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Original Articles

# Shake it baby, but only when needed: Preschoolers adapt their exploratory strategies to the information structure of the task

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ABSTRACT

Previous research has suggested that active engagement with the world drives children's remarkable learning capabilities. We investigated whether preschoolers are "ecological learners," that is, whether they are able to select those active learning strategies that are most informative in a given task. Children had to choose which of two exploratory actions (open vs. shake) to perform to find an egg shaker hidden in one of four small boxes, contained in two larger boxes. Prior to this game, children either learnt that the egg was equally likely to be found in any of the four small boxes (Uniform condition), or that it was most likely to be found in one particular small box (Skewed condition). Results of Study 1 show that 3- and 4-year-olds successfully tailored their exploratory actions to the different likelihood-distributions: They were more likely to shake first in the Uniform compared to the Skewed condition. Five-year-olds were equally likely to shake first, irrespective of condition, even when incentivized to shake only when needed (Study 2a). However, when the relevance of the frequency training for the hiding game was highlighted (Study 2b and Study 2c), the 5-year-olds showed the same behavioural pattern as the younger preschoolers in Study 1. We suggest that ecological learning may be a key mechanism underlying children's effectiveness in active learning.

## 1. Introduction

Imagine you were 5 years old. Every day after school, your 4-year-old sister wants to play her favourite game–hide and seek. Fond of cookies as well as of hide and seek, she *always* hides in the pantry, and the crumbs on the floor are a good clue about what she is doing in there while she waits! A safe bet to find your sister would be to head straight for the pantry, as you can be relatively certain that she will be in there munching on some cookies—and if you are fast, there may still be some left for you! However, what would you do if you were playing with a new friend? Without any prior expectation as to where she may be hiding, heading straight to the pantry would probably not be the most sensible thing to do. Hide and seek may be a trivial example, but it illustrates that the effectiveness of a search strategy cannot be measured in absolute terms. Instead, strategies vary in informativeness depending on the characteristics of the task at hand, as well as on the previous knowledge and expectations of the searcher (Todd, Gigerenzer, & The ABC-Research Group, 2012). As a result, being able to adapt one's learning strategies to the current learning context, an ability referred to as *ecological learning* (Ruggeri & Lombrozo, 2015; Ruggeri, Sim, & Xu, 2017), is crucial to maximize learning effectiveness.

Previous research has shown that young children use probabilistic information to form judgments, to make predictions and generalizations, and to guide their information search (Denison & Xu, 2014; Gweon, Tenenbaum, & Schulz, 2010; Kushnir & Gopnik, 2005), integrating prior probabilities with feedback and subsequent evidence (Denison, Bonawitz, Gopnik, & Griffiths, 2013; Girotto & Gonzalez, 2008; Gonzalez & Girotto, 2011) and making inferences that are consistent with the general principles of Bayesian inference (e.g., Eaves & Shafto, 2012; Schulz, Bonawitz, & Griffiths, 2007). We also know from a growing body of literature that even infants prefer to explore surprising events (Schulz, 2015; Stahl & Feigenson, 2015), and that preschoolers are more likely to explore when they are presented with confounded evidence—that is, when they are uncertain about the causal mechanism at work (e.g., Cook, Goodman, & Schulz, 2011; Schulz & Bonawitz, 2007)—or when they face evidence that violates

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their prior beliefs (e.g., Bonawitz, van Schijndel, Friel, & Schulz, 2012; Legare, Gelman, & Wellman, 2010). The idea that children preferentially explore under conditions of uncertainty is further supported by work on curiosity (e.g., see Jirout & Klahr, 2012; Kidd & Hayden, 2015). Information gap theory (Loewenstein, 1994) for instance proposes that curiosity arises when an individual becomes aware of a gap in their knowledge—that is, when they are uncertain about something. Awareness of this knowledge gap induces a desire to reduce this gap – which is resolved by seeking the missing information.

In this sense, prior work has demonstrated that even young children use their understanding of probabilities to decide *whether* to explore, and to what extent. In this paper we investigate whether 3- to 5-year-olds leverage their sensitivity to probabilities and their ability to track statistical regularities to decide *how* to explore. In particular, we developed a novel nonverbal exploration paradigm to investigate whether children as young as three years of age are ecological learners. Do these young children choose their exploratory actions to maximize the information that can be gained in the current learning situation, by adapting their exploration to the statistical structure of the given task?

Studies employing the 20-questions game (see Mosher & Hornsby, 1966), in which the goal is to find the solution to a causal inference task (e.g., "Yesterday, Toma was late for school. Why?") by asking as few yes/no questions as possible, suggest that children are indeed ecological learners. In particular, 7- to 10-year-olds take into account the likelihood distribution across the potential candidate solutions to decide which kind of question to ask. For example, they tend to ask questions targeting a single hypothesis (*hypothesis-scanning questions*; e.g., "Is Toma late because he woke up late?") when this hypothesis is presented as more likely than the others. When all candidate hypotheses are presented as equally likely, children tend instead to ask questions targeting multiple hypotheses (*constraint-seeking questions*; e.g., "Is Toma late because he could not find something?"; Ruggeri & Lombrozo, 2015), which narrow down the space of potential candidate solutions more quickly. There is evidence that even 5-year-olds are able to select the most informative of two given questions adaptively (Ruggeri et al., 2017). However, little is known about whether children younger than five are able to adapt their active learning strategies to the task at hand. Moreover, it is unclear whether the ecological learning abilities demonstrated by older children would extend beyond the question-asking paradigm.

