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# Infants anticipate probabilistic but not deterministic outcomes

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ABSTRACT

Infants look at physically impossible events longer than at physically possible events, and at improbable events longer than at probable events. Such behaviors are generally interpreted as showing that infants have expectations about future events and are surprised to see them violated. It is unknown, however, whether and under what conditions infants form proactive expectations about the future, as opposed to realizing *post hoc* that outcomes do not comply with their previous knowledge or experience.

Here we investigate the relation between expectation and surprise at probabilistic or deterministic events in preverbal infants. When a situation is uncertain, 12-month-olds anticipate probable outcomes and are surprised at improbable continuations of the scene. However, they do not anticipate the only possible outcome of a physically deterministic situation, although they are surprised when it does not occur. The results suggest that infants are sensitive to the tradeoff between information gain and programming efforts, showing higher propensity to anticipate those future events that carry novel knowledge.



## 1. Introduction

> *What do we mean when we say, in ordinary language, that an event is more or less probable? We mean that we would be more or less surprised to learn that it has not happened.*
> [*Bruno de Finetti, Probabilism (1989/1931, p. 174).*]

Our life is a constant bet about the future. Whether it is for estimating the next position of a moving object, deciding our next immediate action, or assessing our best option for achieving a long-term goal, we are obliged to make scores of predictions about what will happen next. Our expectations are often informed by our experience of the past, that is, by the statistical properties of events that have already occurred. Yet when our experience of the past is poor or unreliable, or simply when we do not care to collect it, we rely on a particularly important source of inferences employing a system capable of estimating the probability of a future state of affairs, independently of any experience we may have of its past occurrence.

Recent evidence suggests that infants are surprised when they witness single-case improbable events (Téglás, Girotto, Gonzalez, & Bonatti, 2007; Téglás, Ibanez-Lillo, Costa, & Bonatti, 2014; Téglás et al., 2011). Thus, in the words of de Finetti (1989/1931), infants know what it means that "an event is more or less likely". Téglás et al. (2007) suggested that infants possess an intuitive sense of probability that guides their expectations in situations of uncertainty, even when past experience that may be informative for such expectations is missing. A growing amount of converging evidence documents preverbal infants' ability to form probabilistic expectations in a variety of situations. For example, infants understand the statistical relation between a population and a sample (Denison, Reed, & Xu, 2013; Denison & Xu, 2010a; Xu & Garcia, 2008). They can attribute preferences on the basis of sampling information (Kushnir, Xu, & Wellman, 2010; Ma & Xu, 2011). They also modulate their probabilistic expectations in sophisticated ways, flexibly integrating physical and numerical information to improve the accuracy of their expectations (Denison & Xu, 2010b; Lawson & Rakison, 2013; Téglás, Ibanez-Lillo, Costa, & Bonatti, 2014; Téglás et al., 2011).

It is unclear, however, how infants *put to use* their intuitive sense of probability. The methodological rock on which our knowledge about infant cognition is built is the violation of expectations method, arguably the most used looking time based paradigm in infant research (examples abound from studies of naïve physics to social cognition). Unfortunately such a method is structurally unfit to clarify this question. Its logic is to compare looking time at a 'surprising' event relative to an 'unsurprising' one. This comparison, however, can only be made after the fact. Importantly, surprise at an improbable outcome that has already occurred is a very

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different cognitive state than active anticipation of a probable future outcome.[1] Surprise is *post hoc*; anticipation is pro-active. Surprise may induce one to call into question previous ideas, striving to make sense of how the present can be compatible with the past (Stahl & Feigenson, 2015). By contrast, anticipation prepares us for the future. A method based on surprise is not suited to reveal whether infants really *anticipate* anything before experiencing the outcome of an event (see Kochukhova & Gredebäck, 2007 for a similar point). As such, the violation of expectations method opens only a very narrow window onto the dynamics of expectations in infants. Indeed, infants may show surprise without ever anticipating anything.

Eye movements collected before the onset of a certain stimulus may provide us with a better tool to reveal strategies of anticipation. Anticipatory eye movements in infants have been documented in a variety of domains, particularly in reasoning about physical events and intentional actions. Thus, infants can anticipate the position of a moving object (e.g., Gredebäck & von Hofsten, 2004; Johnson, Amso, & Slemmer, 2003; Johnson et al., 2003; McMurray & Aslin, 2004; Rosander & von Hofsten, 2004), or the end state of a motor action (Ambrosini et al., 2013; Falck-Ytter, Gredebäck, & von Hofsten, 2006; Kanakogi & Itakura, 2011; Rosander & von Hofsten, 2011). However, even when anticipation is tested in more general domains, like acquisition of spatial regularities (e.g., Canfield & Haith, 1991; Wentworth & Haith, 1998), associations between spatial patterns and visual or auditive categories (McMurray & Aslin, 2004; Albareda-Castellot, Pons, & Sebastián-Gallés, 2011) or rule switching (Kovács & Mehler, 2009), most studies expose infants to repetitive trials, thus injecting a strong component of learning into the establishment of an anticipatory behavior.

In some cases, however, anticipation for physical events can occur in the presence of minimal direct experience. Six-month-olds can anticipate the position of an object moving on a linear (but variable) trajectory even if it passes behind an occluder, and in a few trials they can even learn to anticipate a non-linear, but fixed trajectory (Kochukhova & Gredebäck, 2007). However, this occurs when the outcomes to be predicted are the endpoints of simple physical events – like a ball rolling behind an occluder - or can be guessed on the basis of recent experiences with similar outcomes. Self-propelled agents, in contrast to inert physical objects, are not constrained to move on predefined paths. Infants seem to assume that an intentional agent will realize a goal-directed action by choosing the most efficient trajectory (Gergely & Csibra, 2003), and anticipate the endpoint of intentional actions on the bases of this principle (Biro, 2013). Thus, anticipation with little or no previous familiarization can also occur in the perception of intentional actions. However, even in these cases a familiar action (e.g. a hand grasping a goal-object expressing a preference, Cannon & Woodward, 2012) and goal-directed motion trajectories of novel, self-propelled agents (e.g. an animated fish repeatedly approaching his favorite choice alternative, Daum, Attig, Gunawan, Prinz, & Gredebäck, 2012) work differently. Only a familiar action, but not any goal-directed behavior, triggers spontaneous anticipation towards the location of the goal.

