Intuitions of probabilities shape expectations about the future at 12 months and beyond

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Rational agents should integrate probabilities in their predictions about uncertain future events. However, whether humans can do this, and if so, how this ability originates, are controversial issues. Here, we show that 12-month-olds have rational expectations about the future based on estimations of event possibilities, without the need of sampling past experiences. We also show that such natural expectations influence preschoolers' reaction times, while frequencies modify motor responses, but not overt judgments, only after 4 years of age. Our results suggest that at the onset of human decision processes the mind contains an intuition of elementary probability that cannot be reduced to the encountered frequency of events or elementary heuristics.

cognitive development | early numerical reasoning | early probability reasoning | infant cognition

> The theory of probabilities is at bottom only common sense reduced to calculus; it makes us appreciate with exactitude that which exact minds feel by a sort of instinct without being able oft times to give a reason for it.
>
> P. S. Laplace (1)

Rational agents should integrate probabilities in their predictions about uncertain future events. However, whether humans can do this, and if so, how this ability originates, are controversial issues. One influential view (2, 3) is that human probabilistic reasoning is severely defective, being affected by heuristics and biases. Another influential view (4, 5) claims that humans are unable to predict future events correctly without experiencing the frequency of past outcomes. Indeed, according to this view, in the environment in which we evolved only "the encountered frequencies of actual events" (5) were available, hence predicting the probability of an event never before observed is meaningless.

A third, largely unexplored view is that intuitions about possible future events ground elementary probabilistic reasoning (1, 6). Against this view, several classic (4, 5, 7), although not unchallenged (8), studies seemingly show that probabilistic reasoning appears late in development and requires frequency information. However, if, as Laplace wrote, probability theory "makes us appreciate with exactitude that which exact minds feel by a sort of instinct" (1), humans must have intuitions about probabilities early in their life.

Current Research

We checked whether infants have expectations about future single events never before seen, based on their likelihood. This ability may better surface when simple events reduce the difficulty of representing future states of affairs. Because infants can represent objects within the subitizing range (9) and bind them into sets (10, 11), encompassing three to four objects (12), we explored the hypothesis that at least within this limit they can also make predictions about the likelihood of future events without prior exposure to their actual frequency. We presented movies in which three identical objects and one different in color and shape bounced randomly inside a container with an open pipe at its base, as in a lottery game [supporting information (SI) Movies 1 and 2]. After 13 s, an occluder hid the container and one object, either one of the three identical objects (probable outcome) or else the different one (improbable outcome), exited from the pipe. To avoid memory load, after 1 s the occluder was removed and all objects became visible. Because the understanding of the underlying probability distribution requires the ability to classify objects according to their properties, we tested 12-month-old infants, who can track object identities by using properties in tasks involving occlusions (13–15). Infants had no information about frequency distributions of actual outcomes, so their reactions could not be primed by previous experience. In experiment 1, after being familiarized with two "neutral" movies containing two pairs of bouncing identical objects, infants (n = 20, mean age 12 months, 12 days) saw four movies (two probable and two improbable) with the 3÷1 object distribution (Fig. 1). Despite the complexity of the task and the lack of habituation, infants looked significantly longer when they witnessed the improbable outcome ($M_{\text{Probable}} = 9.34$ s, $M_{\text{Improbable}} = 12.55$ s; $F_{1,19} = 7.379$, $P = 0.013$).

This result suggests that infants do not need to experience outcome frequency to respond to probabilities. However, they may still respond on the basis of simple heuristics. Although the nature of heuristics has never been studied at a very early age, some simple and economical procedures unrelated to probability reasoning could be plausible candidates. For example, infants may respond to the perceptually more salient outcomes or track the minimal number of objects. Such biases could lead infants in experiment 1 to look longer at the different object outcome not because it was improbable, but because it was perceptually more salient.

