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Infants' understanding of rates and probability matching in a foraging task

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Abstract

Cognitive scientists have long debated whether human learners are rational decision-makers. Much work has found that adults and children tend to use probability matching strategies in probability learning tasks despite probability maximizing being the optimal strategy. However, other work provides conflicting findings on what decision-making strategies are used and under what circumstances. Unlike previous studies that employed a typical design with a single individual making decisions (where probability maximizing is the optimal strategy), we investigate decision-making strategies in a group foraging context where probability matching is the optimal strategy. In the current study, we tested 14- to 20-month-old infants' ability to (1) distinguish rates of reward distribution in a group foraging scenario and (2) their expectations for probability matching based on these rates. Our results are the first to suggest infants are capable of quantitative reasoning involving rates and they form expectations for optimal decision-making strategies based on rate information.

Keywords: foraging; probability matching; decision making; human infants

Introduction

Rational choice theory suggests that individuals should calculate the costs and benefits of an action and take actions that maximize payoff. A common method used to study this behavior is through probability learning tasks, where participants are typically presented with two options that produce rewards, with each option varying in the probability of producing a reward (e.g. one option produces a reward 30% of the time vs. another at 70%). In this paradigm, there are two main decision-making strategies that can be employed to attempt to maximize payoff – probability maximizing and probability matching (e.g., Estes & Straughan, 1954; Gardner, 1957; Koehler & James, 2010).

Probability maximizing refers to the strategy of consistently selecting the most probable outcome, whereas *probability matching* refers to responding in a way that is proportional to the observed reward probabilities. For example, in the case of a 70:30 probability task, a probability maximizing strategy would be selecting the 70% option on every single trial, resulting in an overall 70% rate of reward. In contrast, a probability matching strategy would be selecting the 70% option on 70% of trials and the 30% option on 30% of trials, resulting in an overall 58% rate of reward. Thus, probability maximizing is the optimal strategy to maximize payoff. However, previous research has found conflicting evidence as to whether humans and other animal

species use probability maximizing strategies and have thus questioned whether they make rational decisions.

Several studies have found that adults tend to use probability matching over maximizing strategies when completing probability learning tasks. Gardner (1957) found that when adults were asked to predict which of two lightbulbs would illuminate next, participants' responses exhibited a probability matching strategy. Similarly, Neimark and Shuford (1959) asked adults to predict which of two letters would appear next in a deck of cards and found that the frequency of participants' responses for each letter matched the actual observed frequencies of each letter occurring. Other work has found that although some adults tended to *over-match*, such that they tended to select the higher-probability option more than the observed frequency, the frequencies of selection were far from probability maximizing (Edwards, 1961).

However, additional empirical evidence suggests that human adults' use of these two strategies vary depending on several factors. For example, Gardner (1958) manipulated the number of response options from two options up to eight options, with the usage of probability maximizing strategies increasing with the number of response options. Other factors, such as increasing the task length to provide more opportunities to extract the reward probabilities (Shanks et al., 2002) and changing the framing of the task (Goodnow & Postman, 1955), have also been shown to increase the usage of maximizing over matching strategies.

This picture of optimal strategy-use becomes even more blurry when considering developmental findings. Although some research suggests a U-shaped developmental trend in what strategies are used, such that younger children (3- to 5-year-olds) and older teenagers tend to maximize whereas children between these ages tend to probability match (Derks & Paclisanu, 1967; Stevenson & Weir, 1959; Weir, 1964), other studies have found that children tend to respond randomly or do not adhere to either probability matching or maximizing strategies (Craig & Myers, 1963; Thoma & Schulze, 2025). A comprehensive review by Montag (2021) found no consistent results in children.

Taken together, these studies suggest that humans are quite mixed in the decision-making strategies they employ, which vary widely depending on a variety of factors. The vast majority of studies exploring probability matching and maximizing behavior utilize similar paradigms, presenting an individual with two or more response options with varying reward probabilities. In this case, probability maximizing is clearly the optimal strategy. However, in more naturalistic

contexts, such as the context of foraging for food in groups, the optimal strategy differs.

