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PAPER

Twelve- to 14-month-old infants can predict single-event probability with large set sizes

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Abstract

Previous research has revealed that infants can reason correctly about single-event probabilities with small but not large set sizes (Bonatti, 2008; Teglas et al., 2007). The current study asks whether infants can make predictions regarding single-event probability with large set sizes using a novel procedure. Infants completed two trials: A preference trial to determine whether they preferred pink or black lollipops and a test trial where infants saw two jars, one containing mostly pink lollipops and another containing mostly black lollipops. The experimenter removed one occluded lollipop from each jar and placed them in two separate opaque cups. Seventy-eight percent of infants searched in the cup that contained a lollipop from the jar with a higher proportion of their preferred color object, significantly better than chance. Thus infants can reason about single-event probabilities with large set sizes in a choice paradigm, and contrary to most findings in the infant literature, the prediction task used here appears a more sensitive measure than the standard looking-time task.

Introduction

Over the past several decades much research has investigated probabilistic reasoning in humans. In the adult literature, some researchers have suggested that people can use observed frequency information to only predict the likelihood of future events and that they are incapable of using probabilistic reasoning alone in order to make these judgments (e.g. Cosmides & Tooby, 1996). Other researchers have claimed that human probabilistic reasoning is faulty, as it is affected by heuristics that can often lead to inaccurate conclusions (e.g. Kahneman, Slovic & Tversky, 1982). However, many studies have shown that adults can reason normatively correctly under a variety of circumstances, especially when the tasks were implicit or when the format of the information provided was more ecologically friendly (e.g. Chater & Oaksford, 2008; Gigenrenzer & Hoffrage, 1995). Furthermore, an emerging body of research investigating the developmental origins of probabilistic reasoning suggests that infants and young children can make accurate probabilistic inferences in rudimentary tasks (Bonatti, 2008; Denison, Konopczynski, Garcia & Xu, 2006; Denison & Xu, 2009; Falk & Wilkening, 1989; Schlottmann, 2001; Teglas, Girotto, Gonzalez & Bonatti, 2007; Xu & Denison, 2009; Xu & Garcia, 2008).

One line of research investigating probabilistic reasoning in infants provides evidence that both 8- and 11-month-old infants can make probabilistic inferences from samples to populations and vice versa in a looking-time paradigm (Xu & Denison, 2009; Xu & Garcia, 2008). In these experiments, infants were familiarized to two large populations of ping-pong balls, one with a 9:1 ratio of red to white balls and the other with the opposite ratio. On test trials infants watched as an experimenter removed samples of, for example, four red balls and one white ball or four white balls and one red ball from a large, occluded population. The experimenter then revealed a population of, say, mostly red ping-pong balls, and infants' looking behavior was recorded. Infants looked longer at samples that were less probable given the population of ping-pong balls in the box (i.e. they looked longer at a sample of four white and one red balls than a sample of four red and one white balls from a mostly red box). This finding suggests that infants can make inferences about the relationship between samples and populations with multi-object samples and large populations.

Another line of research suggests that 12.5-month-old infants can make judgments about single-event probabilities when making predictions about future events based on their likelihood and not on their observed frequencies (Teglas *et al*., 2007). In a looking-time experiment, Teglas *et al*. (2007) showed infants a lottery machine on a computer screen with four objects moving inside the machine, three that were identical in shape and color and one that differed from the other three in shape and color. An occluder then covered the

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machine and, on alternating test trials, one object – either one of the identical objects or the different object – exited the machine. They found that infants looked longer at the event when the one different object exited the machine. This experiment provides evidence that infants can make predictions about a future event based on probability and not on the observed frequencies of past events.

In a follow-up study, Bonatti (2008) tested another group of 12.5-month-old infants in the same procedure with 16 objects in a 3:1 ratio. Surprisingly, the infants did not differentiate between the more and less probable outcomes on the test trials with the larger set size, even though the ratio was the same as before. Teglas *et al.* (2007) used four objects in their study in order to make the task accessible to infants, given previous evidence that infants and adults can represent and bind into sets a maximum of three or four objects, and track them over time (e.g. Feigenson, Carey & Hauser, 2002; Feigenson & Halberda, 2004; Ross-Sheehy, Oakes & Luck, 2003; Scholl & Pylyshyn, 1999). In contrast, with a larger population, infants were unable to reason about single-event probabilities in the same looking-time paradigm that they had succeeded in with a smaller set of objects. Bonatti (2008) interpreted infants' failure with a large set size as suggesting that infants can only reason about single-event probability in the context of an object tracking task (i.e. tasks with a maximum of four objects). He suggests that infants' inferential abilities are limited by domain-specific knowledge of object-file representations. This raises the question of whether infants can make inferences about the likelihood of single events with set sizes larger than four, and thus outside the context of object tracking.

