the data, 50% of test trials from the experiment (64 out of 128 trials) were re-coded Datavyu by an additional researcher who was naive to test event order. Reliability was high, intraclass correlation coefficient (ICC)=0.969, 95% CI [0.948, 0.982]. All decisions to include or exclude trials or participants from our analysis were made by researchers who were blind to the events seen by infants.

Infant looking times are often log-normally distributed (Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016), including in this dataset (log-likelihood of data for Experiments 1-3 under normal distribution = -1008.85, under lognormal distribution = -956.41), so our pre-registered dependent measure was the average looking time towards the higher- or lower-danger choice at test in log seconds, and the values of unstandardized B coefficients and 95% confidence intervals are reported in this unit. Nevertheless, we include summary statistics and plots of untransformed looking times for interpretability. We analyzed all looking times using mixed effects models (Bates, Mächler, Bolker, & Walker, 2015) implemented in R. All analyses including repeated measures included a random intercept for participant identity. Analyses conducted over multiple experiments included a random intercept for experiment, except in one case where including this intercept lead to issues with convergence[2]. For every model, we checked for influential participants using Cook's Distance (Nieuwenhuis, te Grotenhuis, & Pelzer, 2012) and excluded any participants who exceeded the standard 4/*n* threshold, where *n* is the number of participants. The number of participants that met this criterion is listed in every model result.

Results

Pre-registered results. We compared infants' looking times when the agent approached the target for which it performed the more dangerous action (Higher Peril, and therefore higher value) to the looking times when the agent approached the other target (Lower Peril). Thirteen-month-old infants looked longer when the agent chose the target achieved through the lower-danger action (M_{lower}=24.60s, M_{higher}=21.48s, 95% confidence interval (CI) over difference in log seconds [0.019,0.417], standardized beta coefficient (ß)=0.354, unstandardized coefficient (B)=0.218, standard error (SE)=0.100, p value (p)=0.037, two-tailed, excluding one influential participant).

Discussion

[2] This occurred in the analysis comparing the results from Experiment 2 with the results from Liu et al. (2017).

As in past research (Liu et al., 2017), infants looked longer when the agent approached the target for which it had undertaken less costly actions in the past. Because the actions in the present experiment all were successful and equal in physical cost and risk, this finding provides evidence that 13-month-old infants expect agents to trade off the perils of acting against the rewards that actions bring.

Experiment 2

Experiment 2 used the method of Experiment 1 with 10-month-old infants, who expect trade-offs between physical costs and rewards (Liu et al., 2017).

Methods

Participants. Our final sample of participants included N=32 10-month-old infants (M=10.13 months, range=9.60-10.63, 15 female). We chose the sample size of this experiment based on a power analysis over the results from Experiment 1 (see SOM for code). An additional 6 infants participated but were excluded from and replaced in the final sample due to fussiness (2 infants), inattentiveness during test trials (1 infants), online coding error (2 infants), and interference from caregivers (1 infant). The design, sample size, hypotheses, and analyses of this experiment were pre-registered and open access at https://osf.io/uh8ns/.

Materials, Procedure, Data Coding, Analysis. The materials, procedures, coding, and analyses of Experiment 2 were identical to those of Experiment 1. Eight out of 128 test trials were marked and excluded from further analysis because of inattentiveness or coding error. To assess the reliability of the data, 50% of test trials from the experiment (64 test trials) were re-coded Datavyu by an additional researcher who was naive to test event order. Reliability was high, ICC=0.995, 95% CI [0.991, 0.997].