In sum, only little is known about infants' spontaneous strategies of anticipation. Overall, most experimental protocols employed to study anticipation are not suited to reveal spontaneous anticipations in the absence of relevant prior information about the possible continuations of the event sequences, unless very specific conditions (e.g., exposure to repeated scenarios or to familiar actions) are met. In infant research, anticipatory eye movements have been studied in a variety of specific domains, ranging from naïve physics to social cognition (see Fawcett & Liszkowski, 2012 for anticipation elicited by social preference, or anticipation of actions based on false belief in Senju, Southgate, Snape, Leonard, & Csibra, 2011; Southgate, Senju, & Csibra, 2007; Surian & Geraci, 2012). Here we ask the broader question of whether infants can anticipate the outcomes of future unknown states in general, when they see situations that contain probabilistic or deterministic information. Such information may modify the degree of certainty that infants entertain about the final outcomes of the events they are witnessing and influence their anticipatory behaviors. To study this issue, we devised a task associating a measure of anticipation with a traditional measure of surprise, adapting a reaction-times paradigm that Téglás et al. (2007) introduced to test preschoolers' anticipations of probable events. In this experiment children were presented with a series of movies in which a ball bounced inside a rectangular frame with one single exit point on one vertical wall and three exit points on the opposite wall. After some time, an occluder covered the container completely while the ball was still bouncing. Then, the ball exited from one of the openings while the occluder covered its trajectory inside the frame. Thus, the ball could exit either from the right or from the left side, but the probabilities of exiting from either side were different. Participants were asked to press a button as quickly as possible when they detected the ball's exit. If participants were sensitive to differences in probabilities, then they could predict the side where the exit was more likely, although they could not know *when* the ball would exit. Both three and five-year-old children were faster when the ball came out from the side with the three exit points than when it appeared from the side with a single exit point. This suggests that children prepared their motor responses by considering the possible outcomes (1 vs. 3) and their probabilities, and used this information to reduce the temporal and spatial uncertainty of the outcome.

In the current work, we adapted this paradigm to 12-month-old infants. We monitored two variables. Firstly, we recorded infants' eye movements during occlusion as a measure of online anticipatory behavior. Secondly, after the object exited the frame and the occluder was removed, we monitored post-occlusion looking time, as in a standard violation-of-expectations paradigm (Fig. 1). If infants anticipate the occurrence of a future single outcome before experiencing it, they should tend to move their eyes towards the side where the ball is more likely to exit (even if they cannot know when it will in fact exit) as they prepare for the expected outcome before it occurs. Because during occlusion infants can see only the occluder (that is, they fixate a completely neutral rectangle), any predictive behavior could depend only on their memory of the situation and of their intuitions about the likely side from which the ball would exit. Furthermore, after the occlusion ends and the infants see the outcome, a violation of their probabilistic intuitions (that is, an exit from the less probable side) should induce longer looking time at the improbable event, following the logic of the violation of expectation paradigm. This pattern of results would indicate that intuitions of probability influence both the anticipation of a future event and the *post hoc* reaction at an outcome discordant to their sense of probability. However, the two factors (anticipation and surprise) can be independent (Daum et al.,

[1] We do not mean to suggest that the term "surprise" indicates an emotional reaction. Instead, it is an umbrella term to describe a specific attentive state and engagement caused by events that are in conflict with infants' representation of a scene. In the Violation of Expectation paradigm, it is customary to use longer looking and "surprise" as equivalent expressions, although other, less studied, physiological measures may also indicate 'surprise' (e.g. pupil dilation; Jackson & Sirois, 2009). Traditionally violation of expectation paradigms were constructed in accordance with three assumptions: infants (i) form expectations about the end states of the events they witness, (ii) detect the violation of events incongruent with these expectations, and (iii) react with "surprise" to the unexpected continuations (see Wang, Baillargeon, & Brueckner, 2004 for discussion). Here, we abide to the accepted use without any further commitment. However, we suggest that infants may express "surprise" even in absence of a priori expectations.

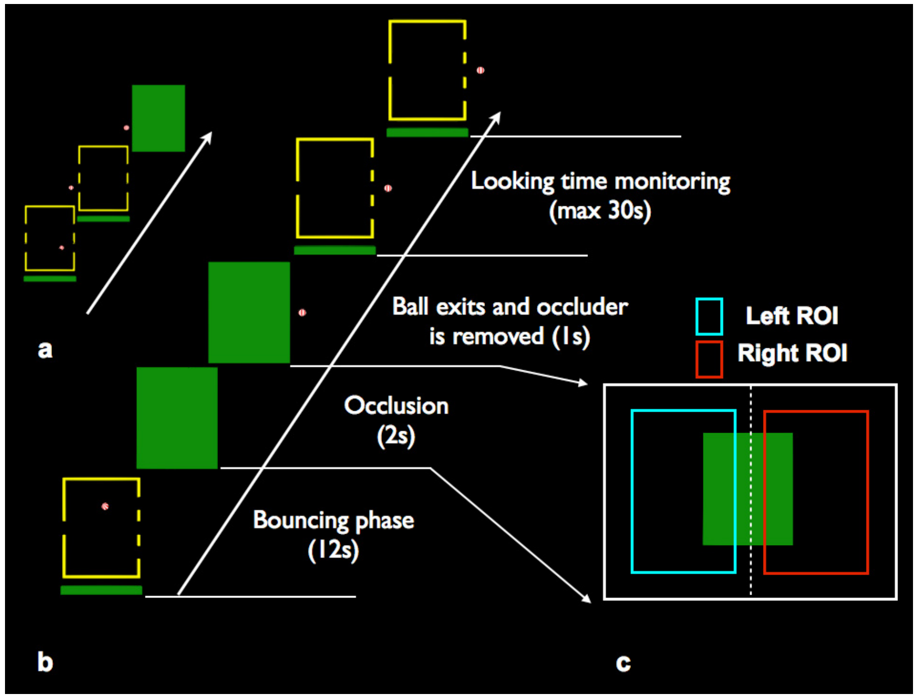


**Fig. 1.** Structure of the experiments. (a) Familiarization trials: After bouncing, the ball, completely visible to infants, exits the frame and the occluder covers it. (b) Experimental trials: The occluder covers the frame prior to the ball's exit. Thus, infants' reactions can only depend on their memory representation of the scene behind the occluder. During occlusion, gaze displacements are monitored to probe anticipations for an exit to the right or left sides of the frame. After the ball exits, the frame is revealed again. The last static image with the occluder lowered remains visible until a timeout is detected. Gazes during occlusion are anticipatory if they are located in the regions of interest indicated in (c).