We question the claim that infants can represent and compute probabilities only in the context of object tracking for several reasons. First, according to previous experiments, infants appear to be able to make probabilistic inferences with large set sizes and multi-object samples without the benefit of past frequency information (Denison & Xu, 2009; Xu & Denison, 2009; Xu & Garcia, 2008). Second, the task used by Teglas *et al.* (2007) and Bonatti (2008) was designed to encourage object tracking, that is, a set of objects moved on a screen, much like the standard multiple object tracking task in adult studies (e.g. Scholl & Pylyshyn, 1999), and past research has shown that this is precisely the context in which adults had difficulty tracking more than four objects at one time. Therefore we attempt to devise a different task that might allow infants to reason about probability with large set sizes outside of the object tracking paradigm.

In the current study, we used an explicit behavioral task modeled after the choice procedure developed by Feigenson *et al.* (2002). Each infant completed two trials, a preference trial and a test trial. For half of the infants, we began with a preference trial to determine which of two different colored objects infants preferred. Infants then completed a test trial where we showed them two populations of objects: one with a 4:1 ratio of preferred to not preferred objects and the other with the opposite ratio. We then occluded the populations and removed one covered object from each population and placed the objects in separate opaque cups. At the conclusion of the test trial, we encouraged infants to crawl or walk to a cup of their choice in order to determine whether they could make a prediction about which jar was most likely to have produced their preferred object. The design was counterbalanced such that the other half of the infants completed the test trial first and the preference trial second. If infants can succeed at this task it will provide the first evidence that they are capable of reasoning about single-event probability without the use of object-file representations.

Method

Participants

Participants were 32 12- to 14-month-old infants (16 girls, 16 boys; mean age = 13;16 [months;days], range = 12;2–14;17) recruited by phone from the greater Vancouver area. An additional six infants were tested but not included in the final sample due to experimenter error (one), failure to provide a preference (two), or failure to make a choice on test trials (three). In order to compare our findings to the 12.5-month-old infants' performance in Teglas *et al.* (2007) and Bonatti (2008)[1], infants were split into a younger age group (*n* = 16; seven girls, nine boys; mean age = 12;16, range = 12;2–13;13) and an older age group (*n* = 16; nine girls, seven boys; mean age = 14;7, range = 13;17–14;17). Infants received a T-shirt and diploma for their participation.

Materials

The objects used were lollipops covered with construction paper. The lollipops measured about $5.5 \times 5 \times 1.3$ cm each and were covered such that the stick remained visible (4.5 cm in length). Two glass cylindrical jars (1320 cm^3 in volume) were used to hold the populations of lollipops; both jars had a strip of black duct tape covering the top 7 cm of the jars. One jar contained 50 lollipops in a 4:1 ratio of pink to black lollipops and the other contained the opposite ratio. Two large cylindrical covers made from orange construction paper were used as covers for the jars. The samples of lollipops removed during test trials were placed in two blue, opaque cups (10 cm in diameter, 9 cm in height) and each cup had a cover (12 cm in diameter). In order to allow the sticks to remain visible while the lollipops were in the

[1] Infants in Teglas *et al.* averaged 12 months, 12 days. Infants in Bonatti (2008) averaged 12 months, 19 days and ranged from 12;15 to 12;19.

cups and the covers were closed, each cover had a small (2 square cm) cut out.

Design and procedure

Infants were tested individually in a forced-choice paradigm. A video camera recorded the infants' and experimenter's behavior. Each infant sat on her parent's lap on the floor 1 meter from the experimenter. Parents were instructed to hold on to their infant and avoid influencing them in any way. They were also told that they would be asked to let go of their infant twice during the experiment and that they should simply place their infant on the floor directly in front of their lap and remove their hands from the infant.

Preference trial

Each infant completed one preference trial. The experimenter brought one pink lollipop and one black lollipop out from behind her back. She drew the infant's attention to each saying, 'See this one? Look at that one. Do you want to come pick one?' She then placed the lollipops approximately 1 meter apart on the floor in front of the infant, far enough that the infant could not reach both lollipops simultaneously. The parent was then instructed to let go of the infant. Once the infant had crawled or walked to one of the two lollipops the preference trial was over and the experimenter instructed the parent to put their infant back on their lap. The experimenter then gave the infant the lollipop that she did not choose so that she could briefly play with both lollipops. The experimenter took both lollipops back from the infant. The preference trial lasted approximately 2 minutes.