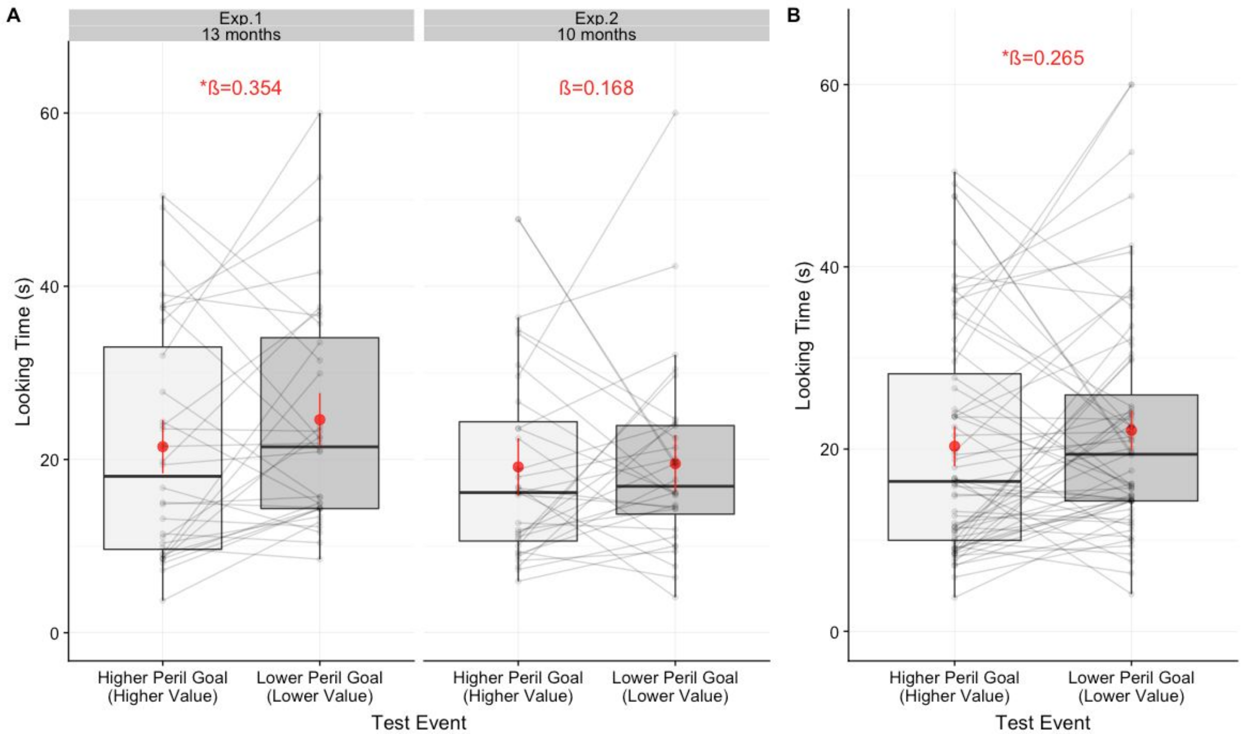

Figure 3. Looking time towards the test events presenting approaches to the goals attained through actions of higher vs. lower peril in Experiments 1-2, both (A) within and (B) collapsed across experiments. Red error bars around means indicate within-subjects 95% confidence intervals. Pairs of points indicate data from a single participant. Horizontal bars within boxes indicate medians, and boxes indicate the middle 2 quartiles of data. Beta coefficients (ß) indicate effect sizes in standard deviations.

Results

Pre-registered results. Ten-month-old infants did not show a statistically significant looking preference between the test events, (M_{lower}=19.51s, M_{higher}=19.15s, [-0.301,0.121], ß=-0.168, B=-0.09, SE=0.106, p=0.202, one-tailed, mixed effect model with fixed effect of test event and random intercept for participant identity, excluding one influential participant based on Cook's Distance using the same criterium as Experiment 1). See Figure 3.

Exploratory results.

Comparing 10-month-old infants' responses to danger and physical effort. To test whether 10-month-old infants responded differently to jumps over trenches of varying *depth* (i.e. danger), than to jumps over trenches of varying *width* (i.e. physical effort), we compared their looking preferences in Experiment 2 to those in Experiment 3 of Liu et al. (2017). There was no difference in infants' reasoning about physical effort and danger across these two studies ([0.054,0.518], ß=-0.417, B=-0.243, SE=0.166, p=0.149, two-tailed, excluding one influential participant). Collapsing across both experiments, 10-month-old infants looked longer when the agent chose the goal for which it previously performed actions that were less dangerous (current experiment) or less costly (Experiment 3, Liu et al., 2017) [0.017,0.336], ß=0.298, B=0.176, SE=0.081, p=0.033, two-tailed, excluding one influential participant).