To investigate these questions, we developed a task in which 3- to 5-year-old children had to choose which of two exploratory actions (open vs. shake) to perform to find an egg shaker hidden in one of four small boxes, contained in two larger boxes (see Fig. 1). They were told that they could open *only one* large box. Prior to this game, children learned that the egg was equally likely to be found in any of the four small boxes (Uniform condition), or that it was most likely to be found in one particular small box (Skewed condition). These two actions were differently informative in the two conditions. Children in the Uniform condition could not know in which small box the egg was hidden. Shaking at least one large box before deciding which one to open was therefore necessary to avoid opening the wrong box. However, children in the Skewed condition should know where the egg was hidden and could open the correct large and small box to find the egg right away. Drawing a parallel with the question-asking paradigm, shaking a large box in our task corresponds to asking a constraint-seeking question that targets multiple hypotheses (i.e., the two small boxes inside the same large box), whereas opening a small box corresponds to asking a hypothesis-scanning question targeting one single hypothesis. If during training children learned how likely the egg was to be found across the four small boxes and adapted their exploratory actions accordingly, they would be more likely to shake the box first in the Uniform condition than in the Skewed condition.

## 2. Study 1

### 2.1. Method

#### 2.1.1. Participants

Participants were 114 children (61 female; 3-year-olds: $n = 38$, $M_{age} = 42.01$ months, $SD = 3.05$ months; 4-year-olds: $n = 37$, $M_{age} = 54.32$ months, $SD = 3.21$; 5-year-olds: $n = 39$, $M_{age} = 64.41$ months, $SD = 3.43$ months) recruited from preschools and museums in the East Bay of the San Francisco area. Twenty additional children were excluded from analysis because they failed the attention check (see below; $n = 4$), or due to experimenter error and missing video recordings ($n = 16$). Sample size for all studies was based on previous research investigating active learning with preschoolers. For all studies, written informed consent of parents was obtained prior to participation. Study 1, 2a and 2c were approved by the ethical review board of the University of California, Berkeley (protocol: CPHS#:2010-01-631).

#### 2.1.2. Materials

For the frequency training and test phase of this task we built two large cardboard boxes, one black and one white, each containing two smaller differently colored round boxes (green/blue or yellow/red). To ensure that the small boxes were easy to open, plastic rings were attached to their lids. The large boxes were closed with three Velcro strips. The boxes used for the action training were identical to the two test boxes, except for the colors. Two identical egg shakers were used, one for the frequency training and test phase (white with green dots),

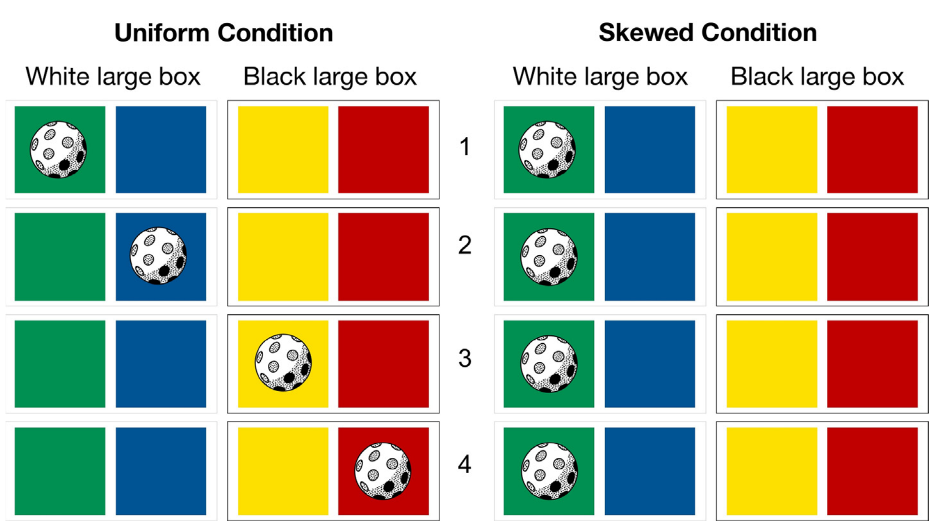


**Fig. 1.** Frequency training phase. An egg shaker was placed four times into one of four small boxes (green, blue, yellow, and red) contained in two larger boxes (white or black). After each placement, children were asked to retrieve the egg and use it to activate a light-up toy. We manipulated between subjects whether the egg was always hidden in the same (Skewed condition) or a different (Uniform condition) small box. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and one for the action training phase (white with red dots). The toy consisted of a spinning light-up toy sitting on top of a black cardboard box covered with silver star stickers, which was activated via remote control by the experimenter whenever the child placed the egg on it.

#### 2.1.3. Design and procedure

Children were randomly assigned to the Skewed or the Uniform condition. The experiment consisted of four phases. During the *familiarization phase*, the experimenter presented the egg and placed it on the light-up toy to demonstrate that it could be used to activate the toy. She then told the children, "In this game, when you find this egg, you'll get to put it on the toy and play with it!" Next, she showed children the two large boxes, which sat on the table with their lids open. She then opened and closed the four small boxes one after the other to demonstrate that they were empty.

The *frequency training phase* consisted of four rounds. On each round, the experimenter opened one of the four small boxes, placed the egg inside it, and closed it again. In the Skewed condition ($N = 56$), the experimenter always placed the egg in the same small box, either the leftmost or the rightmost (counterbalanced across participants), saying, "See? In this game, I always put the ball in the *same* box." In the Uniform condition ($N = 58$), the experimenter placed the egg in a different small box on each round in an ordered fashion, either right-to-left or left-to-right (counterbalanced across participants), so that at the end of the training phase the experimenter had placed the egg once in each small box, saying, "See? In this game, I always put the ball in a *different* box." At the end of each round, the experimenter prompted children to retrieve the egg and use it to activate the light-up toy. Children ($n = 4$) who failed to retrieve the egg from the correct small box on all rounds were excluded from the analyses.