A rich body of research has examined foraging behavior in many species (see Gallistel, 1990 for a review). Harper (1982) explored foraging behavior of mallard ducks. When two people tossed pieces of bread into a pond of ducks at different rates, with one person tossing the bread twice as fast as the other, the flock of ducks dispersed in a manner consistent with the rate of tossing. That is, twice as many ducks dispersed towards the faster tosser than towards the slower tosser (2:1 ratio). In this scenario, probability matching, as exhibited by the ducks, is the optimal strategy: if all ducks individually maximized and dispersed towards the faster tosser, the entire flock would receive less food (only 2/3 of the total amount of bread pieces) than dispersing in a manner consistent with the reward probabilities. Other research has also found similar results with non-human animal species such as bumblebees (Dreisig, 1995) and cichlid fish (Godin & Keenleyside, 1984).

Given humans' history of foraging in groups, it is possible that probability matching may be evolutionarily ingrained as the optimal strategy, which would suggest even young infants may have an expectation for probability matching. However, little research has explored what strategies human learners use in group contexts. Some studies have explored whether children and adults use probability matching in group competitions, though results are mixed as to whether these groups employ a true probability matching strategy (Disma, Sokolowski, & Tonneau, 2013; Kraft & Baum, 2001).

To our knowledge, almost no studies have explored these decision-making strategies in infancy. In the current study, we focus specifically on probability matching to explore whether infants have an expectation for probability matching in a group foraging context based on reward probabilities using a paradigm inspired by studies with non-human animals. Additionally, although some studies to date have explored whether infants by 6 months of age can differentiate temporal duration (Brannon, Suanda, & Libertus, 2007; VanMarle & Wynn, 2006), no research to date has explored whether infants can distinguish between rates. Our study is the first to explore whether infants have this ability, which is essential for employing a probability matching strategy in foraging contexts as in Harper (1982).

Methods

Participants

Thirty-three 14- to 20-month-old infants participated in this study (Mean Age = 16.43 months, Range = 14.00 – 20.35 months). Participants were recruited via ChildrenHelpingScience.org (Scott & Schulze, 2017). Six additional infants participated in this study but were excluded due to participating on a device that was deemed too small to be able to properly view the stimuli ($n=1$) or for leaving the study before completing at least one test trial ($n=5$).

For participants whose parents reported demographic information ($n=32$), the sample was approximately as

follows: 19% Latino, 37% White or Caucasian, 13% Asian, 0% Black or African American, 3% Other, 25% mixed race, and 3% prefer not to answer. All parents who reported parental education reported having a Bachelor's degree or higher.

Stimuli and Procedure

Animated videos were created using Blender. All participants completed the study on ChildrenHelpingScience.org. Before starting the study, all participants completed a calibration phase in order to define their looking window.

Introduction. To first introduce infants to the scene, including the tossing actions and the goal of group members, infants were presented with two agents, each standing behind a box (Figure 1). One agent wore a red shirt and the other a green shirt. Two children stood at the front of the room, with all characters facing the infant participant. Each child jumped up and down a few times, followed by both children turning around to face the two agents simultaneously tossing candies into their respective boxes at the same rate (one candy every three seconds). In addition to visual cues representing the rates of tossing (i.e. the speed of candies being tossed from the hand into the box), additional audio cues were synchronized with each toss to further distinguish the rates from one another, with a higher pitched water droplet sound playing when candies were tossed for one agent and a lower pitched metal can sound playing for candies tossed by the other agent. After tossing four candies into the box, the agents stopped. Then the children dispersed towards the tossers (one child for each tosser). Each child took two candies out from the box, turned around, and ate the candy (paired with crunching sound effects).