Comparing Experiments 1 and 2. To test whether 10- and 13-month-old infants performed differently, we compared the data from Experiments 1 and 2. Ten- and 13-month-old infants did not significantly differ in their looking preferences, [-0.111,0.29], ß=0.213, B=0.122, SE=0.144, p=0.398, two-tailed. Pooling results from Experiments 1 and 2, infants looked longer overall when the agent chose the goal that was achieved by the less dangerous action (M_{lower}=22.06s, M_{higher}=20.32s, [0.01,0.293], ß=0.265, B=0.152, SE=0.072, p=0.038, two-tailed, excluding one influential participant).

Discussion

Whereas the findings of Experiment 1 provided evidence that 13-month-old infants infer goal values from action perils, the findings of Experiment 2 support no clear conclusions: Ten-month-old infants both failed to show the differential looking patterns found in Experiment 1, and their looking patterns did not differ reliably from those of their older counterparts. Ten-month-old infants may fail to see cliffs as dangerous (Adolph, 2000; Gibson & Walk, 1960) or to take account of action costs based only on the context in which actions occur. Alternatively, the younger infants may be sensitive to peril but fail to exhibit that sensitivity clearly, because the present task requires that infants remember four action choices toward two goals in three action contexts. In

Experiment 3, we reduce these task demands and continue exploring infants' understanding of dangerous actions at the two ages.