During the *action training phase*, the experimenter demonstrated two actions children could perform to find out whether or not a large box contained the egg: They could either *shake* the large box, to hear if one of the small boxes inside contained the egg, or *open* the large and the small boxes to explore their contents. Each action was demonstrated using novel large and small boxes. For the shake/open training, the experimenter presented a grey/brown large box and said, "Oh look, here is another big box. This big box also has two small boxes inside, like those [points to the two test boxes]. Hmm… I wonder if there is a ball in one of the two small boxes inside here." After a short moment, she continued, "Here is one thing we can do to find out: we can shake/open the big box!" For the share training, the experimenter then proceeded to shake the box, ensuring that the children had noticed the egg inside it from its rattling sound. For the open training, the experimenter demonstrated how to open the large and the two small boxes inside it. Children were then prompted to shake/open the box/boxes themselves.

The order in which the two actions were demonstrated was counterbalanced across participants.

During the *test phase*, the experimenter told the children, "Okay, now we are going to play a hiding game! I'm going to hide the ball in one of the small boxes, and you'll have to find it!" Children were then asked to cover their eyes with the help of their parents. To hide the egg, the experimenter opened the lids of all four small boxes, placed the egg in the target box, and closed all four small boxes again but left the lid of the large boxes open. Opening and closing of the four small lids was performed in random order. In the Uniform condition the egg was hidden in a random small box. In the Skewed condition, it was placed in the small box where it had been hidden during the frequency training.

After having hidden the egg, the experimenter pushed the large boxes to the edges of the table so that they would be hard to reach for the children and said, "I'm ready now! You can look! I hid the ball in one of the four small boxes, that are over there now. When you find it, you can play with the toy!" Next, she closed both large boxes and told the children that they could either shake or open [order of presentation of the two actions counterbalanced across participants] any or both large boxes, but were allowed to open *only one* of the two large boxes to find the egg.

### 2.2. Results

The Database containing the data for all the studies included in this manuscript is archived in the Open Science Framework repository: https://osf.io/3naxu/ (Database: Ruggeri, Swaboda, Sim, & Gopnik, 2019).

To analyse the action children performed first—shake or open—we conducted for all studies a logistic regression using age (months), condition (Uniform vs. Skewed), the interaction between age and condition, and order of training (open first vs. shake first) as predictors.

The logistic regression model was statistically significant, $\chi^2(4) = 20.03$, $p < .001$. The Wald criterion demonstrated that age ($p = .013$) and condition ($p = .005$) made a significant contribution to predicting the action children performed first. Older children had an increased likelihood of shaking one or both boxes first ($OR = 1.017$ [1.004, 1.031]), and children in the Skewed condition had a decreased likelihood of shaking first ($OR = 0.004$ [0.000, 0.187]). Across both conditions, most of the 3-year-olds opened one large box right away (66%), whereas most of the 4- (59%) and 5-year-olds (72%) shook first. Overall, more children (67%) shook first in the Uniform than in the Skewed condition (43%). This suggests that children had learned how likely the egg was to be found across the four small boxes in the two conditions and correctly used this information to decide which exploratory action to perform.

Crucially, we found a significant interaction of age group and condition ($p = .023$), indicating that the difference between the likelihood of shaking and opening first across the two conditions was smaller for older children ($OR = 1.082$ [1.011, 1.158]). Indeed, as can be seen in Fig. 2, a larger proportion of 3- and 4-year-olds shook first in the Uniform as compared to the Skewed condition. However, this was not the case for 5-year-olds, the majority of whom shook first in both conditions.

Finally, the order in which the actions were presented during the action training was not a significant predictor ($p = .691$; $OR = 0.848$ [0.377, 1.910]).

### 2.3. Discussion

Study 1 investigated whether 3- to 5-year-olds leverage their sensitivity to probabilities and ability to track statistical regularities to decide *how* to explore, that is, whether they would tailor their exploratory actions to the statistical structure of a given task to maximize search effectiveness. We found a developmental shift in children's default strategy, that is, in the overall proportion of children who shook one or both large boxes before opening one. When looking at their action choices across conditions, most 3-year-olds opened a box right away, whereas 4- and 5-year-olds were overall more likely to shake a large box first, suggesting that with increasing age children's default strategy changed from opening to shaking. This developmental shift is consistent with the general progression from hypothesis-scanning to constraint-seeking questions observed later in development (Mosher & Hornsby, 1966; Ruggeri & Feufel, 2015; Ruggeri & Lombrozo, 2015; Ruggeri, Lombrozo, Griffiths, & Xu, 2016). Potential explanations for this shift include better inhibitory control, required for instance to overwrite the temptation of a quick win (e.g., Davidson, Amso, Anderson, & Diamond, 2006), and improvements in metacognitive skills (e.g., Lyons & Ghetti, 2011, 2013), categorization abilities (Ruggeri & Feufel, 2015), or cognitive flexibility (Legare, Mills, Souza, Plummer, & Yasskin, 2013).