Example of Introduction

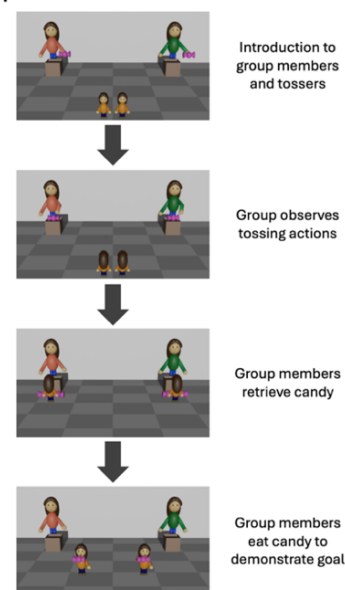


Figure 1: Example of sequence of events of introduction

Familiarization trials. Infants were then introduced to the different tossing rates of the two agents. The same two agents tossed candies into their respective boxes (Figure 2). The first agent, wearing a red shirt, tossed candies into their box for 30 seconds at a rate of *one per three seconds*. Then the second agent, wearing a green shirt, tossed candies into their box for 30 seconds at half the rate of the first agent (i.e. *one per six seconds*). Then, infants were presented with two 30-second trials depicting both agents tossing at the same rates as before, but this time with both agents tossing simultaneously. The tossing rates were again paired with the same auditory sound effects to provide additional information to distinguish the rates from one another.

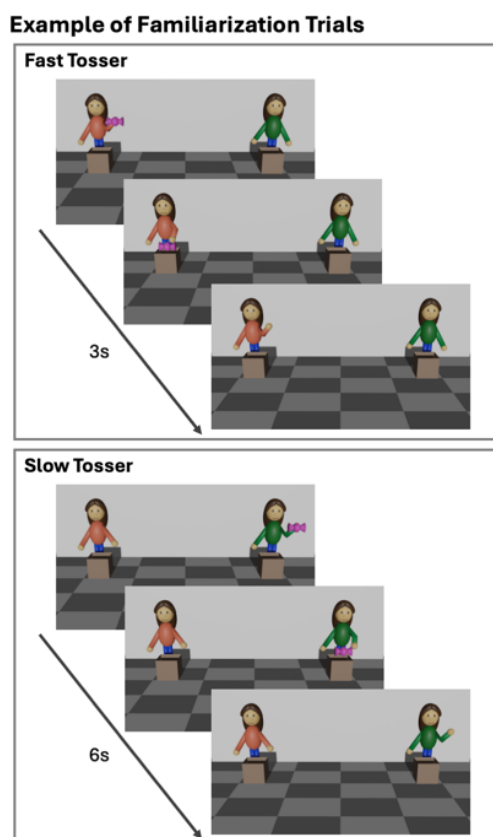


Figure 2: Example of familiarization trials for fast and slow tossers

Test trials. During the test trials, a group of 12 children stood in front of the same two tossing agents. The number of group members was again highlighted by each child jumping up and down individually, followed by the children turning around to face the two tossing agents. Similar to the familiarization trials, infants then viewed the agents tossing simultaneously for 30 seconds at their same respective rates with the same sound effects as previously shown (i.e., the red agent tossed at a rate twice as fast as the green agent). Then infants heard a verbal cue, “Look!”, followed by the group of children dispersing in one of two ways towards the tossers based on trial type. In the Expected trial, the children dispersed in a

manner consistent with the tossing rates: twice as many children (i.e. eight) moved towards the faster tosser as the number of children who moved towards the slow tosser (i.e. four). In the Unexpected trial, the group dispersion was reversed: twice as many children moved towards the *slower* tosser as the number of children who moved towards the faster tosser. After this group dispersion, the agents continued tossing at their respective rates for 25 seconds with the group members frozen, during which looking time was coded. Each infant was presented with two pairs of test trials, each comprised of one Expected and one Unexpected trial. The order of trials was counterbalanced across participants. The study lasted a total of seven minutes.