2012). If so, other patterns of results are possible. In particular, lack of anticipation but surprise at the outcome would indicate that infants reason about outcomes only after having experienced them. Experiment 1 was designed to test these different predictions.

## 2. Experiment 1

### 2.1. Methods

#### 2.1.1. Participants

Twenty-four full-term 12-month-old infants were retained for analysis (11 females, mean age = 12 m 18d, range 12 m 3d-13 m). Another 19 infants were excluded (15 fussed out, 1 had more than 2 cumulative timeouts, 2 turned away in synchrony with the ball's exit, and 1 was sleepy). This rejection rate is comparable to that obtained in our previous work with analog methodology (Téglás et al., 2007, 2011) and not unusual in infant experiments (Slaughter & Suddendorf, 2007).

#### 2.1.2. Stimuli and apparatus

We generated 25 fps QuickTime movies with Maya 6.0. The movies presented a ball moving at constant velocity (9 deg/s) inside a rectangular frame ($11 \times 14$ cm). In the familiarization movies, the frame had two exits on its vertical sides (1.8 cm, approximately 1.2 deg of visual angle). After 12 s of bouncing, the ball exited from one of the openings, an occluder covered the container for 2 s, and the movie ended (Video S1). In all movies, the center of the occluder corresponded to the center of the computer screen that presented the stimuli at $1280 \times 1024$ pixels resolution. The test movies differed from the familiarization movies in two respects (Fig. 2A). First, the frame had three exits on one vertical side and one on the opposite side. Second, the occlusion preceded the ball's exit, so that infants could not anticipate side or location of the exit on the basis of visual cues. The ball always exited the frame from its right side, which had three exits in half of the trials (probable outcomes; Video S2), and one in the other half (improbable outcomes; Video S3). In designing the stimuli, we could have either counterbalanced the positions of the exit points in the frame and kept the direction of the ball's exit constant, or else varied the exit side and kept the frame structure constant. We opted for the former solution for several reasons. Notably, by flipping the position of the exits across trials, while maintaining the direction of the exit constant, infants could better focus their attention to the exits. Indeed, pilot data showed that for infants this design was less confusing than its alternative.

The number and distribution of the ball's bounces and the direction of its last visible trajectory were controlled. Contacts with the left and right vertical sides were equalized (i.e. 4 contacts each/trial), and the last visible trajectory was parallel to the vertical axis at the center of the frame (which also corresponded to the center of the computer screen). Because the ball bounced on the side walls equally often, bounces alone could not be used to predict the ball's exit side. Sounds accompanied the contacts of the ball with the frame and continued during occlusion, to signal that the ball continued moving.

The stimuli (presented on a 17-inch screen) were controlled by PsyScope X (http://psy.cns.sissa.it; Cohen, MacWhinney, Flatt, & Provost, 1993) on an Apple DualG5. Eye movements were recorded with a Tobii 1750 Eye Tracker (Stockholm, Sweden). After a five-point calibration protocol was successfully completed, Psyscope X sent event log information to the gaze data file (recorded on a separate computer by the Clearview 2.5.1 software package at 50 Hz), marking the onset of the relevant movie sequences in each trial for further analyses.

#### 2.1.3. Procedure

Infants sat on their caretakers' laps, approximately 60 cm from the screen. Before the experiment, caretakers were instructed not to interact with the infant. They were also asked to reorient the

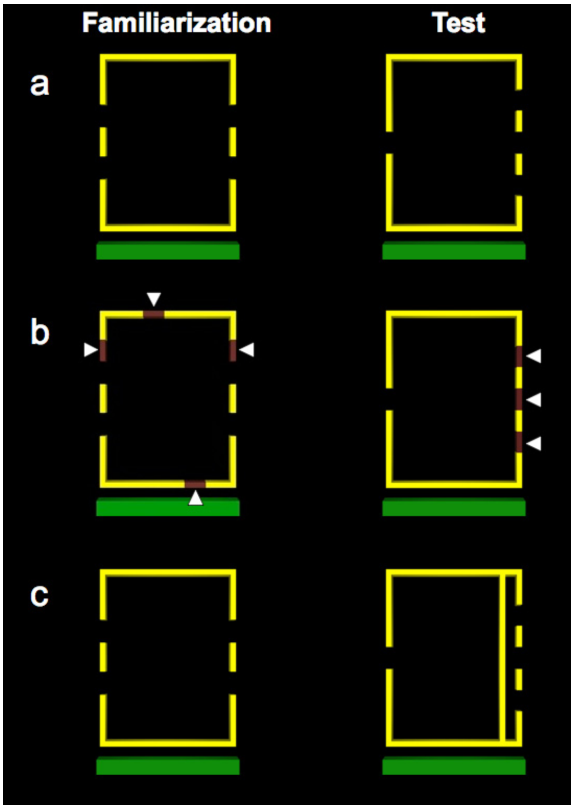


**Fig. 2.** Schematic representation of the stimuli in the experiments. (a) Familiarization and test stimuli in Experiment 1. The familiarization frame has an even number of exits on its sides. The test frame has three exits on one side and one exit on the opposite side. (b) Experiment 2: The familiarization frame has as many exits as the frame in Experiment 1, with color segments placed on the frame not occluding the exits. In the test frame, the segments close the exits of the 3-exit side, so as to convey the perception of a solid barrier. For easiness, arrows indicate the placement of the segments. (c) Experiment 3. The familiarization frame is as in Experiment 1. In the test frame, a solid barrier blocks the ball to ever reach the proximity of the three exits, so as to make even more evident that the ball cannot exit from the 3-exit side.

infant towards the screen if s/he turned his/her full body from the initial position (facing the screen) for more than 5 s. This procedure ensured that during a trial infants could freely explore the stimuli and turn their heads or bodies away from the screen when they were not interested, but at the same time allowed the experimenter to continue collecting data in successive trials. It also ensured that caretakers' interventions did not interfere with the detection of trial timeouts, thus diminishing undesired influences over the quality of the data collection. The caretakers wore opaque sunglasses during the entire experiment. The experimenter, who was blind to the experimental conditions, monitored infants via an infrared camera, which also recorded the session for further coding offline. To ensure that infants saw every movie entirely, the presentation of the stimuli was infant-controlled. Movies paused when infants were looking away, and continued playing when they reoriented towards the screen.

