Anim Cogn
DOI 10.1007/s10071-016-1043-9

ORIGINAL PAPER

Intuitive probabilistic inference in capuchin monkeys

Emma C. Tecwyn[1,4] · Stephanie Denison[2] · Emily J. E. Messer[1,5] · Daphna Buchsbaum[1,3]

Received: 2 August 2016 / Revised: 26 September 2016 / Accepted: 7 October 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract The ability to reason about probabilities has ecological relevance for many species. Recent research has shown that both preverbal infants and non-human great apes can make predictions about single-item samples randomly drawn from populations by reasoning about proportions. To further explore the evolutionary origins of this ability, we conducted the first investigation of probabilistic inference in a monkey species (capuchins; *Sapajus* spp.). Across four experiments, capuchins ($N = 19$) were presented with two populations of food items that differed in their relative distribution of preferred and non-preferred items, such that one population was more likely to yield a preferred item. In each trial, capuchins had to select between hidden single-item samples randomly drawn from each population. In Experiment 1 each population was homogeneous so reasoning about proportions was not required; Experiments 2–3 replicated previous probabilistic reasoning research with infants and apes; and Experiment 4 was a novel condition untested in other species, providing an important extension to previous work. Results revealed that at least some capuchins were able to make probabilistic inferences via reasoning about proportions as opposed to simpler quantity heuristics. Performance was relatively poor in Experiment 4, so the possibility remains that capuchins may use quantity-based heuristics in some situations, though further work is required to confirm this. Interestingly, performance was not at ceiling in Experiment 1, which did not involve reasoning about proportions, but did involve sampling. This suggests that the sampling task posed demands in addition to reasoning about proportions, possibly related to inhibitory control, working memory, and/or knowledge of object permanence.

Keywords Capuchin · Intuitive statistics · Numerical cognition · Primate cognition · Probabilistic inference · Proportional reasoning

This research was supported by an Economic and Social Research Council Future Research Leaders grant to Daphna Buchsbaum.

Electronic supplementary material The online version of this article (doi:10.1007/s10071-016-1043-9) contains supplementary material, which is available to authorized users.

✉ Emma C. Tecwyn
emma.tecwyn@utoronto.ca

[1] School of Psychology and Neuroscience, University of St Andrews, St Andrews, Scotland, UK

[2] Department of Psychology, University of Waterloo, Waterloo, Canada

[3] Department of Psychology, University of Toronto, Toronto, Canada

[4] Present Address: Department of Psychology, University of Toronto, Toronto, Canada

[5] Present Address: Department of Psychology, School of Life Sciences, Heriot-Watt University, Edinburgh, Scotland, UK

Introduction

Numerical competence is ecologically relevant in many contexts. It enables efficient foraging, reduces predation risk, increases the likelihood of success in group conflict situations, and makes it possible to keep track of group members and prey items (e.g. Addessi et al. 2008; Beran et al. 2011; Schmitt and Fischer 2011; Wilson et al. 2001). Extensive research has revealed that basic numerical abilities are evolutionarily ancient: a wide range of nonhuman animals (hereafter animals) including several species of mammals, birds, fish and insects are capable of using

Published online: 15 October 2016

representations of quantity to guide their behaviour (see Reznikova and Ryabko 2011; Vallortigara 2014, for recent reviews).

One specific aspect of numerical cognition that has been much less studied in animals is the ability to reason about probabilities or make probabilistic inferences. The key distinction between this ability and other types of numerical competence is that reasoning about probabilities involves reasoning about *relative* quantities, or proportions (e.g. in a population consisting of two types of item, the quantity of one type of item *relative* to the total quantity of both types of item) as opposed to simple comparisons of *absolut*e quantities (Bryant and Nunes 2012). In some situations in the natural environment, the ability to make accurate absolute quantity judgements is not sufficient for informing decision-making; being able to use proportion judgements is also required (Rugani et al. 2015). For example, to gain access to the largest quantity of food, an individual needs to consider both the amount of food in alternative locations, and the number of other individuals feeding at these different locations (Rugani et al. 2015). Relative judgments are also important outside of the number domain: there is a growing literature on inequity aversion in animals—the sensitivity to one's own effort and payoff *relative* to another individual's (e.g. Brosnan and de Waal 2003; Brosnan et al. 2005; Cronin and Snowdon 2008; Range et al. 2009).