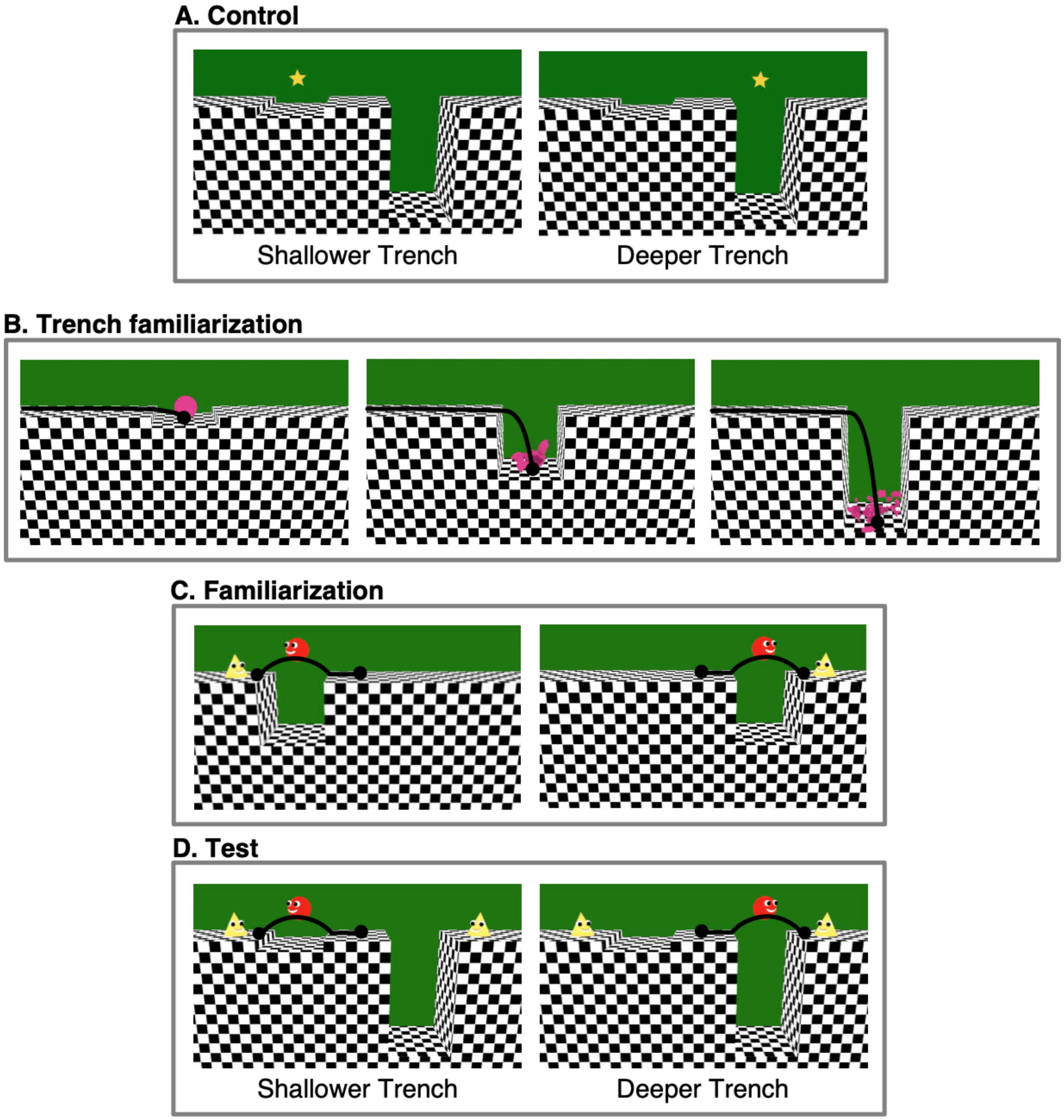

Figure 4. Still frames from videos shown to infants during Experiment 3. Black lines indicate trajectories of motion, and circles indicate start- and end-points of motion.

Experiment 3

Experiment 3 tested whether 10- and 13-month-old infants expect agents to minimize action peril when goals are equal in value. After an agent attained two identical targets through identical actions, it faced a choice between the targets, which now appeared beyond two trenches of differing depth (Figure 4). If infants expect agents to minimize action peril, they should look longer when the agent chose to jump the deeper trench to reach a target.

Methods

Participants. Our final sample of participants included N=30 10-month-old infants (M=9.95 months, range=8.97-10.47, 17 female) and N=30 13-month-old infants (M=12.89 months, range=12.53-13.5, 12 female). We chose this sample size using a power analysis from a pilot study (effect size ß=0.323), as well as estimates of effect sizes of studies with similar displays and design (Liu & Spelke, 2017; Liu et al., 2017). Eight infants were excluded and replaced in the final sample due to fussiness (3 infants), inattentiveness during test trials (3 infants), or interference from caregivers (2 infants). The methods, sample size, hypotheses, and analyses of this experiment were pre-registered and open access at https://osf.io/kx928/.

Methods. Study materials, design and procedure followed those of Experiments 1 and 2, except as follows. During familiarization events (Figure 4C), infants watched an agent perform identical jumps over trenches of 3 intermediate varying depths (6, 7, and 8 Blender units) towards two targets with identical properties (8.9s). For each event, the agent began at the center of the screen, while a target was situated beyond a trench, either to its left or its right. The target then jumped up and down twice, making a noise, the agent turned to look in its direction, moved towards the trench, looked down, and backed up and jumped over it, landing next to the target, making the same positive “Mmmmm!” vocalization as Experiments 1 and 2. The side of the trench and target (left vs right), and the depth of the obstacle varied pseudorandomly within trials. These events were followed by a test probing whether infants expected the agent to choose a less perilous over a more perilous action when the actions led to targets of equal value. For the test events, the agent appeared equidistant between one shallow and one deep trench (respectively, 1 and 15 Blender units), and the two targets stood beyond each trench and jumped up and down at the same time. The agent then turned towards each target, making the same uncertain “Mmmmm…” sound as in Experiments 1 and 2, and chose to jump across the deeper or shallower trench on alternating trials, following the same action path as during familiarization (Fig 4D) (7.2s). If infants expect agents to minimize the peril of their actions, they should look longer at the test events in which the agent chose to jump over the deeper trench.

To familiarize infants to these test displays and measure their interest in the two trenches outside of the context of goal-directed action, the experiment began with two *control* events (Fig 4A) (3.0s), featuring the same shallow and a deep trenches. Instead of presenting a jumping animated character, a star appeared and made a sound above each trench at the highest position of the jumps in the test displays (order of sides counterbalanced across participants). These events were followed by *trench familiarization videos* (Fig 4B), as in Experiments 1 and 2, in which an inanimate object rolled into a shallow, medium, and deep trench. In addition to the counterbalancing used in Experiments 1 and 2, the side of the deeper trench and the order of the more vs. less dangerous actions in the control, familiarization, and test events were orthogonally counterbalanced. All videos except for control events played on a loop with 0.5s blank screens interspersed between videos, and control events played once, freezing on the last frame until the end of the trial.