Infants saw four familiarization and four test movies. Half of the infants saw a probable outcome first (with the three-exit side to the right), and the other half saw an improbable outcome first (with the three-exit side to the left). After the exit of the ball, the occluder was lowered so that the frame would be entirely visible, in this way, the lack of visual access to the frame structure was kept at a minimum, thus reducing unnecessary memory load. Test trials ended if infants looked away for more than 2 consecutive s, or looked for more than 30 cumulative s.

#### 2.1.4. Results and discussion

To assess anticipatory behavior, we measured mean shifts in eye $x$ gaze coordinates during the 2 s occlusion. By design, the reference point was the center of the occluder, where the last visible motion of the ball occurred. Generally, an eye movement is considered anticipatory if changes in fixation coordinates take place before the onset of an otherwise predictable event sequence. In these cases, the eye is traversing between two locations in the form of discrete, ballistic saccades. Our pilot measures, however, indicated that during the time of the occlusion these kinds of fixations - targeting areas in the vicinity of the occluder - are rare. As an alternative to these measures, in our analysis a gaze shift was considered anticipatory if, by moving away from the center of the occluder (where the last motion trajectory of the object was seen), it was directed towards the probable side (e.g. to the right when the three-exit side was to the right). We divided the occlusion period in 200 ms time bins, starting from its beginning and ending with the 200 ms post-occlusion period, so as to compensate the time range of reactive saccades at 12 months, which is longer than 200 ms (Canfield, Smith, Brezsnyak, & Snow, 1997; Reznick, Chawarska, & Betts, 2000).

We were interested in infants' first, intuitive reactions, unaffected by potential learning effects across trials (which can occur very quickly; Kochukhova & Gredebäck, 2007). From this perspective, ideally, those anticipations that occur in the first test trial, after minimal familiarization with the outcomes of the relevant test events, are the most informative data. This is the kind of evidence that would reveal whether infants form predictive expectations about scenes they have never experienced before. Accordingly, we restricted our analysis of anticipation to the first test trial.

Considering that when the potential anticipation period ended the ball exited always towards the right side, and that for half of the infants (11) the rights side had 3 exits whereas for the other half (12) it had 1 exit, the first anticipation analyses amounted to a between-participant comparison. To prepare the data for analysis, we discarded eye coordinates recorded in the immediate vicinity of the edges of the computer screen (100 pixels). We also removed gazes exceeding 3 SDs of the mean gaze shifts on the $x$ coordinate axis, computed for each experimental condition. According to these criteria, 23 participants provided data and 21.1% of the data points were removed.

We ran a mixed ANOVA with probable exit side (three-exit side on the left/on the right) as the between-participant factor, time bins (1–11) as the within-participant factor, and eye $x$ coordinates in pixels, setting 0 to the center of the occluder, as the dependent variable. There was a main effect of exit side ($F(1, 182) = 4.853$, $P = 0.039$; Fig. 3B). During occlusion, infants moved their eyes towards the left if the three-exit side was to the left ($M_{3\text{-exit-left}} = -48.1$ px), and to the right if it was to the right ($M_{3\text{-exit-right}} = 51.9$ px), although the container was not visible to them. No other factor or interaction was significant.

An analysis of infants' looking behavior during occlusion confirmed the result. We split the frame into three equal areas. We established two regions of interest (hereafter ROI) by excluding the middle area from analysis (Fig. 1C). We then checked the total time spent inside these two ROIs that consisted of the left/right side of the occluder and its surroundings. Of the 23 participants who gave eye gaze data, eight did not disengage from the center, where the last motion trajectory occurred, whereas 15 participants looked inside the relevant ROIs. A restricted ANOVA for these participants, with total anticipation time as a dependent variable and exit number on each ROI (3-exit/1-exit) showed that, during occlusion, infants gazed longer at the ROI where the probable future event would occur ($M_{3\text{-exit}} = 818.6$ ms, $M_{1\text{-exit}} = 216$ ms; $F(1,14) = 6.15$, $P = 0.026$, $\eta^2 = 0.3$, $P_{rep} = 0.91$). Most participants that