In humans, traditional theory suggests that the ability to make probabilistic inferences does not develop until around seven years of age (Piaget and Inhelder 1975). However, recent research using violation of expectation looking-time paradigms (based on the premise that infants look longer at surprising or unexpected events) and action-based choice tasks has revealed that human infants are capable of basic reasoning about probabilities (Denison and Xu 2010, 2014; Teglas et al. 2007, 2011; Xu and Garcia 2008). Denison and Xu (2010) also demonstrated that infants are capable of drawing inferences from populations to randomly drawn single-item samples to guide their decision-making in a choice task. When presented with two visible populations that differed in their distributions of preferred to non-preferred items (4:1 vs. 1:4), infants accurately predicted which of two single-item samples drawn from the two populations was more likely to consist of a preferred item, indicated by crawling towards the location of that sample.

In all of these studies, however, absolute quantity was confounded with proportion, because in each case the highest proportion object in a population was also the most numerous. For example, suppose a person has a stronger preference for pink than green objects. When comparing a population containing 40 pink and 10 green objects against a population of 10 pink and 40 green objects, one could compare the two proportions (4:1 vs. 1:4) or one could use a shortcut and simply compare the quantity of pink objects only across populations (40 vs. 10). Though correct use of either strategy is likely to result in the same behaviour in this case (i.e. approach the sample from the 40 pink and 10 green population), only the latter strategy reflects accurate probabilistic reasoning, as using a strategy of relying on numerators and ignoring denominators will lead to errors in many cases. Indeed, ignoring denominators is a strategy that children have been shown to use in some mathematics problems until middle childhood, and evidence of proportional reasoning is required for a population to be credited with true probabilistic reasoning (Falk et al. 2012; Bryant and Nunes 2012).

To address this issue, Denison and Xu (2014) ran a series of experiments to determine whether infants are using this type of quantity-based heuristic or comparing proportions when making inferences. Infants were presented with two visible populations that differed in their distributions of preferred to non-preferred items, as in Denison and Xu (2010). However, in this series of experiments, infants could not succeed by basing their selection on the greater quantity of preferred items, because the quantity was the same in both populations, or because quantity was pitted directly against proportion (i.e. the population containing the greater quantity of preferred items contained a lower proportion of preferred items). Their results provided strong evidence that 12-month-old infants are capable of using proportions to predict which of two single-item samples randomly drawn from two populations is more likely to consist of a preferred (as opposed to non-preferred) item.

In addition to investigating the developmental origins of probabilistic reasoning in Western children, recent research has begun to explore this capacity cross-culturally, and has revealed that preliterate and prenumerate human cultures are able to make implicit probabilistic inferences, suggesting that this ability may be universal within our own species (Fontanari et al. 2014). There is also a growing body of literature investigating the evolutionary origins of intuitive statistics; that is, the extent to which any animals might share intuitive statistical abilities with humans. Rakoczy et al. (2014) ran a study based on the tasks developed by Denison and Xu (2010, 2014) with all four species of nonhuman great ape (hereafter ape). They found that apes share with human infants the ability to draw inferences from populations to randomly drawn single-item samples. Several control conditions ruled out the possibility that apes were solving the tasks by using simple quantity heuristics or subtle experimenter-given cues, as opposed to reasoning about proportions (Rakoczy et al. 2014). Further evidence that apes are capable of making basic probabilistic inferences comes from a study by Hanus

and Call (2014), which investigated chimpanzees' ability to use probabilistic reasoning to find a food item hidden under one of several cups on one of two trays. Performance in the task was correlated with the probability ratio between the two trays (a signature property of the analogue magnitude system (AMS); a mechanism for quantification of arbitrarily large magnitudes that is shared by many species, e.g. Jordan and Brannon 2006), so the greater the discrepancy between the two trays in terms of probability of finding the reward, the more likely chimpanzees were to select a cup from the more probable tray.