Crucially, our results suggest that this developmental shift toward the often more effective constraint-seeking strategies may come at the cost of less adaptiveness. Indeed, 3- and 4-year-olds were more likely to perform the shaking action in the Uniform condition, where it was necessary to resolve the uncertainty as to which large box should be

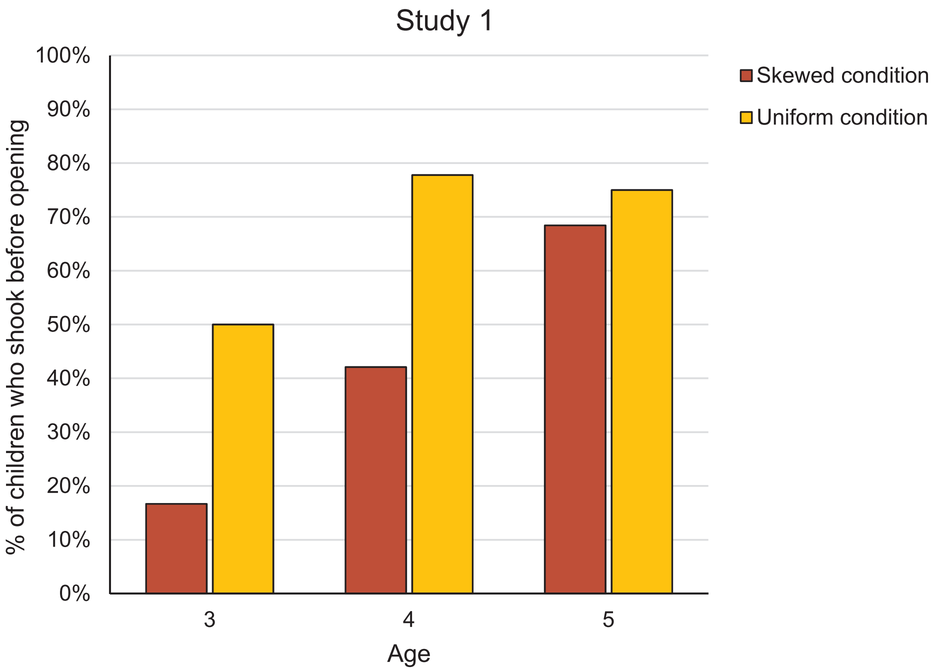


**Fig. 2.** Proportion of children who shook one or both large boxes before deciding which one to open in the Uniform and Skewed conditions. Three- and 4-year-olds efficiently adapted their exploratory actions to the task: They were more likely to shake a large box before opening it in the Uniform than in the Skewed condition. Five-year-olds were equally likely to shake first, irrespective of condition.

opened, as compared to the Skewed condition, where they knew where the egg was hidden and could therefore bet on a quick win. However, 5-year-olds did not adapt their actions, preferring to shake first independently of the condition they were presented with. This finding, although counter-intuitive, is in line with previous research on question asking suggesting that the *adaptiveness* of search strategies may not increase in adulthood. For example, Ruggeri and Lombrozo (2015) found that, despite the general developmental increase in the proportion of constraint-seeking questions, adults do not *adapt* the kind of questions they ask to the statistical structure of the task at hand more promptly than children do. On the contrary, some preliminary results seem to suggest the opposite: Children can sometimes be even more sensitive to the statistical structure of a task than adults. For instance, 9-year-old children, but not adults, asked different types of questions depending on the likelihood of the solution in a 20-questions game where they had to find out why John was late for work. In particular, when they were told that the solution to the game was unlikely (i.e., infrequent), children asked more constraint-seeking questions than when they were told the solution was very likely. However, adults always asked a majority of constraint-seeking questions, irrespective of the solution's likelihood (see Ruggeri & Lombrozo, in preparation). Similarly, evidence from causal learning studies suggests that although overall younger children are less efficient learners, they might be more *sensitive* than adults to the evidence they observe, especially when learning about unusual causal systems (Lucas, Bridgers, Griffiths, & Gopnik, 2014).

In three follow-ups, we explore the reasons why 5-year-olds failed to demonstrate adaptiveness in Study 1. In particular, we investigate the possibility that, by intervening on the incentive structure (Study 2a) or changing the instructions to highlight the relevance and deterministic nature of the frequency training for the hiding game (Study 2b and 2c), 5-year-olds might be able to select the most informative exploratory actions as 3- and 4-year-olds did in Study 1.

## 3. Study 2a

As discussed in the Introduction, from a purely information theoretical perspective, shaking the large boxes in the Skewed condition of Study 1 was an *unnecessary* action. However, it was not penalised in any way. One possible explanation for our surprising developmental findings in Study 1 is that older children, despite having learned the likelihood distribution presented during the frequency training, were more conservative or not motivated enough to search in the most efficient way. Older children may have decided to shake the large boxes first to ensure that the egg actually was where they expected it to be—sacrificing efficiency in favour of certainty—considering that this would come at no cost. To rule out this explanation, in Study 2a we introduced an additional cost by asking children to pay a sticker if they wanted to shake a large box. The aim of this manipulation was to motivate children to shake when it was strictly necessary to determine which large box should be opened, that is, in the Uniform but not in the Skewed condition. We therefore predicted that, compared to Study 1, the proportion of children shaking a large box first would decrease in the Skewed condition, since the shaking action wasn't necessary to find the egg. In contrast, we predicted that in the Uniform condition, where the hiding location of the egg was uncertain, most children would still shake the large boxes before deciding which one to open, in order to avoid opening the wrong large box. However, we also expected children to be generally more reluctant to shake the large boxes in both conditions, as compared to Study 1, because of the cost involved.

### 3.1. Method

#### 3.1.1. Participants

Thirty-two 5-year-olds (19 female; $M_{age}$ = 66.21 months, $SD$ = 3.50 months) were recruited from preschools and museums in the East Bay of the San Francisco area. Three additional children were excluded from analysis due to experimenter error.