Experiment 2 (n = 20, mean age 12 months, 12 days) addresses this possibility. We transformed the events from improbable/probable to possible/impossible, while maintaining object distributions and outcomes identical to those of experiment 1. By interposing a separator in the middle of the container, we created movies with the three identical objects confined in an area where it was physically impossible to exit (Fig. 2; SI Movies 3 and 4). Infants saw four movies, two presenting a possible outcome where the unconstrained object exited the container, and two presenting an impossible outcome where one of the confined objects exited. If infants in experiment 1 looked longer at the different object outcome not because it was improbable, but because they applied shallow perceptual or minimum effort heuristics, then in experiment 2 they should also look longer at

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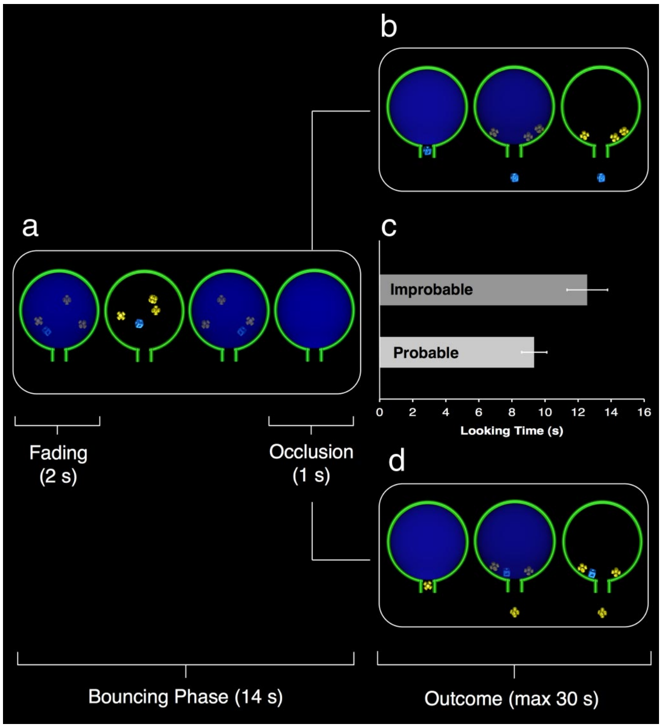

Fig. 1. Experiment 1: infants' looking time to improbable/probable outcomes never experienced before. (*a*) Three identical and one different object bounced in a container, simulating a lottery. After an occlusion period, one of the objects exited, presenting a probable outcome (*b*) in which one of the three identical objects exited, or an improbable outcome (*d*), in which the unique different object exited. Afterward, the occluder faded out and infants could see all of the objects. (*c*) Mean looking time (SEM) during the outcome phase.

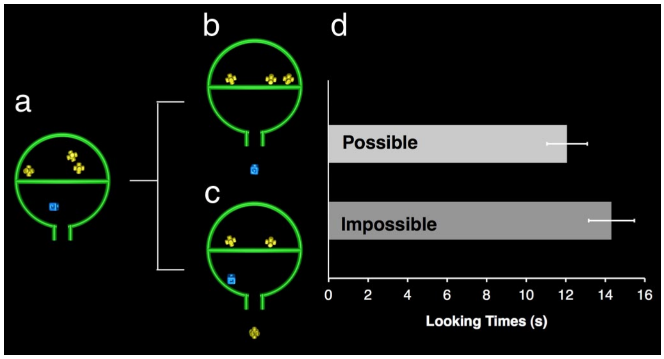

Fig. 2. Experiment 2: infants' looking time at impossible/possible outcomes closely mirroring the probable/improbable outcomes of experiment 1. (*a–c*) By interposing a bar between the three identical objects and the single different object (*a*), the movies were transformed (*b*) so that the probable outcome of experiment 1 became impossible and the improbable outcome became possible (*c*). (*d*) Mean looking time (SEM) during the outcome phase.

the same outcome. Instead, infants looked longer at the impossible outcome ($M_{\mathrm{Impossible}} = 14.31$ s, $M_{\mathrm{Possible}} = 12.06$ s; $F_{1,19} = 6.305$, $P = 0.021$) although it displayed an object from the more probable class, that is, the one less looked at in experiment 1. A joint analysis of experiments 1 and 2 revealed an interaction between experiment and exited object ($F_{1,38} = 13.555$, $P = 0.0007$), showing that infants reacted at the probability or possibility of the outcomes, rather than at features extraneous to the experimental manipulation.