Test trial

Each infant completed one test trial. Half of the infants completed a standard test trial wherein the experimenter brought out the two covered large glass jars and placed them 80 cm apart on the floor. She also brought out two opaque cups and placed them between the jars so that they were approximately 7 cm to the left or right of the jar and approximately 7 cm in front of each jar. She began the trial by flipping open the top cover on each cup and saying, 'Look it's empty!' beginning with the cup on the left. She then removed the covers from both jars simultaneously to reveal the populations to the infants. Next, the experimenter drew the infant's attention to each jar by lifting the jar off the floor, turning it and saying, 'Look at this! See all of those?', always starting with the jar on the left side. After placing each jar back on the floor, the experimenter closed her eyes and reached into the jar on the left. She pulled out one lollipop such that the infant could see the stick but could not see the color of the lollipop, as it was occluded by the experimenter's hand the entire time. She then placed the lollipop in the cup next to the jar while saying, 'Watch me do this!' and closed the cover on the cup without letting the infant see the color of the lollipop. The experimenter did not take the lollipop from the jar unless she was certain that the infant was watching. She repeated this action with the jar on the right and placed the lollipop in the cup next to the jar. Finally, the experimenter lowered the covers over the jars simultaneously and said, 'Come choose one. Do you want to come and get one?', and instructed the parent to let go of their infant. Once the infant crawled or walked to a cup the trial was over and the parent was asked to place their infant back on their lap. The experimenter then gave the infant both lollipops to play with. The test trial lasted approximately 3 minutes.

The other half of the infants completed a test trial identical to the one described above with one exception. When the experimenter removed the lollipops from the jars, instead of placing each lollipop into the cup next to the jar from which the object was removed, she placed them in the opposite cups. For example, when taking the first lollipop out of the jar on the left, the experimenter pulled the lollipop out and said, 'Watch me do this!' while placing the lollipop in the cup next to the jar on the right (see Figure 1).

Four factors were fully counterbalanced across infants: (1) the side that the lollipops were on during the preference trials – pink on the left for half of the infants, pink on the right for the other half; (2) the side that the jars were on

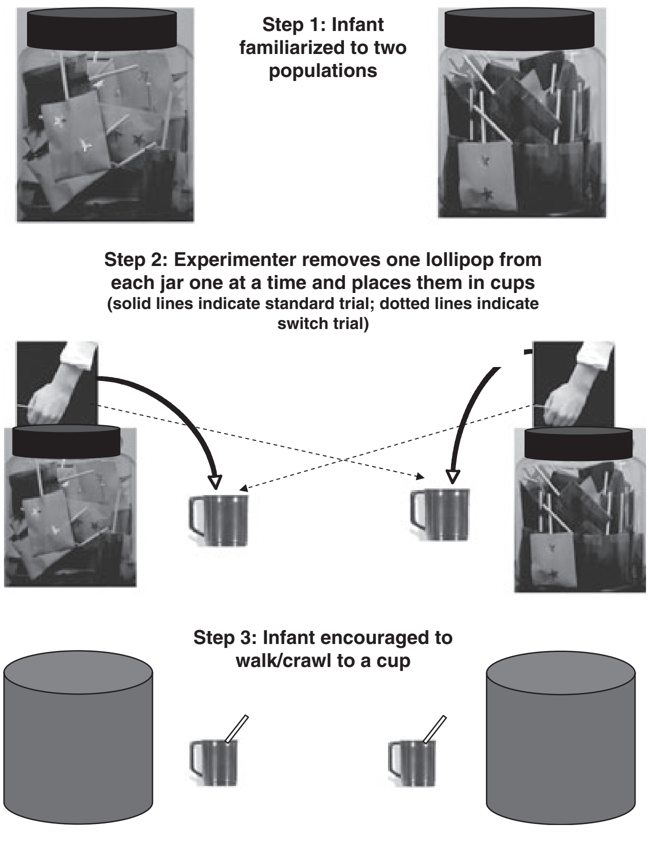

Figure 1 *Schematic representation of the test trials.*

during the test trials – the mostly pink jar on the left for half of the infants, the mostly pink jar on the right for the other half; (3) the order of the trials – half of the infants completed the preference trial first and half completed the test trial first; (4) the sampling procedure – the experimenter did not switch sides when placing the sample into the cup for half of the infants and did switch sides when placing the sample in the cup for the other half, i.e. the experimenter reached into each jar and placed the lollipops in the cups next to the jars from which they were removed (not switched) or the experimenter placed the lollipops in the opposite cups (switched).