#### 3.1.2. Materials, design and procedure

Materials, design and procedure were identical to Study 1, with one exception: At the beginning of the test phase, children received one sticker and were told that they would get three more stickers if, and only if, they found the egg in the first large box they opened. They were also told that, in order to shake a large box, they had to return the one sticker they had been given.

Children's understanding of the rules was checked with three questions: How many large boxes they were allowed to open at test (i.e., one), what happened if the ball was found in the first large box opened (i.e., they received three stickers), and what they had to do if

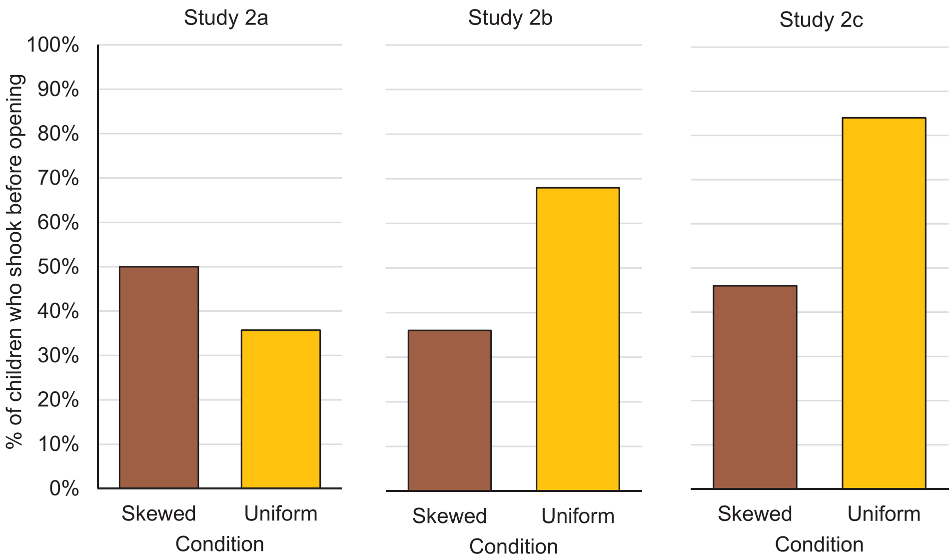


**Fig. 3.** Exploratory actions selected by 5-year-olds in Study 2a, 2b and 2c. When incentivizing children to shake only when strictly necessary (i.e., in the Uniform condition), children were equally likely to shake first in both conditions (Study 2a, left), as in Study 1. However, when highlighting in the instructions the relevance of the frequency training for the test phase, both German (Study 2b, middle) and American (Study 2c, right) 5-year-olds were more likely to shake first in the Uniform than in the Skewed condition.

they wanted to shake a large box (i.e., give back the sticker they had just been given). Children who failed to respond accurately to any of the questions ($n = 4$; 13%) were reminded of the correct answer.

### 3.2. Results and discussion

The logistic regression model was not statistically significant, $\chi^2(4) = 2.39$, $p = .663$, and none of the considered variables made a significant contribution to predicting the action children performed at first (all *ps* > 0.443). The proportion of 5-year-olds who shook first was overall lower than in Study 1 (Skewed condition; 50%; Uniform condition: 36%; see Fig. 3), suggesting that our manipulation effectively impacted children's default exploratory actions, that is, it increased children's general reluctance to shake before opening. However, as in Study 1, 5-year-olds were equally likely to shake first in both conditions. Incentivizing 5-year-olds to shake only when strictly necessary did not enhance their adaptiveness in our task. In this sense, these results seem to suggest that 5-year-olds in Study 1 did not decide to shake the large boxes first in both conditions just to "be on the safe side," considering that this would come at no cost. It could also just be that the incentive system we implemented was not adequate.

## 4. Study 2b

Another possible explanation for the lack of adaptiveness 5-year-olds showed in Study 1 and Study 2a is that children might have discounted the statistical information learned in the frequency training, not deeming it relevant for the hiding game presented at test. This could have happened for several, not mutually exclusive, reasons. First, it could be that, as they grow up, children learn that the world is more likely to be ruled by *uncertainty* than by clearly predictable risk patterns. Along these lines, several studies have shown significant improvements in uncertainty detection and monitoring between 3 and 7 years (Beck & Robinson, 2001; Plumert, 1996; Rohwer, Kloo, & Perner, 2012), suggesting that 5-year-olds may have mistrusted the deterministic model of the world we presented in the Skewed condition, in which the egg was again to be found in the same small box where it had been hidden already four times. Second, a more enhanced understanding of the social world, including subjective beliefs, intentions and the possibility of deception (e.g., Bosco & Gabbatore, 2017; Lee, 2013; Polak & Harris, 1999; Wellman, Cross, & Watson, 2001) may have led older preschoolers to distrust the experimenter. Children may have thought that she was tricking them by inducing a false belief about the egg's hiding location, deeming the task as suspiciously too simple. Third, 5-year-olds' tendency to shake in both conditions may just be rooted in the *pragmatics* of our task. In Study 1 and 2a, the test phase was introduced with the sentence "*Now* let's play a *hiding* game." This wording may have led older children to believe that the hiding game in the test phase had different rules from the one they had played earlier during training. This effect may have been aggravated by a further discontinuity in the instructions' wordings: In the frequency training of Study 1 and 2a, the experimenter said that she always *put* the ball in the same/different box. However, in the test phase she said that she would *hide* the ball in one of the four small boxes. As a result of these inconsistencies between frequency training and test, 5-year-olds might have discounted the information they had gathered during training as irrelevant for the test phase. In particular, these verbal cues might have introduced uncertainty in the Skewed condition, leading children to doubt that the egg had a 100% chance of being found in one particular small box. Indeed, recent work has shown that older preschoolers, compared to 3-year-olds, are more sensitive to pedagogical cues and make stronger inductive inferences following pedagogical demonstrations (e.g., Butler & Markman, 2012, 2014, 2016).