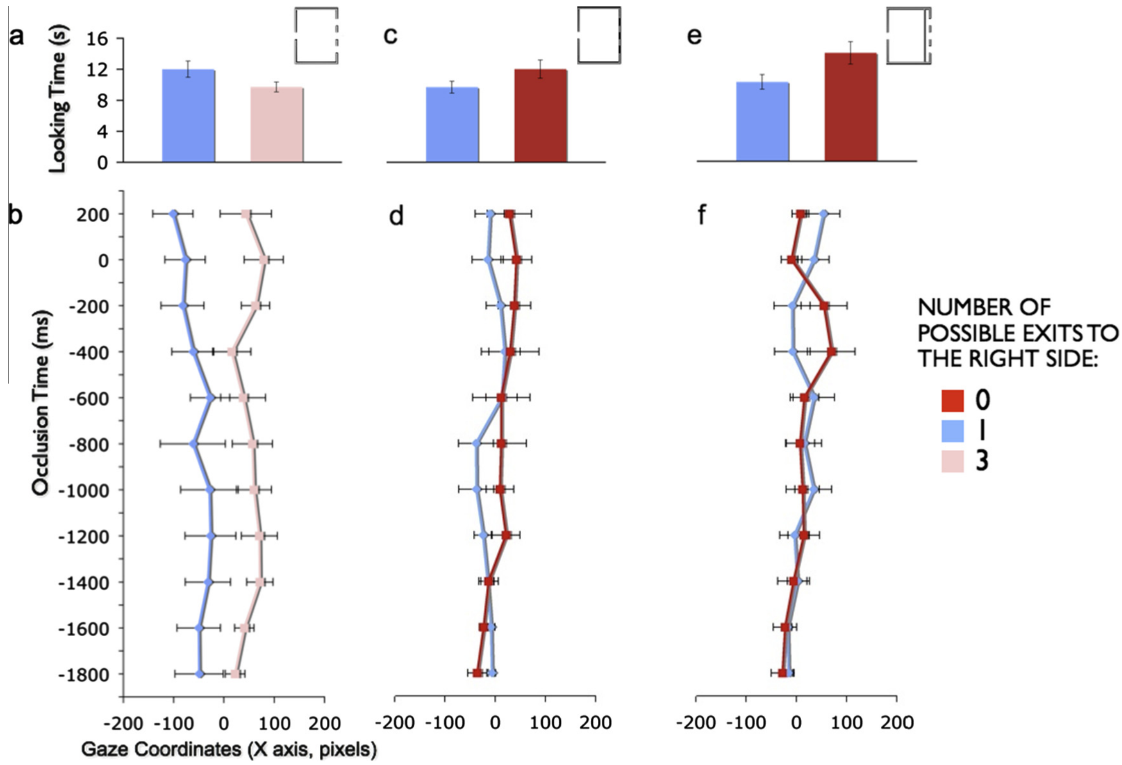


**Fig. 3.** Anticipation and surprise in the three Experiments. Panels a, c and e report cumulative looking time and (s.e.m.) after the outcome, for the three experiments, averaged across the experimental trials. After occlusion, in Experiment 1, infants looked longer at the 1-exit (improbable) than at the 3-exit (probable) outcome (a). However, they looked longer at the 3-patches outcome in Experiment 2 (c), despite the fact that the display was very similar to the 3-exit display, when the ball's exit was made physically impossible (0-exits). They also looked longer at the physical impossible exit in Experiment 3 when the display was made perceptually more complex, but the exit of the ball was made even more clearly impossible (e). Thus, after the end of the event, infants clearly reacted to the nature of the outcomes (either probable/improbable or possible/impossible), and not to surface indexes of stimulus complexity. Panels b, d and f report mean eye gaze displacement during the occlusion in the first test trial of each experiment. In this trial, any possible anticipation could only be spontaneous. Occlusion time was split in 200 ms time bins from its beginning to 200 ms after its end. Horizontal axis represents gaze coordinates on the X axis (pixels), 0 marking to the center of the occluder corresponding also to the center of the screen. Accordingly, plotted data are mean eye gaze horizontal position in pixels (s.e.m.), at each time bin. In each experiment half of the infants saw the probable/possible side on the right another half on the left side of the frame. When the outcome was uncertain in Experiment 1, infants tended to shift their gaze away from the center towards the 3-exit side (b), but there was no anticipation when the outcome was certain, in either Experiment 2 (d) or 3 (f).

contributed to this analysis looked only to one ROI (11). Thus, any higher-level strategies characterized by gaze shifts between sides can be excluded.

We now turn to *post hoc* violation of expectations, analyzing infants' looking time after the end of the occlusion. To stabilize the data, we averaged the experimental trials across the two conditions, after excluding data beyond 2.5 SDs from the mean looking time of each condition (2%). An ANOVA with number of exits at the ball's exit side as a within-participant factor (1 exit/3 exits), participants as random factor and post-occlusion mean looking time as the dependent variable showed that infants looked longer at the ball when it appeared from the 1-exit side than the 3-exit side ($M_{1\text{-exit}} = 12$ s, $M_{3\text{-exit}} = 9.71$ s, $F(1,23) = 9.17$, $P = 0.006$, $\eta^2 = 0.28$, $P_{rep} = 0.96$; Fig. 3A). Eighteen out of the 24 participants looked longer at the 1-exit side ($p \leqslant 0.01$, cumulative binomial test).

Finally, we checked the stability of this looking time patter over the experiment. For this analysis we divided the test phase into two blocks, separating looking times in the first two trials and looking times in the last two trials. For each block we subtracted the looking time elicited by the 3-exit-outcome from those measured after 1-exit outcomes. By comparing the two scores, we could see whether the contrast between conditions changed from block 1 to block 2. Twenty-two infants provided data in each trial for this analysis. There was no difference between blocks ($F(1,21) = 0.405$, $p = 0.53$), suggesting that in this paradigm infants' expectations do not change across the experiment.

Together, these results suggest that not only were infants *surprised* at improbable outcomes, but also that they *anticipated* the occurrence of a probable future event, even without any previous experience with them. This is the first demonstration that, in situations of uncertainty, infants construct a forward representation of possible future outcomes, preparing themselves for the occurrence of the most likely scenario. The results also generalize the findings of Téglás et al.'s (2007) with 12-month-olds to novel experimental paradigms and entirely different situations, showing that 12-month-olds represent the probabilities of single events in a broad range of situations.

How crucial was the probabilistic structure of the events in inducing anticipatory behaviors? To investigate this question, in Experiment 2 we created movies in which the nature of the outcome became deterministic. We 'closed' the exits on the three-exit side by covering the exit points with patches that behaved like solid closed gates. Thus, the ball could only leave the frame through a single exit that remained open in the 1-exit side. In this way, what was probable in Experiment 1 become impossible in Experiment 2, and what was improbable in Experiment 1 became the only possible outcome in Experiment 2. We took care to modify the movies in such a way that the new scenes were perceptually as similar as possible to those of Experiment 1. In this way, we also controlled other potentially low-level confounding factors. Indeed, because the frame of the container in Experiment 1 was asymmetric, infants could have potentially anticipated the outcome during the occlusion because they had better retained the perceptually richer side, regardless of the probabilities of the outcomes. In Experiment 2, the perceptually richer side remained the three-patches side, but the ball could no longer exit from it (0-exit in Fig. 2B). If the results of Experiment 1 were due to the perceptual differences between the two sides, we should find anticipation towards the more segmented, perceptually richer side also in Experiment 2. If, instead, it was the probabilistic nature of the outcome that influenced infants' anticipatory behavior, then anticipation may be different, or absent, in Experiment 2.

## 3. Experiment 2

### 3.1. Methods

#### 3.1.1. Participants

Twenty-tree full-term 12-month-olds were retained for analysis (12 females, mean age = 12 m 18d; range 12 m 4d-13 m 5d). Another 20 infants were excluded (10 fussed out, 3 turned away in synchrony with the ball's exit, 6 had more than two cumulative timeouts and 1 for caretaker interaction).

#### 3.1.2. Stimuli, apparatus and procedure

We created new test movies in which dark, wooden-like segments filled the exits of the three-exit side, so as to make it perceptually very similar to that of Experiment 1, but conveying the impression of a continuous solid bar (Fig. 2B). During the movement, the ball would bounce over the segments, reinforcing the impression of solidity (Video S4). Thus, in the experimental scenes the probable future outcomes of Experiment 1 were transformed into perceptually very similar, but impossible future outcomes. In half of the trials, after the occlusion infants found the ball outside the three-patch side (now being without any exit point, thus presenting an impossible outcome). For uniformity, we also added segments to the familiarization movies, although they did not obstruct the exits, so that the familiarization scenes were as in Experiment 1 but infants would be familiar with the presence of the segments. In the familiarization movies, two of the segments were close to the exits and two were placed at random locations. In this way, the segments could not be a cue to the exit locations. The procedure was otherwise identical to Experiment 1.