Data Coding and Analysis. The data coding and analysis strategy for Experiment 3 were identical to those of Experiments 1 and 2. Thirty-eight out of 360 total trials (4 test trials and 2 control trials per participant) were excluded from the analysis based on inattentiveness or coding error. To assess the reliability of the data, 50% of test trials from the experiment (120 of 240 total test trials) were re-coded Datavyu by an additional researcher who was naive to test event order. Reliability was high, ICC = 0.999, 95% CI [0.999,0.999].

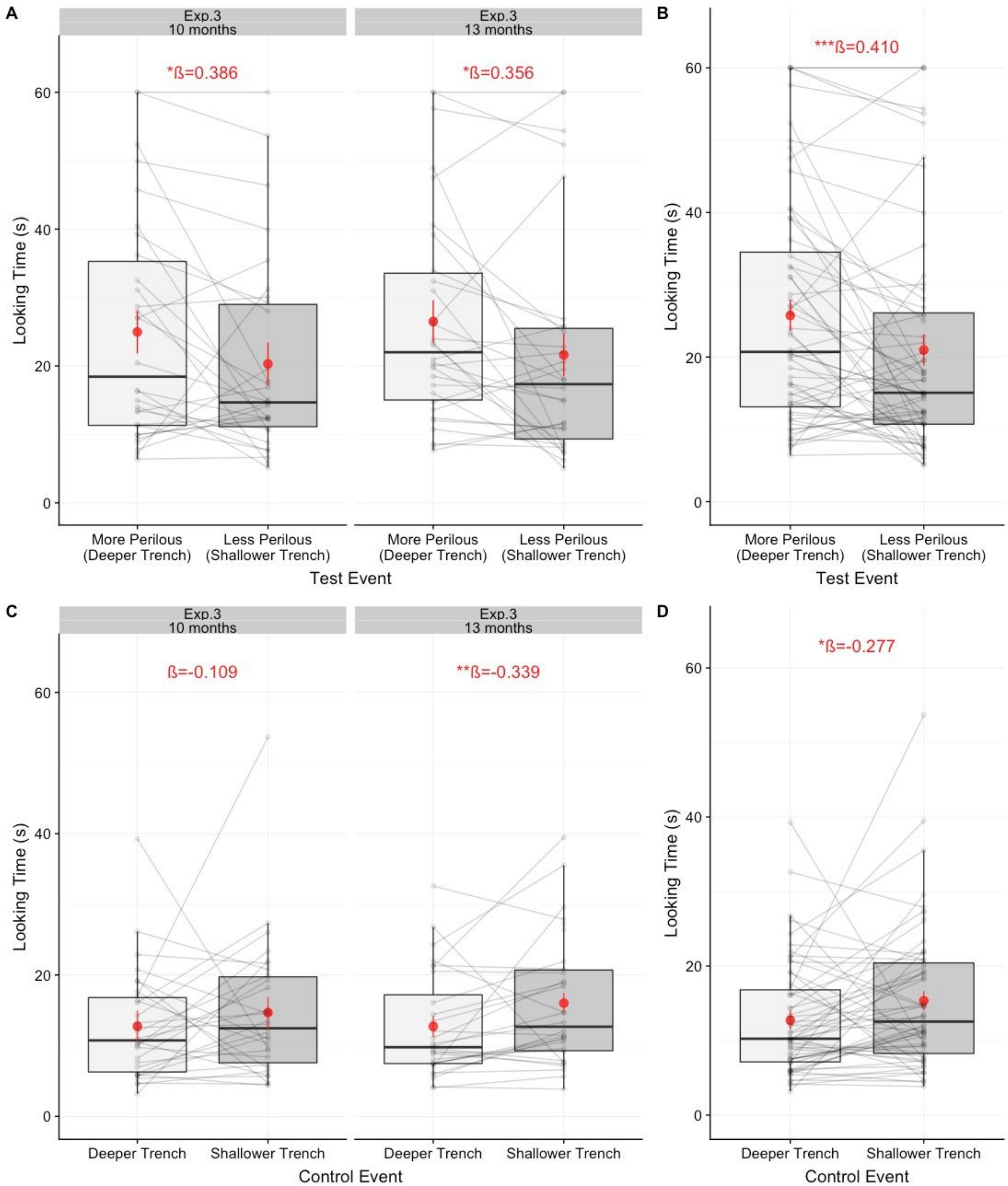

Figure 5. Looking times from Experiment during the test events, in which the agent chose to jump across a deeper or shallower trench for a goal (A and B), and during the control events, in which infants' attention was drawn over the deeper and shallower

trenches (C and D). The looking times are presented separated by (A and B) and collapsed across (B and D) age groups. Red error bars around means indicate within-subjects 95% confidence intervals. Pairs of points indicate data from a single participant. Horizontal bars within boxes indicate medians, and boxes indicate the middle 2 quartiles of data. Beta coefficients (ß) list effect sizes in standard deviations.