In Study 2b, we aimed to highlight the relevance and deterministic nature of the frequency training for the hiding game by implementing two procedural changes: First, we removed the conflicting verbal cues (i.e., "put" vs. "hide") and ensured that the egg placing action was referred to as "hiding" throughout the game. Second, we added an additional instructions-check question right before the test phase (see Method below), reminding children of the hiding pattern observed during the frequency training immediately prior to test, with the hope that this would highlight its relevance for the hiding game and make them more trustful of the deterministic nature of the hiding patterns.

### 4.1. Method

#### 4.1.1. Participants

Fifty-five 5- and 6-year-olds (21 female, $M_{age} = 71.63$ months, $SD = 6.70$ months) were recruited at local museums in Berlin, Germany. Nine additional children were excluded from the analyses because their parents intervened ($n = 2$), they opened their eyes during the hiding phase at test ($n = 5$), they were not native speakers ($n = 1$), or due to experimenter error ($n = 1$). Study 2b was approved by the ethical review board of the Max Planck Institute for Human Development, Berlin (protocol: "Boxes").

#### 4.1.2. Materials, design and procedure

Materials, design and procedure were identical to Study 1, with several small changes to the instructions aimed at highlighting the relevance of the frequency training for the test. First, the experimenter referred to the egg placing action as "*hiding*" throughout the experiment. Second, we introduced a different instructions check at the end of the game. Children were asked how many large boxes they were allowed to open during the hiding game, what actions could be performed to find out whether a large box contained the egg, and where the experimenter hides the egg in this game (i.e., "in the *same* box" or "in a *different* box"). Apart from ensuring that children possessed all the task relevant knowledge, the instructions check also helped to make children aware that the same rules that had applied in the frequency training also applied in the test phase. Children who failed to respond accurately ($n = 17$; 31%) were reminded of the correct answer.

### 4.2. Results and discussion

The logistic regression model was statistically significant, $\chi^2(4) = 15.21$, $p = .004$. The Wald criterion demonstrated that age ($p = .008$), condition ($p = .033$) and order of the first action demonstrated ($p = .024$) made a significant contribution to predicting the action children performed at first.

Older children had an increased likelihood of shaking the box first ($OR = 1.023$ [1.006, 1.040]), and children in the Skewed condition had a decreased likelihood of shaking the box first ($OR = 0.000$ [0.000, 0.471]): More children (68%) shook one or both large boxes before deciding which one to open in the Uniform than in the Skewed condition (37%, see Fig. 3). We found that the interaction of age group and condition ($OR = 1.116$ [0.991, 1.258]) was not a significant predictor.

Children were more likely to shake first when the shaking action was demonstrated at first (62%) but to open first (62%) when the opening action was demonstrated at first ($OR = 0.226$ [0.062, 0.823]). However, we found no interaction between the order in which the actions were demonstrated and condition ($OR = 12.014$ [0.636, 226.966]).

These results demonstrate that, once the relevance of the frequency training for the hiding game is highlighted, 5-year-olds do adapt their exploratory actions to the statistical structure of the task, as younger children could already do in Study 1. It is crucial to notice that the data of Study 2b were collected with a German sample, instead of the American sample participating in the previous studies, and using a German translations of the instructions, which may introduce subtle changes in meaning. To control for these differences, we conducted a replication of Study 2b—Study 2c—with the same population targeted in Study 1 and Study 2a and with English instructions.

## 5. Study 2c

### 5.1. Method

#### 5.1.1. Participants

Fifty-one 5- and 6-year-olds (21 female, $M_{age} = 74.90$ months, $SD = 8.99$ months) were recruited from museums in the East Bay of the San Francisco area. Nine children were excluded from analysis because their parents intervened ($n = 2$), or due to experimenter error ($n = 7$).

#### 5.1.2. Materials, design and procedure

Materials, design and procedure were identical to Study 2b. Note that most of the English script is identical to that used in Study 1 and Study 2a, with the exceptions described in the Methods section of Study 2b.

### 5.2. Results and discussion

The logistic regression model was statistically significant, $\chi^2(4) = 12.43$, $p = .006$. The Wald criterion demonstrated that age ($p = .004$) and condition ($p = .011$) made a significant contribution to predicting the action children performed at first.

Older children had an increased likelihood of shaking the box first ($OR = 1.023$ [1.007, 1.039]), and children in the Skewed condition had a decreased likelihood of shaking the box first ($OR = 0.185$ [0.051, 0.675]): More children shook one or both large boxes before deciding which one to open in the Uniform (84%) than in the Skewed condition (46%; see Fig. 3).

The order of the action training ($OR = 0.702$ [0.198, 2.486]) and the interaction of age group and condition ($OR = 0.971$ [0.895, 1.053]) were not significant predictors.

The results of Study 2c replicated the behavioural pattern found in Study 2b with the same population of participants considered in Study 1 and Study 2a, and with the same English version of the instructions. Once the relevance of the frequency training for the hiding game was highlighted, 5-year-olds adapted their exploratory actions to the statistical structure of the task. In particular, the results are strikingly similar to those obtained by 4-year-olds in Study 1.