### 3.2. Results and discussion

Data selection and analysis were as in Experiment 1. For eye gazes, 16 participants provided valid data in the first test trial (7 infants contributed to the 1-exit and 9 to the 0-exits trials), and 22.9% of the data was excluded. When we analyzed anticipatory behavior during the occlusion, an ANOVA with the side of the correct prediction as between subject factors (1-exit/0-exits with 3 patches), and the time (1–11 time bins) as within subject factors revealed no effect ($F(1,124) = 0.77$, $P = 0.34$; Fig. 3D). Infants' gaze did not shift towards the 1-exit side ($M_{1\text{-exit}} = 10$ px and $M_{0\text{-exits}} = -20$ px), where the only possible future outcome could occur.

Turning to the ROI analysis of the first trial, 8 out of 16 participants moved their eyes towards the ROIs; of those, only 4 showed anticipatory behavior (ns). An ANOVA with total anticipation time spent in the ROI as a dependent variable and the possibility for the ball to exit from the side of the ROI (1-exit/0-exits) showed no significant differences ($M_{1\text{-exit}} = 340$ ms, $M_{0\text{-exits}} = 177.5$ ms; $F(1,7) = 0.75$, $P = 0.414$. Considering the direction of the effect and the very low number of infants who even looked at the ROIs during the anticipation period, it seems unlikely that the absence of an effect of anticipation towards the possible exit side is due to the small sample size.

We then analyzed infants' *post hoc* violation of expectations. Applying the same criteria as in Experiment 1, 8.3% of the total data points were excluded. An ANOVA with the side of the correct exit as a within-participant factor (1-exit/0-exits with 3 patches), and post-occlusion mean looking time as the dependent variable showed that infants looked longer at the ball when it exited the now-impossible side ($M_{0\text{-exits}} = 14$ s, $M_{1\text{-exit}} = 10.2$ s; $F(1,22) = 5.28$, $P = 0.032$, $\eta^2 = 0.19$, $P_{rep} = 0.9$; Fig. 3C). Sixteen participants looked longer at the impossible outcome, with 0 exits and 3 patches (cumulative binomial 0.04).

In both Experiments 1 and 2 one side of the frame is perceptually more complex than another side. Potentially, infants could react to the complexity of certain outcome configurations, and not to the nature of the outcome. Because Experiment 2 was perceptually similar to Experiment 1, we could also check the role of stimulus complexity in shaping infants' expectations. We marked as "simple" visual patterns formed by outcomes from the sides with one exit and labeled as "complex" outcomes from the side with three exits in Experiment 1 and the side with the color patches in Experiment 2. The analysis showed no main effect of Experiment nor of exit complexity, but the two factors interacted, ($F(1,46) = 9.52$, $P < 0.01$), demonstrating that complexity was not a factor *per se*, but the nature of the outcome was. Although the complexity of the outcomes was reversed, infants looked longer at the Improbable outcome of Experiment 1 (1 exit, perceptually simple) and at the Impossible outcome in Experiment 2 (3 patches, perceptually complex, but 0 exits). These results show that infants' reactions to the stimuli in Experiment 1 were not driven by the low-level perceptual differences between the two exit sides of the ball.

In sum, in line with the previous studies using the violation of expectation paradigm, infants were surprised at the impossible events. However, they did not bother *anticipating* the only possible outcome, even if in Experiment 1, when the expected outcome was a probable event, they did. This dissociation between surprise and anticipation is remarkable. It shows that expectations do not always translate into anticipations. A possible scenario for this result is that when infants experience a violation of basic physical principles, surprise at an impossible outcome is not the result of the violation of a positive anticipation of the possible outcome, but somehow a *post hoc* reaction at the experience of an impossible event.[2]

Infants' reactions to our stimuli largely depend on their ability to process dynamic events online. The advantage of the design of Experiment 2 is that the display was very similar, perceptually, to that of Experiment 1. However, to establish anticipation this could also be a disadvantage: perhaps when infants looked at the dynamic scene in which the ball bounced inside the occluder, the evidence for the solidity of the patched side was too weak for them to establish a clear enough representation, sufficient to program anticipations towards the exit side. That is, maybe, the physical constraints we implemented in Experiment 2 were too subtle to be integrated online. Indeed, by analyzing the stability of the looking-time pattern at the outcomes across the experiment, we found that looking time differences between conditions increased in the second block, compared to the first block ($F(1,17) = 8.53$, $p < 0.01$). Although we do not want to over-interpret this result, because only 18 infants provided data in all the 4 trials and so such a difference may depend on changes in the analyzed sample, it may suggests that infants may better grasp the nature of the outcomes as they collect more experience with the stimuli. Hence, perhaps

[2] Here, we have to emphasize, however, that looking-time analysis in itself is insufficient to disentangle whether positive expectations for a certain event are formed a priori or whether the longer looking time normally found after unexpected events is due to a *post hoc* understanding of the scene. While we agree that there are many factors that may influence anticipations, we did not plan to develop an exhaustive taxonomy regarding the relation between expectations (as expressed in longer looking time if they are violated) and anticipatory eye movements.

infants did not spontaneously anticipate the only possible outcome in the first test trial because they did not fully grasp the constraints that made certain scenarios inadmissible. To exclude this possibility, in Experiment 3 we created stimuli that made the fact that the ball could not exit from the three-exit side even more salient.

## 4. Experiment 3

### 4.1. Methods

#### 4.1.1. Participants

Twenty-four full-term 12-month-olds were retained for analysis (16 females, mean age = 12 m16d, range 12 m 3d-13 m 1d). Another 18 infants were tested but not retained (11 fussed out, 3 turned away when the ball exited, 3 had more than two cumulative timeouts and 1 because of caretaker intervention).

#### 4.1.2. Stimuli, apparatus and procedure

We created new test movies in which a solid bar was interposed between the ball and the exits, so that access to the three-exit-side was completely blocked (Fig. 2C). The ball repeatedly hit the interposed barrier, never reaching the space close to the exits, so that the only accessible exit point was clearly on the one-exit side (Video S5). In half of the trials, the ball exited from that side having the only possible exit, while in the other half it exited from the side with the interposed barrier, thus producing a physically impossible outcome. Because already 3-month-olds can understand that one solid object cannot pass through another solid object (Spelke, Breinlinger, Macomber, & Jacobson, 1992), infants attending to these scenes should easily realize that the ball could not pass through the solid barrier. The procedure was otherwise identical to Experiment 1.