These recent findings suggest that the capacity for probabilistic inference is not uniquely human; rather it is shared by our closest relatives, the great apes. However, the question remains of how evolutionarily ancient and therefore how widespread in the animal kingdom the ability may be. Recent research has demonstrated that two individuals of an Old World monkey species (rhesus macaques; *Macaca mulata*; Drucker et al. 2016), as well as day-old chicks (*Gallus gallus*; Rugani et al. 2016) possess the prerequisite ability of distinguishing between proportions of discrete items; however, these studies did not address whether these individuals were able to make inferences on the basis of probabilities. Probabilistic inference goes one step beyond the ability to compare proportions, because the subject also needs to understand the sampling part of the procedure; that is, they need to make inferences about the probable identity of items drawn from populations, based on the distribution of items in those populations. The aim of the present set of experiments was to investigate whether capuchin monkeys (*Sapajus* spp.), like human infants and apes, are able to use proportional reasoning to make probabilistic inferences about single-item samples randomly drawn from populations. To our knowledge this is the first study to investigate probabilistic inference in a monkey species. Capuchins are interesting from a comparative perspective, because as a New World primate they share a more evolutionarily ancient common ancestor with humans than the apes (and the Old World monkeys), the two lineages having diverged over 30 million years ago (Fragaszy et al. 2004). Previous research on numerical cognition in capuchins has generally demonstrated that they have abilities comparable to those exhibited by apes. Like apes, capuchins have displayed an ordinal concept of quantity (Judge et al. 2005); they are able to judge relative quantity of sets of objects and amounts of substance when they are presented as discrete sets (e.g. Addessi et al. 2008) and to some extent when they are presented sequentially (e.g. dropped into a cup one item at a time; Evans et al. 2009; VanMarle et al. 2006); and they can make accurate numerosity judgements when presented with moving dots of two different colours on a screen (Beran et al. 2011). There is also some evidence that capuchins may be sensitive to inequity between themselves and another individual (Brosnan and de Waal 2003), which also involves making relative judgements. We therefore predicted that capuchins should also perform comparably with apes in proportional reasoning tasks.

We presented capuchins with a series of experiments based on those used in recent studies with infants (Denison and Xu 2010, 2014), young children (Girotto et al. 2016) and apes (Rakoczy et al. 2014), as well as a novel experimental condition that has not previously been presented to any species (Experiment 4). In all of the experiments, subjects were presented with two populations of food items in transparent jars. The two populations differed in terms of their distribution of two types of food item: one preferred and one non-preferred; so that in each case one population was 'favourable', in terms of the probability of a randomly drawn single-item sample consisting of a preferred item. Across all experiments we refer to the favourable population as Jar A, and the unfavourable population as Jar B (though jar placement is always counterbalanced on the left and right). In each trial, the experimenter randomly drew a single-item sample from each jar, kept them hidden in her hands, and allowed the subject to choose between the two samples. To select the sample most likely to consist of the preferred item, subjects had to distinguish between the two populations and infer the relative probability that each of the samples would consist of a preferred item. They then had to use this information to guide their decision-making behaviour when selecting one of the samples. We also extended the recent work with infants and apes by including a novel experimental condition (Experiment 4) that directly addressed the possibility that subjects could potentially succeed at the task by using a quantity heuristic based on avoiding the population containing the greater quantity of non-preferred items, by presenting populations that were both unlikely to yield a preferred item, but one was more unlikely than the other.

Methods

Subjects

Nineteen capuchins (*Sapajus* spp.) participated in this study (see Table 1). The subjects were housed at the 'Living Links to Human Evolution' Research Centre at the Royal Zoological Society of Scotland, Edinburgh Zoo, UK. There were 6 females and 13 males aged between 2 and 16 years (mean = 6.4 years). The subjects did not have any previous experience with numerical or quantity-based cognitive tests. The subjects were housed in two groups (East and West; referring to the geographical location of the enclosures at the zoo), and both groups cohabited with

Table 1 Details of capuchins that participated in this study

Name	Group	Sex	Age	Experiment participation
Alba	West	F	2	1, 2, 3, 4
Anita	East	F	16	1, 2, 3, 4
Carlos	East	M	8	1, 2, 3, 4
Chico	East	M	4	1, 2, 3, 4
Diego	West	M	11	1, 2, 3, 4
Figo	West	M	7	1, 2, 3, 4
Flojo	East	M	2	1, 2, 3, 4
Inti	West	M	4	1, 2, 3, 4
Junon	East	F	13	1, 2, 3, 4
Kato	East	M	8	1, 2, 3, 4
Luna	West	F	2	1, 2, 3, 4
Manuel	East	M	8	1, 2
Pedra	West	F	5	1
Reuben	East	M	3	1, 2, 3, 4
Rufo	West	M	4	1, 2, 3, 4
Sylvie	West	F	10	1, 2, 4
Toka	West	M	9	1
Torres	West	M	2	1, 2, 3, 4
Ximo	West	M	3	1, 2, 3, 4

All individuals were born in captivity and mother-reared, except for Kato who was wild-born and hand-reared. Group refers to the geographical location of the enclosures at the zoo and age is in years

common squirrel monkeys (*Saimiri sciureus*). Each group was housed in an indoor enclosure (189 m^3) with access to a ~900 m^2 outdoor enclosure, both of which had ample climbing substrates. For further details of housing and husbandry see Leonardi et al. (2010).