Results

Data were obtained from the videotape by a coder who was not present during the study. A second coder also coded data, and inter-rater reliability was 97%. Infants received one point for choosing the cup from which they were most likely to obtain their preferred color lollipop (e.g. the infant chose pink on the preference trial and then went to the cup with the lollipop from the mostly pink jar). Infants received zero points if they chose the cup from which they were less likely to obtain their preferred color lollipop.

An analysis of variance revealed no differences in performance based on gender ($F(1, 13) = .10$, $p > .5$), order of trials ($F(1, 13) = 0.23$, $p > .5$), whether the experimenter switched sides when placing the lollipops in the cups ($F(1, 13) = .41$, $p > .5$) (see Table 1 for descriptive statistics for these factors), whether the pink or black lollipop was on the left during the preference trial ($F(1, 13) = .04$, $p > .5$), or whether the mostly pink or mostly black jar was on the left during test trials ($F(1, 13) = .00$, $p > .5$). There were also no interactions between these factors. Therefore we collapsed across these variables for subsequent analyses. Overall, 78.13% ($SE = 7.42$) of infants selected the correct cup, which is reliably different from chance (50%), $t(31) = 3.79$, $p < .001$; .95 confidence interval (63.13%, 93.13%).

Table 1 *Descriptive statistics*

Factor	Percent correct	*SE*	# of infants correct
Sampling procedure			
No Switch ($n = 16$)	81.25%	10.01	13
Switch ($n = 16$)	75.00%	11.18	12
Order of trials			
Preference trial first ($n = 16$)	75.00%	11.18	12
Test trial first ($n = 16$)	81.25%	10.01	13
Gender			
Male ($n = 16$)	75.00%	11.18	12
Female ($n = 16$)	81.25%	10.01	13
Age split			
Younger ($n = 16$)	81.25%	10.01	13
Older ($n = 16$)	75.00%	11.18	12
Color preferred			
Pink preference ($n = 25$)	80.00%	8.17	20
Black preference ($n = 7$)	71.43%	18.44	5
All infants ($n = 32$)	78.00%	7.42	25

Both the younger (Mean age = 12;16; percent correct = 81.25%) and the older (Mean age = 14;7; percent correct = 75.00%) age groups performed significantly better than would be expected by chance, $t(15) = 3.10$, $p < .01$; .95 confidence interval (61.63%, 100%) and $t(15) = 2.24$, $p < .05$, respectively; .95 confidence interval (53.09%, 96.91%). These two age groups did not differ in performance, $F(1, 30) = .17$, $p > .5$. There was also no difference in performance between infants who chose pink ($n = 25$, percent correct = 80%) versus black ($n = 7$; percent correct = 71%) lollipops on the preference trials, $F(1, 30) = .27$, $p > .5$ (see Table 1).

Discussion

Infants chose to walk or crawl to the cup from which the experimenter had a higher probability of obtaining an object of their preferred color on 78% of trials. This suggests that infants were able to use the statistical information in the two populations to determine which of two cups would most likely contain their preferred object. Because infants completed only one test trial, they could not have used observed frequency information to determine which jar was more likely to produce their preferred color lollipop but instead were forced to reason solely based on probability. Therefore we provide the first evidence that infants can reason about single-event probabilities with large set sizes in an explicit behavioral task that requires infants to make a prediction.

This result, which suggests that infants can reason about single-event probability in large populations, diverges from those of Bonatti (2008) and Teglas *et al.* (2007), even though the 12-month-old group was of a similar age to those in Teglas *et al.* (2007) (mean age = 12;12) and Bonatti (2008). Why did our findings differ from those of earlier studies?

One possibility may be related to Bonatti's (2008) suggestion regarding object tracking. In the previous studies, the objects were moving randomly in a lottery machine, in much the same way as in adult multiple object tracking studies. However, object tracking is difficult when dealing with more than four objects (Ross-Sheehy *et al.*, 2003; Scholl & Pylyshyn, 1999). Thus, infants may have failed Bonatti's task because they could not track a large number of moving objects. In contrast, infants may have succeeded in the current task because the objects were stationary and this allowed infants to make probability estimations with the large populations.