Together, these experiments show that just as infants expect that future events will respect physical constraints (16) they also expect that in the future the most likely outcome will occur. Because no frequency information about actual outcomes was provided, these expectations are grounded on intuitions about single event probabilities based on future possibilities. Undoubtedly, infants respond to frequencies (17, 18). However, our experiments show that the origin of the concept of probability cannot be reduced to experiencing frequencies.

In experiments 3 and 4, we studied the relation between probability intuitions based on event possibilities and experienced frequencies of events, testing 3- and 5-year-olds because infants cannot undergo long sessions with our stimuli. We devised a reaction time (RT) paradigm that directly pitted prior probabilities against frequencies. To generate expectations of probability that could affect RTs while keeping stimuli as simple as possible, we created movies where the geometry of the stimulus represented the information about likely and unlikely outcomes, while the probability ratio was 3÷1 as in experiment 1. A ball bounced inside a rectangular box with one hole in a wall and three in the opposite wall (Fig. 3*a*; SI Movies 5 and 6). Number and distribution of bounces and direction of the last visible trajectory (always parallel to the vertical axis and centered) were controlled; hence, no cue but the number of holes could predict the exit side. After 13 s of visible movement, an occluder covered the box except for the holes in the walls. Children had to press a button when they saw the ball exiting the box. As the movies subtended 15 × 20° of visual angle, children could respond simply by monitoring modifications of the display popping out foveally. Furthermore, because the one-hole side presents one single exit point, focusing attention on it should be easy, whereas the three-hole side demands spreading attention across three positions simultaneously. Thus, shallow heuristics based on the simplicity of the display or on lower attentional efforts predict faster responses to the one-hole side. Instead, if children prepare their responses by considering the most probable outcome, their attention should be directed more toward the three-hole side, leading to faster initial responses at the ball exit. Finally, by presenting the movies repeatedly, a likely outcome can become infrequent and an unlikely outcome frequent. If experienced frequency and intuitions of probabilities can be dissociated, frequent repetitions of an improbable event should reduce initial expectations for the probable outcome, making RTs for the improbable but frequent event faster as frequency detection mechanisms gather information about the actual outcomes. We tested 3-year-olds (experiment 3, $n = 50$, mean age 3 years, 9 months) and 5-year-olds (experiment 4, $n = 50$, mean age 5 years, 8 months), in two conditions ($n = 25$ each). In one, children saw six blocks of four movies, each containing three one-hole outcomes and one three-hole outcome, thus making the improbable event frequent. In the other condition, frequencies were inverted, so that frequencies and probabilities agreed. We compared how fast children reacted in the first block, where an initial intuition of probability may emerge, and how any initial difference evolved according to the actual frequency distributions. To study how event frequency affects the initial intuitions of probability, at the beginning of the experiment, we also asked children to say where they thought the ball would exit (probability question), and at the end where they thought the ball had exited the most often (frequency question).