Results

Pre-registered results. Across both age groups, infants looked longer at test when the agent chose to jump the deeper trench than when the agent chose to jump the shallower trench (M_{deeper}=25.74s, $M_{shallower}$=20.97s, [0.123,0.424], ß=0.41, B=0.273, SE=0.076, $p<.001$, one-tailed, excluding one influential participant). See Figure 5B.

Comparing test events to control events. To test whether this looking preference reflected the relative danger of the different jumps, or other perceptual features of the shallow and deep trenches, we compared infants' looking times during the control events, where their attention was drawn to each trench using an attention-getting star that was placed in the path of the agent's subsequent actions. We found that infants showed a preference for the *shallower* trench in this context (M_{deeper}=12.73s, $M_{shallower}$=15.35s, [-0.299,-0.02], ß=-0.277, B=-0.159, SE=0.071, $p=0.028$, two-tailed, excluding 2 influential participants). Infants' looking preferences between the control events and the test events significantly differed from each other ([-0.501,-0.007], ß=-0.381, B=-0.254, SE=0.126, $p=0.046$, two-tailed). Thus, infants' expectations at test cannot be due to an intrinsic preference for events occurring over deeper to those over shallower trenches. See Figure 5D.

Exploring age differences.

Results in 13-month-old infants. Thirteen-month-old infants looked longer at test when the agent chose the deeper trench over the shallower trench (M_{deep}=26.504s, $M_{shallow}$=21.641s, [0.033,0.43], ß=0.356, B=0.232, SE=0.1, $p=0.014$, one-tailed, excluding one influential participant. During control events, 13-month-old infants preferred to look at the shallow trench (M_{deep}=12.728s, $M_{shallow}$=16.016s, [-0.314,-0.075], ß=-0.339, B=-0.193, SE=0.06, $p=0.003$, two-tailed, excluding 2 influential participants).

Their looking preferences significantly differed across the two conditions, [-0.883,-0.114], ß=-0.751, B=-0.498, SE=0.197, p=0.013, two-tailed. See Figure 5A and 5C.

Results in 10-month-old infants. Ten-month-old looked longer at test when the agent chose the deeper the shallower trench (M_{deep}=24.97s, $M_{shallow}$=20.31s, [-0.301,0.174], ß=-0.109, B=-0.064, SE=0.119, p=0.299, one-tailed, excluding one influential participant. During control events, 10-month-old infants displayed no strong looking preference (M_{deep}=12.738s, $M_{shallow}$=14.675s, [-0.301,0.174], ß=-0.109, B=-0.064, SE=0.119, p=0.598, two-tailed, excluding 1 influential participant). In contrast to the data from the 13-month-old infants, these two patterns of looking preference did not differ from each other, [-0.728,0.073], ß=-0.483, B=-0.327, SE=0.206, p=0.115, two-tailed. See Figure 5A and 5C.

Comparing 10-month-old and 13-month-old infants. The two groups of infants did not differ in their looking preferences between the two test events ([-0.275,0.328], ß=0.04, B=0.026, SE=0.154, p=0.864, two-tailed, excluding one influential participant), or between the two control events ([-0.363,0.194], ß=-0.146, B=-0.084, SE=0.142, p=0.559, two-tailed, excluding 2 influential participants). Infants of the two ages also did not show different looking preferences between the control and test events, [0.418,0.592], ß=0.131, B=0.087, SE=0.26, p=0.738, two-tailed.