The similarity between the results of Study 2b and 2c also suggests a robustness of active learning adaptiveness across populations of children from different nationalities. We are currently further exploring how the developmental trajectory in active learning effectiveness and adaptiveness—the capacity for ecological learning—may be affected by cultural (non-western) and educational contexts, and how it may relate to more general cognitive and motivational factors at the individual level.

## 6. Conclusion

In this project, we investigated whether preschoolers adapt their exploratory actions to the characteristics of the learning environment.

In line with previous research demonstrating that preschoolers and even infants are excellent at tracking statistical regularities (e.g., Denison et al., 2013; Kushnir, Xu, & Wellman, 2010; Waismeyer, Meltzoff, & Gopnik, 2015; Wellman, Kushnir, Xu, & Brink, 2016), our results suggest that preschoolers in our task were able to correctly infer how likely the egg was to be found across the four small boxes based on the frequency pattern they observed during training. Most importantly, we demonstrated that preschoolers exploited this statistical sensitivity to guide their own exploratory actions – choosing the action that promised the largest information gain in the given learning situation. We have thus provided the first evidence that preschoolers as young as 3 are ecological learners, able to efficiently tailor their exploratory actions to the statistical structure of the task. This line of research, focusing on the developmental trajectory of children's adaptiveness and capacity for ecological learning, provides a new perspective on the theoretical and applied investigation of children's search and learning behavior, both in the fields of developmental and cognitive psychology, as well as in education.

To conclude, the present paper provides compelling evidence that children as young as three are *ecological learners*, able to adapt their exploratory actions to task characteristics. Ecological learning may provide a key mechanism underlying children's remarkable learning capacities: We suggest that children are excellent learners *because* they are able to flexibly tailor their exploratory actions to characteristics of the current task to maximize learning effectiveness. Investigating more closely how ecological learning develops across the lifespan and which factors drive its improvement is therefore crucial for increasing our understanding of children's learning processes and strategies.

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## References


Beck, S. R., & Robinson, E. J. (2001). Children's ability to make tentative interpretations of ambiguous messages. *Journal of Experimental Child Psychology, 79*(1), 95–114.

Bonawitz, E. B., van Schijndel, T. J., Friel, D., & Schulz, L. (2012). Children balance theories and evidence in exploration, explanation, and learning. *Cognitive Psychology, 64*, 215–234. https://doi.org/10.1016/j.cogpsych.2011.12.002.

Bosco, F. M., & Gabbatore, I. (2017). Sincere, deceitful, and ironic communicative acts and the role of the Theory of Mind in childhood. *Frontiers in Psychology, 8*.

Butler, L. P., & Markman, E. M. (2012). Preschoolers use intentional and pedagogical cues to guide inductive inferences and exploration. *Child Development, 83*, 1416–1428. https://doi.org/10.1111/j.1467-8624.2012.01775.x.

Butler, L. P., & Markman, E. M. (2014). Preschoolers use pedagogical cues to guide radical reorganization of category knowledge. *Cognition, 130*, 116–127. https://doi.org/10.1016/ j.cognition.2013.10.002.

Butler, L. P., & Markman, E. M. (2016). Navigating pedagogy: Children's developing capacities for learning from pedagogical interactions. *Cognitive Development, 38*, 27–35. https://doi.org/10.1016/j.cogdev.2016.01.001.

Cook, C., Goodman, N. D., & Schulz, L. E. (2011). Where science starts: Spontaneous experiments in preschoolers' exploratory play. *Cognition, 120*, 341–349. https://doi.org/10.1016/j.cognition.2011.03.003.

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia, 44*, 2037–2078.

Denison, S., Bonawitz, E., Gopnik, A., & Griffiths, T. L. (2013). Rational variability in children's causal inferences: The sampling hypothesis. *Cognition, 126*, 285–300. https://doi.org/10.1016/j.cognition.2012.10.010.

Denison, S., & Xu, F. (2014). The origins of probabilistic inference in human infants. *Cognition, 130*(3), 335–347. https://doi.org/10.1016/j.cognition.2013.12.001.

Eaves, B., & Shafto, P. (2012). Unifying pedagogical reasoning and epistemic trust. In F. Xu, & T. Kushnir (Vol. Eds.), *Rational constructivism in cognitive development. Advances in child development and behavior: Vol. 43*, (pp. 295–320). Waltham, MA: Academic Press. https://doi.org/10.1016/B978-0-12-397919-3.00011-3.

Girotto, V., & Gonzalez, M. (2008). Children's understanding of posterior probability. *Cognition, 106*(1), 325–344. https://doi.org/10.1016/j.cognition.2007.02.005.

Gonzalez, M., & Girotto, V. (2011). Combinatorics and probability: Six- to ten-year-olds reliably predict whether a relation will occur. *Cognition, 120*, 372–379. https://doi.org/10.1016/j.cognition.2010.10.006.

Gweon, H., Tenenbaum, J. B., & Schulz, L. (2010). Infants consider both the sample and the sampling process in inductive generalization. *Proceedings of the National Academy of Sciences, 107*(20), 9066–9071.

Jirout, J., & Klahr, D. (2012). Children's scientific curiosity: In search of an operational definition of an elusive concept. *Developmental Review, 32*, 125–160.

Kidd, C., & Hayden, B. Y. (2015). The psychology and neuroscience of curiosity. *Neuron, 88*(3), 449–460.

Kushnir, T., & Gopnik, A. (2005). Young children infer causal strength from probabilities and interventions. *Psychological Science, 16*(9), 678–683.