The analysis of children's RTs shows that, at both ages, in the first block children were slower at detecting the ball exiting the one-hole side (Fig. 3; 3-year-olds: $M_{\text{1-hole}} = 1{,}332$ ms, $M_{\text{3-holes}} = 1{,}186$ ms, $F_{1,49} = 5.165$, $P = 0.028$; 5-year-olds: $M_{\text{1-hole}} = 844$ ms, $M_{\text{3-holes}} = 775$ ms, $F_{1,49} = 9.21$, $P = 0.004$), regardless of the frequency distribution of the outcomes. To exclude that slower responses for the one-hole side depended on factors extraneous

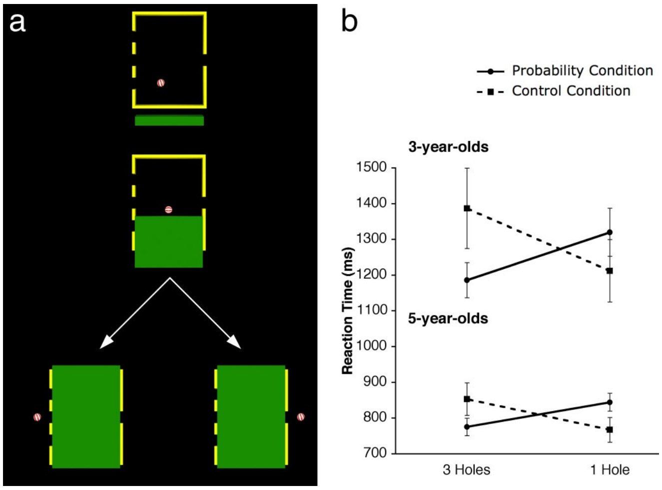

Fig. 3. Three- and 5-year-olds' RTs for improbable/probable events before experiencing outcome frequencies. (*a*) The structure of the experiment. After bouncing inside the frame, a ball exits either from the three-hole side or the 1-hole side, generating either a probable or an improbable outcome. (*b*) The mean RTs (SEM) in the first four trials of experiments 3 and 4 (probability condition) and in the corresponding four trials of experiment 5 (control condition).

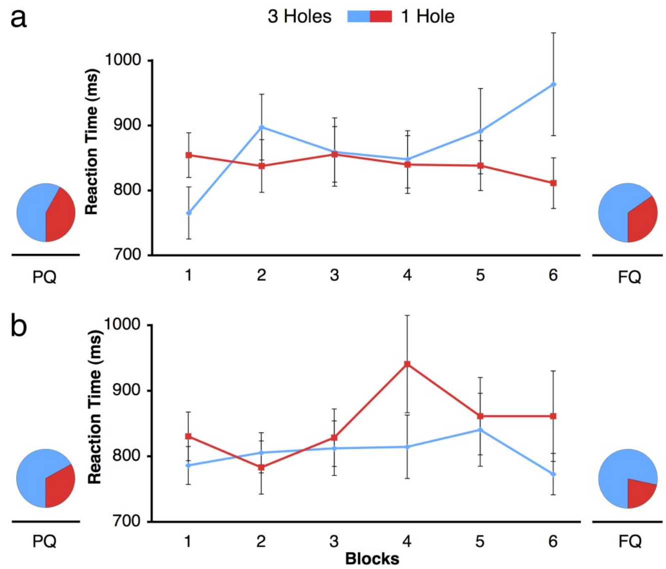

Fig. 4. Five-year-olds' RTs and judgments to improbable/probable events, before and after exposure to experienced frequencies. Improbable events were presented either frequently (*a*) or infrequently (*b*) between participants. The ordinate reports RTs to the appearance of the ball in milliseconds, and the abscise reports the 24 trials infants experienced, grouped in six blocks of four, separately reporting appearance from the three-hole or one-hole sides. Children were asked a probability question (PQ) before seeing the 24 movies and a frequency question (FQ) afterward. Pie charts present the distributions of the answers to the probability and frequency questions, color-coded as in the RT charts.