A second possibility for the difference in these results is that the current task required infants to make an explicit prediction about the outcome of an event, whereas the looking time tasks measured infants' reactions after a sample was revealed. This difference seems to accord with our intuitions. Suppose that someone shows you a box with a ratio of four pink to one black lollipops. If she removed just one lollipop from the population and it happened to be black, would you be extremely surprised? Probably not, even though you know this is the less probable outcome; you might not be all that surprised when one single draw produced the minority color. However, imagine a second situation where you are shown the same population and asked to make an explicit prediction about which of the two color lollipops will be removed from the jar on a single draw. In this situation, you are most likely to answer 'pink'. The procedure employed in the current study addresses the second situation by requiring that infants make a prediction about a single sample, whereas the looking-time paradigm (Bonatti, 2008) addresses the first situation, requiring that infants reason post-dictively about the likelihood of an event.

It is worth noting that infants in the current experiment appear to be capable of reasoning about a large number of objects in the context of a choice task modeled after Feigenson *et al.* (2002). However, in the original Feigenson *et al.* (2002) experiments, infants appeared to be using the core system dedicated to reasoning about small numbers and not the core system dedicated to large number approximations. It is interesting then that infants appear to be able to compute probabilities over large numbers in our choice experiment. Some methodological variations that could have contributed to the disparity are: In the Feigenson *et al.* (2002) experiments, infants watched as the experimenter placed each object one at a time into the buckets. In our experiment, we began with the objects intermixed inside the jars. Infants' small number system may have been engaged in the original experiments partly due to one-at-a-time placement, whereas infants in our experiment had no opportunity to attempt to track the individual objects in the populations. Second, the populations inside the containers in the current experiment included far more objects than those in the experiments from which the paradigm is borrowed. It seems feasible that infants might be more likely to rely on large number approximations in our experiment because of the relatively large number of objects compared to the original choice paradigm (e.g. Lipton & Spelke, 2003, 2004; Xu, 2003; Xu & Spelke, 2000). Finally, infants in our experiment were able to see the entire population of objects in each jar and compare those populations to one another. In the original choice tasks, infants only saw the objects being placed into occluded containers and thus were not able to simultaneously view and compare the contents of the containers to one another. This difference may have allowed infants in our experiment to better estimate and compare a large number of objects. Future studies are necessary to tease apart which of the many differences between this experiment and Feigenson *et al.*'s experiments might be responsible for these different findings.

Another point worth noting is that contrary to a number of studies in the field of infant cognition suggesting that looking-time measures are more sensitive than explicit behavioral measures, the current study found the opposite. Much research in the field to date has found that competencies in other domains of infant reasoning are commonly detected in looking-time measures at earlier ages than in explicit measures (e.g. Diamond, 1985; Hood, Carey & Prasada, 2000; Keen, Carrico, Sylvia & Bertheier, 2003; Munakata, McClelland, Johnson & Siegler, 1997; Piaget, 1954; Spelke, Breinlinger, Macomber & Jacobsen, 1992). Other studies have shown that looking-time and explicit action tasks can provide converging results for some abilities (e.g. Baillargeon, Li, Ng & Yuan, 2009; Hespos & Baillargeon, 2006, 2008). These discrepancies across studies have raised issues about the kinds of representations underlying looking-time tasks and whether the infants' early representations are strong enough to support action (e.g. Hood *et al.*, 2000; Keen *et al.*, 2003; Munakata *et al.*, 1997; Shinskey, Bogartz & Poirier, 2000; Shinskey & Munakata, 2003). The current experiment provides evidence that, in at least one situation, a behavioral measure may be more sensitive than a looking-time measure in demonstrating infants' competence on a probabilistic inference task. Perhaps we cannot draw strong conclusions about infants' early representations based solely on the specific tasks we use. The issue of the nature of these early representations needs to be investigated on a case-by-case basis.

In conclusion, 12- to 14-month-old infants in the current study were able to make a prediction regarding single-event probabilities in a novel procedure. These results have a number of implications. First, they provide the first evidence that infants can reason about single-event probabilities in the context of large populations. This appears to run counter to Bonatti's claim suggesting that infants can only represent and compute probabilities when reasoning about object-files. Infants might instead be capable of computing probabilities over object files as well as analog magnitudes. Second, the results provide corroborating evidence outside of the looking-time paradigm suggesting that infants can engage in probabilistic inference, and the method provides a new measure for investigating probabilistic inference in infants and toddlers. Finally, the current results provide rare evidence demonstrating that an explicit behavioral measure may reveal earlier competence than the standard looking-time measure.

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