Study design

Prior to participating in any experiments, all subjects participated in food preference trials, to establish their preference between a peanut and a monkey pellet. Subsequently, four experiments were carried out (Experiments 1–4). Experiment 1 was designed to familiarise subjects with the single-item sampling procedure, and establish their baseline performance in this task with two populations each consisting of just one type of item (100 % preferred vs. 100 % non-preferred; Fig. 1a). Therefore, all subjects participated in Experiment 1 first.

Experiment 1 consisted of four sessions of six trials (24 trials in total): in sessions 1–3 the experimenter's arms were straight (i.e. the hand containing the item from Jar A was next to Jar A when the subject made their selection; Fig. 2a), and in session 4 the experimenter crossed her arms before allowing the subject to make their selection (i.e. the hand containing the item from Jar A was next to Jar B when the subject made their selection; Fig. 2b).

This design was used in the previous work with infants and apes, so we did the same to allow maximal comparability across taxa. Including the arms-crossed session also allowed us to rule out the possibility that capuchins were simply basing their selection on the location of the favourable population (e.g. choosing the hand next to the jar where they could see the most preferred items, in which case we would expect performance to be below chance in the arms-crossed session), or actually considering the samples drawn from the populations. This is important because choosing on the basis of the probable identity of the sample is an important way in which probabilistic inference differs from the prerequisite ability of being able to compare the proportions of items in populations. Without these arms-crossed trials, it would be difficult to know whether the participants are truly reaching towards the correct sample or are instead perhaps reaching towards the jar with the higher proportion of preferred items.

Experiments 2–4 were designed to investigate the ability of the subjects to make inferences about random samples drawn from mixed populations (Fig. 1b–d), and to rule out the possibility that subjects could solve this type of problem using heuristic rules based on the *absolute quantities* of the items, rather than the *relative proportions* of the preferred to non-preferred items. To control for potential learning effects across experiments, subjects completed Experiments 2–4 in a random order. Experiments 2–4 each consisted of three sessions of six trials (18 trials in total). Within each session, all trials were either presented with the experimenter's arms straight (Fig. 1a) or crossed (Fig. 1b). Within each experiment, subjects were randomly assigned to either arms-straight or arms-crossed presentation, and across Experiments 2–4 subjects either experienced two experiments with arms straight and one experiment with arms crossed, or vice versa (see Table S1 in Online Resource 1). To control for side preferences, in all experiments, the side on which the jar containing the favourable population (Jar A) was presented was pseudo-randomised within each session of six trials, with the constraints that it appeared three times on each side, and not on the same side in more than two consecutive trials.

Procedure and materials

Subjects were tested individually in a test cubicle (49.5 cm × 52.1 cm × 51.4 cm) with a Plexiglas window that had two 5-cm diameter holes 26 cm apart that subjects could reach their arms out of to make selections. Subjects received one session of six trials per session and up to two sessions per day (with approximately 3 h between the morning and afternoon sessions). Populations of peanuts and monkey pellets (Fig. 1) were presented to subjects in two transparent glass jars on a wheeling trolley.

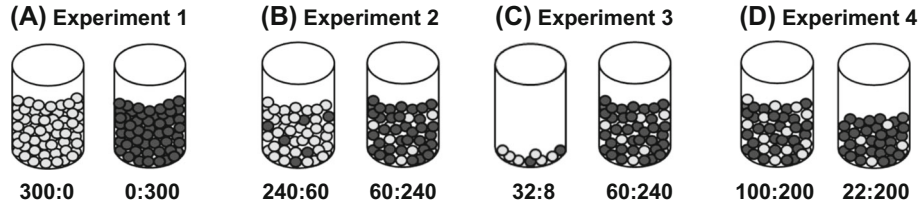

Fig. 1 Schematic representations of the distributions of populations in Jar A (*left* in each pair) and Jar B (*right* in each pair) for Experiments 1–4 (jar placement was counterbalanced on the *left* and *right* in all experiments). *Light grey circles* represent peanuts (preferred food item) and *dark grey circles* represent monkey pellets (non-preferred food item). Ratios underneath the jars represent the peanut/pellet ratio in that jar. All jars were transparent so the populations were continuously visible to the monkeys