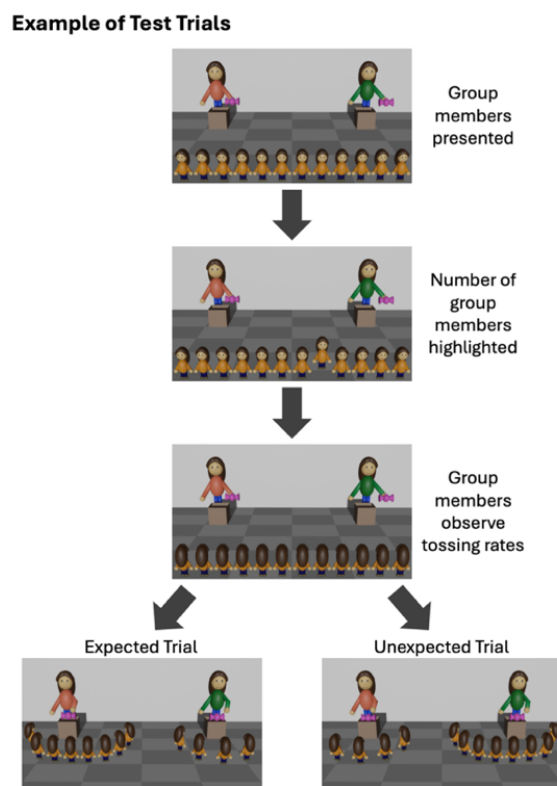


Figure 3: Sequence of events during test trials

Data Coding and Analysis

To assess infants' looking behavior, coding of looking time duration for each test trial started when the infant looked towards the screen for two or more seconds continuously. When the infant looked away for 2 seconds continuously, the trial ended. Each test trial lasted 25 seconds. Due to the nature of online, unmoderated testing where trial lengths could not be infant-controlled, if on a test trial an infant looked at the screen for more than 23 of the 25 second coding period, their data from that trial was excluded. That is, when the coder could not determine when the trial ended with the 2s look away criterion.

Results

We conducted several repeated-measures ANOVAs examining the effects of Age, Trial Type (Unexpected vs. Expected), and Trial Pair (first vs. second) on infants' looking time. Because our critical analysis involves comparing looking times to the unexpected versus expected trials and there are multiple occasions where one of the two trials per pair may have been excluded within a particular participant, we report separate repeated-measures ANOVAs to account for different treatment of the missing data.

First, to maximize our sample, all missing data for participants who provided data for at least one test trial was replaced by the group mean (i.e. participant may have provided data on only one test trial with three additional trials of missing data replaced with the respective group means). This resulted in data from 31 participants. A repeated-measures ANOVA revealed a significant effect of Trial Type ($F(1,27)=10.77$, $p = .046$), and no other main effects or interactions ($ps > .1$). Infants looked reliably longer at the Unexpected ($M = 12.09s$, $SD = 5.47$) than Expected trials ($M = 10.47s$, $SD = 4.75$). (Figure 4).

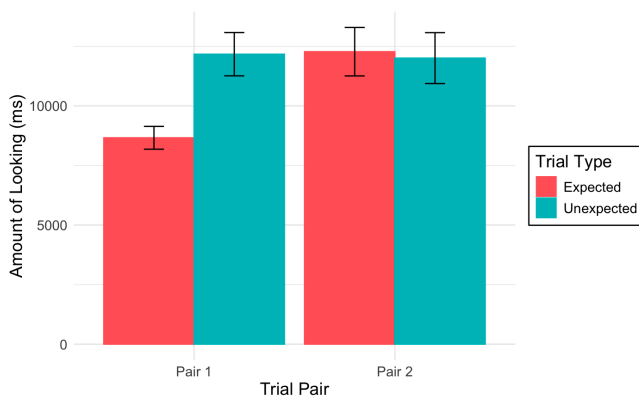


Figure 4: Average looking time per trial type including all participants who provided data on at least one test trial.