### 4.2. Results and discussion

Data selection and analysis were as in Experiment 1. No looking time data needed to be discarded. Twenty-two participants provided valid gaze data in the first test trial and 18.9% of the data was excluded according to our criteria. Analyzing post-occlusion surprise, as in Experiment 2, we found that infants looked longer at the impossible outcome ($M_{0\text{-exit}} = 12$ s, $M_{1\text{-exit}} = 9.7$ s, $F(1,23) = 5.15$, $P = 0.032$, $\eta^2 = 0.18$, $P_{rep} = 0.9$; Fig. 3E). Sixteen participants looked longer at it (cumulative binomial 0.07, ns.). This looking time pattern proved to be stable over the entire test phase, because the comparison of the difference scores in the two blocks of the test phase did not reveal any change ($F(1,23) = 0.721$, $P = 0.4$). Thus, infants quickly understood that the added physical constraint was making the exit of the ball from the side with the solid bar physically impossible. Common analyses of Experiments 1 and 3 further confirmed this conclusion. A mixed ANOVA with Experiment as the between-subject factor, Exit complexity (Simple/Complex) as the within-subject factor, and participant nested in the experiments as the random factor revealed no main effect, but an interaction between the two factors ($F(1,46) = 13.13$, $P < 0.001$), again, showing that infant reacted to the nature of the outcome, and not to the perceptual properties of the display *per se*.

As in Experiment 2, however, anticipatory behavior was absent. An ANOVA with the side of the correct prediction as the between-participant factor (1 exit/0 exits), the time bins (1–11) as the within-subject factors and participants nested within the between-participant factor revealed no significant effect. Twelve infants contributed data to the 0-exits (impossible) condition and 10 to the 1-exit (possible) condition. During occlusion infants did not anticipate the only possible outcome $M_{0\text{-exit}} = 10.9$ px, $M_{1\text{-exit}} = 4$ px, $F(1,185) = 0.001$, $P = 0.93$; Fig. 3F), despite the presence of stronger cues indicating the only possible exit side. During occlusion, only 12 out of 21 infants looked inside the ROIs. Among them, 9 looked towards the only possible exit (cumulative binomial $P = 0.07$). Analyzing the total time spent in the ROIs during occlusion for the 12 participants who provided data, an ANOVA with total anticipation time spent in the ROI as a dependent variable and the nature of the outcome as independent variable (1 exit/0 exits) showed no significant differences ($M_{1\text{-exit}} = 231.6$ ms, $M_{0\text{-exit}} = 305$ ms; $F(1,11) = 0.232$, $P = 0.63$). That is, infants are less prone to anticipate if the scene is deterministic and its outcomes in principle can be predicted with certainty. Only after the presentation of the stimuli did infants react to the nature of the outcomes, looking longer at the impossible outcome.

In Experiment 2, infants' ability to discriminate between conditions was expressed more gradually. In Experiment 3, infants quickly understood the impossible nature of certain outcomes. Regardless of how stable the surprise was across experiments, we found no anticipation in either experiment. This result controls for the fact that the lack of anticipation in Experiment 2 may have been due to an initial misperception of the nature of the stimuli and their affordances. Such results are also difficult to be explained on the basis of the complexity of the test stimuli. It could be thought that the sudden introduction of the vertical bar in the test phase of Experiment 3 may constitute an element of novelty and increase in complexity with respect to the familiarization movies that infants were disoriented, and for this reason they did not program any anticipation. However, infants reacted at the violations of solidity, showing no difficulty to establish which outcome was possible and which outcome was impossible. This should not be surprising. Already at 3 months infants seem to interpret physical scenes in accordance with the solidity principle, which is part of their core understanding of objects (Spelke et al., 1992). By the end of their first year, presumably they also have experienced obstacles and barriers of increasing complexity. Thus, it would be odd to attribute the lack of anticipation to some difficulty in understanding the constraints imposed by the test stimuli, considering how well entrenched the solidity principle is in infants' general concepts of the physical world.

In conclusion, we suggest that the main factor responsible for the lack of anticipation in Experiments 2 and 3, and the presence thereof in Experiment 1 - considering that in the three experiments infants reacted as expected after the outcome - has to be found in the different nature (probabilistic vs. deterministic) of the events they experienced, and possibly in the corresponding degrees of certainty about the outcomes.

## 5. General discussion

The current studies document three phenomena. First, infants can reason about single-case probabilities without previous experience with the outcomes of the scenes as early as 12 months of age. This result adds compelling further evidence to the finding that single-case probabilities are meaningful for young humans when they can represent and track possible outcomes (Cesana-Arlotti, Téglás, & Bonatti, 2012; Téglás et al., 2007, 2011, 2014). A well-known position in evolutionary psychology holds that humans can understand probabilities only as collections of experienced events (Cosmides & Tooby, 1996; Gigerenzer & Hoffrage, 1995). According to this perspective, our intuitions about the future are entirely dependent on our experience of the past. Instead, we showed that infants have no difficulty in reacting to single-case probabilities despite having no information about the past frequencies of the outcomes. Whether, during development, sensitivity to probability changes spontaneously or may be modified by the establishment of inappropriate heuristics, is a question that deserves further extensive investigation.

The second phenomenon we showed is that not only do infants react at single case probabilities *after the fact*, but they also spontaneously anticipate single future events, proactively preparing themselves for the occurrence of the probable scenarios. Thus, their sense of the probability of an event does not reduce to being "more or less surprised by finding out that such an event did not occur", as De Finetti wrote. More than that, it may also be a source of predictions guiding action planning for future events. Thus, it seems that, as early as infants can represent probabilities, they exploit the richness of this construct both to anticipate the possible continuation of a scene as well as to reason about experienced outcomes. This capacity may contribute to establishing their sense of uncertainty and confidence. Our study, however, did not focus on these latter aspects of probabilistic reasoning, which de Finetti considered as central. He treated probability as a construct that "is constituted by a degree of doubt, of uncertainty, of conviction, which our instinct makes us feel in thinking of a future event, or of an event whose outcome we don't know" (de Finetti, 1989/1931, p. 175). While we cannot establish how different levels of probabilities change infants' confidence level about their outcome, the tendency to disengage from the last seen trajectory of the moving object in Experiment 1 towards the probable, but yet unexperienced, exit location is a clear marker that infants are sensitive to the probabilistic information present in the scene. In most cases, previous studies found anticipation using experimental paradigms involving simple motion trajectories, or event sequences involving familiar social behavior. Although finding that infants develop online expectations after being exposed to sequences of experiences is a very important step for our understanding of early cognition, we showed that no specific experience is needed for anticipatory behaviors to arise, provided that the scenes contain possible alternatives. Infants spontaneously anticipate the probable future on the basis of their current analysis of an uncertain situation. Interestingly, recent electrophysiological studies suggest that infants' anticipatory and reactive eye movements have different neuronal substrates (Csibra, Tucker, & Johnson, 2001, but see Richards, 2001 for a review). We speculate that, in situations involving uncertain outcomes, different neural structures are at work.