to initial probability intuitions, in experiment 5 (testing two groups of 3- and 5-year-olds $n = 16$ each; mean age 3 years, 8 months and 5 years, 9 months, respectively), we modified children's prior expectations by telling them that the box contained a special ball that exited from the one-hole side, although it sometimes made mistakes, and then showed three one-hole and three three-hole-outcome movies identical to those of experiments 3 and 4. At both ages children were faster at detecting one-hole exits (3-year olds: $M_{1\text{-hole}} = 1{,}212$ ms, $M_{3\text{-holes}} = 1{,}387$ ms, $F_{1,15} = 6.62$, $P = 0.021$; 5-year-olds: $M_{1\text{-hole}} = 767$ ms, $M_{3\text{-holes}} = 853$ ms, $F_{1,15} = 11.59$, $P = 0.0039$). RT for exit side interacted with the presence or absence of instructions (3-year-olds: $F_{1,59} = 8.83$, $P = 0.004$; 5-year-olds: $F_{1,63} = 13.144$; $P = 0.0005$), showing that no perceptual effect or uncontrolled preference for the three-hole exits could explain the initial speed advantage found in experiments 3 and 4. Thus, the same intuition of probability present at 12 months keeps shaping expectations about future events later in development. However, the relative frequencies of probable and improbable outcomes weighted over children's initial expectations, modulating RTs and inverting them when initial probability and experienced frequency were discordant. Yet, this effect only occurred at age 5 (Fig. 4).[‖] In 3-year-olds, frequency did not reverse the initial probability intuitions (SI Fig. 5), suggesting that, far from being the foundation of probabilistic reasoning, experienced frequency moulds the expectation of future events only at a late stage of development.

How did experienced frequency affect children's explicit verbal responses? When initially asked where the thought ball would exit, at 5, but not at 3, children indicated the more probable outcome. Yet when, at the end of the experiment, they were asked to say where they thought the ball had exited the most often, even at age 5 children were unable to explicitly detect that frequency deviated from prior probability, not realizing that the ball had exited from the one-hole side in 75% of the cases. Thus, apparently experienced frequency affects children's motor responses earlier than their overt judgments.[**] This resistance to integrate experienced frequencies into explicit judgments is not caused by judgment perseveration, as 5-year-olds can modify their judgments integrating information disconfirming their initial hypotheses about the probabilities of future events (19). Rather, it looks like perceived frequencies and explicit reasoning about future states of affairs are computed by different mechanisms.

Conclusion

Our experiments show that natural intuitions of probabilities guide expectations for future outcomes early in development. Infants put their early numerical knowledge of small quantities to the service of higher-level processes of event interpretation (20), shaping rational expectations of what comes next based on the probable outcomes of what they see now. Such intuitions do not arise by the proved human prowess at sampling distributions. When experienced frequency disagrees with prior probability, it is only after substantial exposure to a sample of outcomes that participants' motor responses overcome natural expectations of the likely event, becoming slower for the likely but infrequent outcomes, and this only after 3 years. Indeed, even at 5, when the motor system adapts to experienced frequencies, the original probability intuitions still shape overt judgment.

‖This conclusion is suggested by the interaction between initial/final blocks, outcome probability, and outcome frequency ($F_{1,143} = 7.82$; $P = 0.007$). No such interaction occurred in the 3-year-olds' data.

**When asked the probability question, at the beginning of the experiment, 31 of 49 5-year-olds indicated the three-hole outcome ($P = 0.04$, binomial test for the probability of 31 or more successes). However, when at the end of the experiment children were asked the frequency question, 15 of 23 indicated the three-hole outcome in the group with infrequent three-hole outcomes, and 19 of 24 did so in the group with frequent three-hole outcomes. The difference was not significant [($\chi^2{}_{1}$, $n = 47$) = 1.14, not significant], suggesting that, unlike RTs, frequency exposure did not modify the initial intuitions of probability. Indeed, even for the three-hole infrequent group, that is, for those children who should have changed their judgments, had they been responsive to the low frequency of the three-hole outcomes, the number of children indicating the three-hole outcome before any frequency exposure (14 of 24) and after experiencing the actual frequency of outcomes (15 of 23) did not change [($\chi^2{}_{1}$, $n = 47$) = 0.2, not significant].