Second, we conducted the same analysis but with only imputing data for participants who provided data on at least one test trial for both trial pairs. This resulted in data from 18 participants. A repeated-measures ANOVA revealed a significant effect of Trial Type ($F(1, 14)=22.151$, $p = .018$), with infants again looking longer to the Unexpected ($M = 11.61s$, $SD = 5.87$) than Expected trials ($M = 8.76s$, $SD = 4.06$), and no other significant effects or interactions ($ps > .4$) (Figure 5).

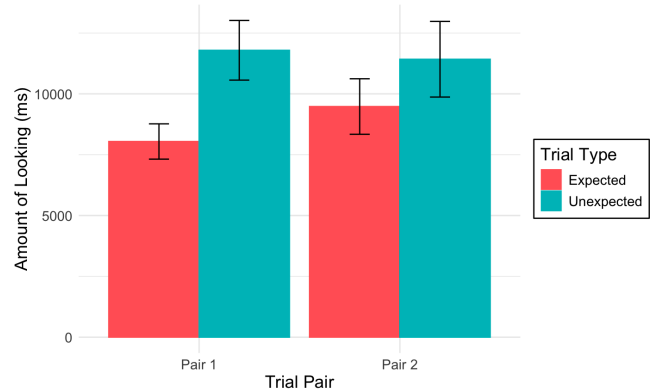


Figure 5: Average looking time per trial type including only participants who provided data for both trial pairs

Lastly, we conducted the same analysis but only including participants who provided data on all test trials. This resulted in data from 8 participants. Due to the small sample size, we removed Age from the model. A repeated-measures ANOVA again revealed a significant effect of Trial Type ($F(1,7)=5.60$, $p = .050$), with infants looking significantly longer at the Unexpected ($M = 10.31s$, $SD = 4.69$) than Expected trials ($M = 7.63s$, $SD = 3.04$). There were no other significant effects or interactions ($ps > .2$).

Discussion

The current study provides evidence that infants by 14 months of age are sensitive to rate information and expect probability matching behavior of groups in accordance with these rates. Our results are the first to suggest that infants are more surprised when a group disperses in a way that is not consistent with the rate of food tossing, suggesting that (1) they are able to distinguish the rates of the two tossers and (2) they can use this information to form expectations about probability matching in a group foraging context. Our findings make two important contributions to developmental cognitive science.

First, previous work has explored extensively quantity discrimination in infancy across a variety of domains. Much work has investigated number discrimination, showing that even by 6 months of age, infants are able to discriminate between quantities of items representing a 2:1 ratio (Brannon, Abbott, & Lutz, 2004; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005), and newborns are able to discriminate 3:1 ratios (Izard et al. 2009). Other work has shown that infants can enumerate action sequences (e.g. number of jumps; Wood & Spelke, 2005) and sounds (Lipton & Spelke, 2003). In addition to numerosity, other work has also explored proportion discrimination, finding that infants by 6 months of age can discriminate between proportions, e.g., 4:1 vs 2:1 (McCrink & Wynn, 2007). Some research has additionally explored temporal discrimination, finding that infants can discriminate between durations of sounds with a 2:1 ratio (VanMarle & Wynn, 2006). These studies show that infants have early quantitative abilities that are critical for later

learning across many domains. However, no work has explored whether infants can discriminate between rates. Here, we provide the first evidence that by 14 months of age, the sensitivity to rates is part of infants' quantitative reasoning toolbox as well.

Second, despite a long-standing debate by cognitive scientists arguing that humans may not be rational decision-makers due to their failure to use probability maximizing strategies in probability learning tasks, our study is the first to explore rational decision making in foraging contexts in infants. Although probability maximizing is the optimal strategy in typical probability learning tasks, where an individual is tasked with guessing which of multiple options varying in the probability of producing a reward will next produce a reward, foraging contexts provide an alternative viewpoint. Specifically, in group foraging, probability matching is the optimal strategy over probability maximizing, as this leads to the highest reward per individual in the group. Here, we show that, just like several non-human animal species (Dreisig, 1995; Harper, 1982), human infants also expect a group of foragers to employ a probability matching strategy based on the rate of reward distribution.