Kushnir, T., Xu, F., & Wellman, H. M. (2010). Young children use statistical sampling to infer the preferences of other people. *Psychological Science, 21*, 1134–1140. https://doi.org/10.1177/0956797610376652.

Lee, K. (2013). Little liars: Development of verbal deception in children. *Child Development Perspectives, 7*, 91–96. https://doi.org/10.1111/cdep.12023.

Legare, C. H., Gelman, S. A., & Wellman, H. M. (2010). Inconsistency with prior knowledge triggers children's causal explanatory reasoning. *Child Development, 81*(3), 929–944. https://doi.org/10.1111/j.1467-8624.2010.01443.x.

Legare, C. H., Mills, C. M., Souza, A. L., Plummer, L. E., & Yasskin, R. (2013). The use of questions as problem-solving strategies during early childhood. *Journal of Experimental Child Psychology, 114*, 63–76. https://doi.org/10.1016/j.jecp.2012.07.002.

Loewenstein, G. (1994). The psychology of curiosity: A review and reinterpretation. *Psychological Bulletin, 116*(1), 75.

Lucas, C. G., Bridgers, S., Griffiths, T. L., & Gopnik, A. (2014). When children are better (or at least more open-minded) learners than adults: Developmental differences in learning the forms of causal relationships. *Cognition, 131*(2), 284–299. https://doi.org/10.1016/j.cognition.2013.12.010.

Lyons, K., & Ghetti, S. (2011). The development of uncertainty monitoring in early childhood. *Child Development, 82*(6), 1778–1787.

Lyons, K., & Ghetti, S. (2013). I don't want to pick! Introspection on uncertainty supports early strategic behavior. *Child Development, 84*(2), 726–736.

Mosher, F., & Hornsby, J. R. (1966). On asking questions. In J. S. Bruner, R. R. Olver, T. M. Greenfield, J. R. Hornsby, H. J. Kenney, & M. Maccoby (Eds.). *Studies in cognitive growth* (pp. 86–102). New York, NY: Wiley.

Plumert, J. M. (1996). Young children's ability to detect ambiguity in descriptions of location. *Cognitive Development, 11*(3), 375–396.

Polak, A., & Harris, P. L. (1999). Deception by young children following noncompliance. *Developmental Psychology, 35*(2), 561. https://doi.org/10.1037/0012-1649.35.2.561.

Rohwer, M., Kloo, D., & Perner, J. (2012). Escape from metaignorance: How children develop an understanding of their own lack of knowledge. *Child Development, 83*(6), 1869–1883.

Ruggeri, A., & Lombrozo, T. (2019) Children, but not adults, adapt their questions to the likelihood of the solution [Manuscript in preparation].

Ruggeri, A., & Feufel, M. A. (2015). How basic-level objects facilitate question-asking in a categorization task. *Frontiers in psychology, 6*, 918. https://doi.org/10.3389/fpsyg.2015.00918.

Ruggeri, A., & Lombrozo, T. (2015). Children adapt their questions to achieve efficient search. *Cognition, 143*, 203–216. https://doi.org/10.1016/j.cognition.2015.07.004.

Ruggeri, A., Lombrozo, T., Griffiths, T. L., & Xu, F. (2016). Sources of developmental change in the efficiency of information search. *Developmental Psychology, 52*(12), 2159–2173. https://doi.org/10.1037/dev0000240.

Ruggeri, A., Sim, Z. L., & Xu, F. (2017). "Why is Toma late to school again?" Preschoolers identify the most informative questions. *Developmental Psychology, 53*, 1620. http://doi.apa.org/getdoi.cfm?doi=10.1037/dev0000340.

Ruggeri, A., Swaboda, N., Sim, Z. L., & Gopnik, A. (2019). *Shake it baby, but only when needed: Preschoolers adapt their exploratory strategies to the statistical structure of the task*. https://doi.org/10.17605/OSF.IO/3NAXU.

Schulz, L. (2015). Infants explore the unexpected. *Science, 348*(6230), 42–43. https://doi.org/10.1126/science.aab0582.

Schulz, L. E., & Bonawitz, E. B. (2007). Serious fun: Preschoolers engage in more exploratory play when evidence is confounded. *Developmental Psychology, 43*, 1045. https://doi.org/10.1037/0012-1649.43.4.1045.

Schulz, L. E., Bonawitz, E. B., & Griffiths, T. L. (2007). Can being scared cause tummy aches? Naive theories, ambiguous evidence, and preschoolers' causal inferences. *Developmental Psychology, 43*(5), 1124–1139. https://doi.org/10.1037/0012-1649.43.5.1124.

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science, 348*, 91–94. https://doi.org/10.1126/science.aaa3799.

Todd, P. M., Gigerenzer, G., & The ABC-Research Group (2012). *Ecological rationality: Intelligence in the world.* New York: Oxford University Press, USA.

Waismeyer, A., Meltzoff, A. N., & Gopnik, A. (2015). Causal learning from probabilistic events in 24-month-olds: An action measure. *Developmental Science, 18*, 175–182. https://doi.org/10.1111/desc.12208.

Wellman, H. M., Cross, D., & Watson, J. (2001). Meta-analysis of theory-of-mind development: The truth about false belief. *Child Development, 72*(3), 655–684. https://doi.org/10.1111/1467-8624.00304.

Wellman, H. M., Kushnir, T., Xu, F., & Brink, K. A. (2016). Infants use statistical sampling to understand the psychological world. *Infancy, 21*, 668–676. https://doi.org/10.1111/i.