We studied simple situations in which the object involved can be independently represented as "object files" (21). More complex situations may force infants, like adults, to rely on heuristics or previous experience; how probability intuitions, sensitivity to frequencies, and influence of heuristics come together is an issue that requires extensive research. However, our results suggest that in those simple cases neither the ability to compute frequencies nor the existence of elementary heuristics can explain the origin of probabilistic reasoning.

Materials and Methods

Experiments 1 and 2. The QuickTime movies were generated at 25 fps and presented on a 17-in screen with the software PsyScope X (22) (http://psy.ck.sissa.it) running on an Apple DualG5 computer. The container covered a 14 × 14-cm area. Infants sat on their parent's laps, 80 cm from the screen. An infrared camera allowed the experimenter, who was blind to the experimental conditions, to monitor the infant's behavior from a separate screen. To ensure that every infant saw every movie in its entirety, the presentation of the stimuli was infant-controlled: movies were paused when infants were not paying attention and continued playing when they reoriented toward the screen. Infants were shown two familiarization movies in which two balls of each type bounced inside the container and four experimental movies. Lists with different orders of experimental movies, half beginning with a probable trial and half with an improbable trial, were counterbalanced across subjects.

Before each experimental movie, a visual attractor helped orient the infant's attention toward the center. In the monitoring phase, at the exit of the ball, the experimenter began recording looking time and ended the trial if the infant looked away for >2 consecutive s or looked for >30 cumulative s. Looking time was further analyzed off-line. Infants were excluded from analysis if they had more than two cumulative timeouts ($n = 5$ in experiment 1; $n = 2$ in experiment 2), if they appeared fussy ($n = 12$ in experiment 1; $n = 9$ in experiment 2), if their caretakers interfered during the experiment ($n = 1$ in experiment 2), or if they turned away in synchrony with the object exiting from the container ($n = 3$ in experiment 1).

Experiments 3 and 4. The movies simulated a ball moving at a constant 12 deg/s from the child's viewing position, hitting the box frame like a solid, elastic object. The walls of the box had a different number of exit points: two each in the familiarization movies, and one and three in the test movies. The test movies ended with an occluder covering the box and the ball exiting from one of the holes. We generated 12 test movies, defined by the position of the single hole relative to the three holes (up/middle/down), the exit side (one-hole side/three-hole side), and the exit direction (right/left). Children were tested in a silent, isolated area of the kindergarten in the presence of the experimenter and one kindergarten assistant, giving their responses by pressing a one-button mouse attached to an Apple 12-in Powerbook.

After familiarization, infants were shown one experimental movie that stopped with the ball at the center of the box before the occluder covered it and asked a probability judgment: "Where do you think the ball will exit? From the side with one hole or that with more holes?," counterbalancing the order in which the sides were mentioned. Either verbal or pointing answers were accepted. After the probability judgment, children were trained on quickly pressing the mouse when seeing the ball's exit during four presentations of familiarization movies. Ball exit direction was counterbalanced. Children who made more than two training errors were excluded from analysis.

In the test phase (24 trials), children were divided in two groups, with frequency of one-hole exits to three-hole exits set to $1 \div 3$ and $3 \div 1$ respectively. The movies were randomized in six miniblocks of four trials respecting the same frequency distribution. The positions (up, middle, or down holes) and direction (left or right) of the ball exits were counterbalanced. A random variable occlusion period (800, 1,000, 1,200, or 1,400 ms) preceded the exit to avoid that participants used timing cues to predict the ball appearance. After the test phase, children saw a last movie that stopped before the ball exited the box, and they were asked a final frequency judgment: "Where do you think the ball came out the most often? From the side with one hole or that with more holes?," counterbalancing the order in which the sides were mentioned. Children were asked to answer, and either verbal or pointing answers were accepted. See *SI Text* for further details.

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