Given the debate on whether humans are rational decision-makers and what strategies are optimal, as well as under what circumstances each strategy is considered optimal, our study provides the foundation for exploring these questions in infancy and probing the developmental origins of these strategies. However, the current study has several limitations that need to be addressed in follow-up studies.

One methodological issue is that due to the unmoderated nature of the study, trials were not infant-controlled as in most in-person in-lab studies. This resulted in some data loss due to infants looking for the maximum duration on the test trials. To explore the possible impact this may have had on our results, we examined whether infants exceeded the maximum looking time more or less often on expected versus unexpected test trials. We found no difference. In future studies, we will extend the duration of the test trials to help reduce data loss.

Several important conceptual questions also remain open. First, we showed that infants can distinguish between rates and expect probability matching behavior of a group in accordance with these rates. However, because we did not directly test infants' expectations for probability maximizing or compare infants' expectations for probability maximizing versus probability matching, the question as to which of the two strategies infants expect and whether they expect the more optimal strategy remains. We plan to run a follow-up experiment directly comparing probability maximizing (i.e. an entire group moves towards the faster tosser) and probability matching strategies to explore whether infants can distinguish between these strategies, as well as which of the two strategies infants expected.

Second, our study only investigated infants' ability to distinguish rates of a 2:1 ratio. However, it is unclear whether these results hold when rates represent different ratios, such as 3:1 (i.e. when tosser throws candy at three times the rate

as another) or 4:1. In follow-up experiments, we plan to manipulate the rate of tossing to further explore the possible limitations on infants' ability to discriminate rates and whether these align with discrimination abilities in other domains (e.g. numerosity), as well as whether infants' probability matching expectations vary as a function of the specific rates of reward distribution instead of using lower-level cues (i.e. infants are encoding the specific rates themselves to determine probability matching behavior, not just expecting generally *more* people to go to the faster tosser and *fewer* to the slower tosser).

Third, the probability matching strategy is optimal in group foraging contexts. However, beyond obvious foraging contexts of searching for and receiving food or another type of physical reward, there are other group contexts where probability matching is the optimal strategy. For example, in a grocery store with two checkout lines, where one cashier is ringing shoppers up twice as fast as the other, probability matching would again be the optimal strategy. However, unlike foraging contexts, the intended goal is not to maximize food or a physical reward, but to maximize time and efficiency. To our knowledge, there is no work to date exploring whether infants, children, or adults have similar expectations for decision-making strategies across different contexts such as this, thus making it unclear whether these expectations hold across a variety of contexts or are strictly applied only to foraging. In future studies, we may compare a foraging context with a non-foraging context to see if infants' expectations differ.

Lastly, little work to date has explored similar decision-making strategy behavior or expectations in group contexts across childhood into adulthood. Some observational studies have explored human children's probability matching behavior in naturalistic group contexts, such as competitions to sell water bottles to multiple lanes of cars (Disma, Sokolowski, & Tonneau, 2013). Similarly, work with human adults exploring decision-making in a competition of a group of individuals for money also found probability matching behavior (Sokolowski, Tonneau, & Baqué, 1999). However, other studies provide conflicting evidence, finding that human adults tended to *under-match*, with too many individuals selecting the less profitable option and too few individuals selecting the more profitable option (Goldstone & Ashpole, 2004; Kraft & Baum, 2001). In future work, we will continue to explore whether young children and adults also form and hold the same expectations as infants based on rate information or whether these expectations change over the course of development.

Our study provides the first evidence that infants' quantitative reasoning abilities extend to rates, and that they can use this information to form expectations of rational decision-making behavior. In future research, we plan to directly compare infants' expectations for probability matching and probability maximizing in group foraging and other contexts, as well as extend these findings to other ratios of rates.

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