Discussion

As in Experiment 2, the findings from the 10-month-old infants support no clear conclusions. Although 10-month-olds looked reliably longer at the test events involving the more perilous action, consistent with an expectation that agents will minimize action danger when goal values are equal, their preference during the test events did not exceed that for the control events, raising the possibility that it reflects an intrinsic preference for the deeper trench context. In contrast, Experiment 3 provided clear evidence that 13-month-old infants expect agents to minimize the danger of their actions, adding to and extending past findings that infants expect agents to minimize their physical action costs (Gergely, Nádasdy, Csibra, & Bíró, 1995; Liu & Spelke, 2017). The absence of any differences between looking times at the two ages raises the possibility that the ability found in 13-month-olds is latently present in 10-month-olds as well: a possibility that further research at the younger age could explore.

General Discussion

Plans go astray: For every good outcome that actions can produce, bad alternatives may arise. In the present research, 13-month-old infants showed sensitivity to the perils in other agents' actions. They expected an agent to minimize danger, looking longer when it chose a more perilous action when a safer action toward a goal of equal value was available (Experiment 3), and they used the potential dangers that an agent faced in achieving two different goals to infer the goals' relative values (Experiment 1). Whereas past research tested infants' sensitivity to the differential physical costs of actions, the present experiments isolate and test for infants' sensitivity to peril, when presented with actions that were identical with respect to all physical variables. The consistent effects of trench depth on the looking patterns of the 13-month-old infants provide clear evidence that infants represent peril as a variable in an integrated calculus trading off positive rewards and negative costs.

Our findings leave open three key questions. First, what is the computational basis for 13-month-old infants' sensitivity to peril? Past work on action understanding conceived of the utility of other agents as composed of two variables: the reward of goals states, $R(S)$, and the cost of actions, $C(A)$ (Equation 1) (Jara-Ettinger et al., 2016):

$$U(A,S) = R(S) - C(A) \qquad (1)$$

Our work is consistent with two distinct extensions to Equation 1. First, infants may assign an additional negative value that expresses the danger of an action, $D(A)$, without explicitly representing either the possible states (e.g. achieving the goal, or falling down the trench) that could result from this action or the probabilities that each state will occur:

$$U(A,S) = R(S) - C(A) - D(A) \quad (2)$$

Under this conception of danger, the act of jumping over deep trenches itself carries negative utility: like physical exertion, danger is a bad feature of an action, so a reward must be greater to justify both efforts and dangers.

Alternatively, a richer interpretation of our findings is possible. Infants may represent the set of possible future states, S, that could result from an action, A, each occurring with probability $P(S_i|A)$, and each associated with a separate reward, $R(S_i)$. Reaching a goal state carries positive utility, while transitioning to a state of injury carries negative utility.

$$U(A,S) = \sum_{S_i \in S} P(S_i|A)R(S_i) - C(A) \quad (3)$$

This notion takes account both of possible (observed and unobserved) states that could result from an action and of the likelihood of transitioning to each state. Conceiving of peril in this way requires more than perceiving the actions that occurred and the states they led to: one must also posit states of the world that did not occur but *could have* resulted from a given action. The nature and development of this potentially counterfactual aspect of action understanding merits further study.

These findings also leave open the basis for infants' representation of peril (as counterfactually possible degrees of injury or as degrees of fear), and the development of this understanding (from their own motor experience, or from social feedback; (Adolph, 2000; Sorce, Emde, & Campos, 1985). Future studies of infants' emotional representations, action capacities, and social learning could shed light on these questions.

Conclusion

The present findings provide evidence that early understanding of other people's actions extends beyond physical costs and rewards. At 13 months, infants expect others to maximize the utility of their actions in an integrated calculus where peril trades off systematically against reward, much as does physical cost (Liu et al., 2017). With this calculus, such infants treat uniformly successful and perceptually and physically identical actions as distinct, when the context suggests that one action is more perilous than another. These findings suggest that 13-month-old infants represent forward planning models describing how other agents choose actions on the basis of their utilities (defined over reward, peril, and effort), and they invert these models to reason about the causes of the actions they observe. For 13-month-old infants, the abstract variable “danger” would be one of these causes for agents who plan and act under peril.

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Author Contributions

SL carried out the experiments and analyzed the data. All authors helped to design the research and write the paper.

Open Practices Statement

All experiments reported in this paper were formally pre-registered. All stimuli, data, code, and pre-registrations of this paper are open access at https://osf.io/kz7br/. The Results sections of this paper were written using RMarkdown (Xie, Allaire, & Grolemund, 2018) to enhance reproducibility and transparency.

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