The third phenomenon is that infants do not treat probable outcomes and certain outcomes in the same way. Their anticipatory behavior responds to differences in the stimuli -- even subtle differences -- that modify the nature of the outcomes. The stimuli of Experiments 1 and 2 were very similar, but the logical nature of the future events changed. In Experiment 1, it was possible for a ball to exit from both sides of a container, although the probabilities of the outcomes were different. In Experiments 2 and 3 the ball could only exit from one side.

In our experiments, infants perceived the improbable or impossible nature of the outcomes, as revealed by their longer looking times *post hoc* at improbable or impossible events. However, they spontaneously anticipated an outcome only when it was the most probable one, but not when it was the only physically possible one. *Prima facie*, this result is very puzzling: If infants anticipate an outcome when they do not know for sure that it will occur, why shouldn't they anticipate it when they know for sure that it will?

This puzzle, however, may have a rational explanation. In a world where uncertainty is pervasive, infants may quickly adapt their limited cognitive resources to the modal nature of the situations, actively anticipating future events by programming their behaviors only when they can obtain a gain in knowledge. When infants *already know* what the next event will be, and nothing is at stake, like in Experiments 2 and 3, they find no reason in programming behavior ahead of time: such effort would lead to no new knowledge. When, instead, infants perceive the uncertainty of an outcome and can compute the relative likelihood of different future situations (as in Experiment 1), anticipation may play a role in quickly updating their prior expectations and, as a consequence, in quickly adjusting appropriate motor actions. Recent evidence suggests that infants consider neither completely random stimuli nor completely predictable stimulus sequences as candidates for learning. Infants' attention allocation (or exploration) seems to change as a function of the perceived information that can be extracted from a stimulus stream (Kidd, Piantadosi, & Aslin, 2012). The speed of orientation towards different stimulus sources is also modulated by the statistical reliability of the information content present in the stimulus sequences (Tummeltshammer & Kirkham, 2013). Even in planning actions, we suggest that infants may be computing a payoff metrics to decide when to program anticipations, reserving them for situations that are neither completely random nor completely deterministic. It is important to note, however, that in our studies infants are only passive observers. They incur no risk if their strategy is wrong. Possibly, when the stakes are higher (e.g. when involves competition with other protagonists, or when the target object is valuable) infants may develop more sophisticated anticipatory strategies.

A final subtle point is worth discussing. Our results may show that infants appreciate what makes a stimulus deterministic. In the statistical learning literature a deterministic situation amounts to a fully predictable stimulus relation, in which the probability of an outcome is 1. However, this predictability is not of the same kind as the full predictability of a deterministic physical outcome, such as those involved in our experiments. In the former case, the predictability of the stimuli is not governed by any other principle but the fact that the experimenter imposes a regularity. As such, nothing, besides the experimenter's plan, guarantees the stability of the relation between stimuli in the long run. Physically deterministic situations are different. Impossible events violate a core principle of object perception. One does not need to track statistical relations in order to perceive that objects are impenetrable, and this fact does not depend on the particular experimental situations to which infant participate. In Experiments 2 and 3, the outcome of the scenes was deterministic in the sense that the ball could only exit from one side. An alternative outcome was physically impossible, although the timing of the exit could not be inferred with certainty (unlike the simple elementary trajectories, often used in studies about anticipation, in which a single object moves constantly back and forth and both the direction and the timing of the exits are fixed). We suggest that in our experiments infants respond to the high-level perception of an event as either physically determined or intrinsically uncertain, planning anticipation only in this latter situation even without the need of repeated exposures. The differences between two kinds of determinism may explain infants' behavior in our tasks, compared with that found when they experienced entirely predictable, but not physically deterministic, situations.

In the experiments presented here, infants could use their theories about the world in order to form their expectations about the possible future states of a situation (excluding, for example, that the ball could exit from a closed side). However, we do not claim that this is the only way in which infants can attain certainty about future events. Infants, being sensitive to statistical information, could learn that an event has a single outcome also by collecting experience about a repeated situation. Indeed, infants could form expectations that reflect the deterministic character of a scene even in this way; however, if no further information could be acquired by anticipating the outcome, the process of exploration, being low in information value, might be interrupted. Thus, statistical mechanisms, intuitive theories about the world, computations of efficiency and the ability to project and test hypotheses may work together to the service of knowledge acquisition and uncertainty reduction. As such, the issue we are raising has to do with uncertainty vs. certainty in general and goes beyond probability vs. determinism. We limited our investigation to the simplest case in which intuitive theories of the world could be a sufficient basis to form expectations; further research is needed to assess whether, as we suggest, any other means by which infants increase their degree of certainty about some outcomes may result in similar reductions of anticipatory behaviors.

Infants anticipatory behavior may also depend on their understanding of the causal origins of events, (Kenward, 2010; Sobel & Kirkham, 2006, 2007). Previous studies have documented that toddlers intervene in reality more often when the causes of an event or an actor's goals are unclear than when they can be determined with certainty (Schulz & Bonawitz, 2007; Schulz, Gopnik, & Glymour, 2007; Schulz, Hooppell, & Jenkins, 2008). Such behaviors can and have been interpreted as strategies to optimize information acquisition.

Our studies suggest that not only is infants' exploratory behavior driven by a basic motive of information-seeking, but also that their anticipatory behavior is equally dependent on potential information gains. Understood in this way, our results show that already at 12 months infants know how to allocate cognitive resources skillfully, suggesting that at the beginning of cognition humans may already be, as Aristotle would have it, little rational animals.

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**Appendix A. Supplementary material**

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.09.003.

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