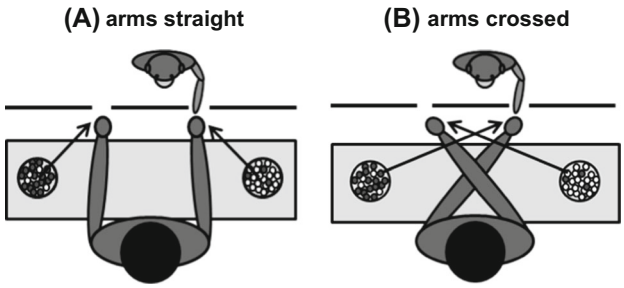

Fig. 2 Schematic representation of the experimental setup and general procedure. Subjects participated individually in a test cubicle (see Leonardi et al. 2010, for full details of the cubicle set up) with a custom-made Plexiglas window. At the start of each trial, the experimenter simultaneously shook both jars while looking at the subject to draw their attention. She then randomly drew a single item from each jar simultaneously and kept them hidden from the subject in her closed fists. The experimenter then extended her arms to present her closed fists containing the concealed items at the two holes in the cubicle window, either keeping her arms straight (**a**) or crossing them over (**b**). In Experiment 1, the experimenter's arms were straight for the first three sessions of trials and crossed for the fourth session. For each of Experiments 2–4, subjects were pseudo-randomly assigned to either arms-straight or arms-crossed presentation, with the constraint that across these three experiments subjects either had arms straight in 2/3 experiments and arms crossed in 1/3, or vice versa

In all experiments, several measures were taken to avoid possible cueing via the experimenter's body posture, facial expression or gaze direction (i.e. a "Clever Hans effect"). The general method for drawing samples from populations and presenting them to subjects followed Rakoczy et al. (2014). At the start of each trial, the experimenter placed her closed fists on the table behind the two jars. She then simultaneously shook both jars while looking at the subject to draw its attention to them. The experimenter then closed her eyes and tilted her head upwards to convey random drawing of samples, drew a single item from each jar simultaneously, and kept them concealed from the subject in her closed fists (in fact the required items were already surreptitiously held in the experimenter's hands prior to shaking the jars and "extracting" the sample). Following Rakoczy et al. (2014), in Experiments 2 and 3, the item "drawn" from each population was the majority item. Because in Experiment 4 the non-preferred item was in the majority in both populations, we manipulated the samples to match the probabilities of the populations (see procedure section of Experiment 4 for details). The experimenter then extended her arms simultaneously to present her fists containing the concealed items centred at the two evenly spaced holes in the cubicle window, at a fixed equal distance from the window. She then held this position until the subject made its choice. When presenting items with arms crossed (Fig. 2b), the experimenter always crossed her right arm over her left arm. During presentation of the items the experimenter fixed her gaze in the centre of the two holes in the window and maintained a symmetrical posture and neutral expression (as in e.g. Albiach-Serrano and Call 2014). This prevented the experimenter from inadvertently gazing at either option or making eye contact with the subject (it was not possible for the experimenter to have her eyes closed or avert her gaze while the subject made their selection for safety reasons). The subject was allowed to select one fist by touching it and the experimenter then opened that hand and allowed the subject to take that item for immediate consumption. Subjects were not praised for selecting either item. The experimental procedure can be seen in the supplementary videos (Online Resources 2, 5, 7 and 8). Any deviations from this general procedure are described under the relevant experiment section below.

Data coding and analysis

All sessions were videotaped. For each trial, we scored whether the subject selected the hand containing the item from Jar A (favourable population) or the hand containing the item from Jar B unfavourable population). To select a hand, the subject had to touch it with one of their hands; just reaching towards one of the experimenter's hands did not constitute making a selection. We also scored the side at which the hand that was selected by the subject was located (left or right window hole, from the subject's perspective). A second coder scored a random 25 % of the recorded sessions to assess inter-observer reliability.

Cohen's kappa was 0.99 for whether the subject selected the experimenter's hand containing the item from Jar A or Jar B (99 % agreement between coders). Disagreements were resolved through discussion. Our main dependent variable was the average proportion of trials correct. We also examined Trial 1 performance for each experiment, as well as Trial 1 performance for each session of each experiment. The reason for this latter analysis was to increase power, given that we had fewer subjects than the previous work with infants and apes. All statistical tests were two-tailed, and the significance level of alpha was 0.05 unless otherwise stated.

Preference trials

Prior to introducing the populations of items in jars, food preference testing was carried out. The aim of this was to establish each subject's preference between a peanut and a similar-sized monkey pellet piece.

Subjects

All 19 subjects participated in the preference trials.

Procedure

Subjects were presented with a single session of 10 preference trials. In each trial, the experimenter presented the two items simultaneously in her open palms at the left and right holes in the cubicle window and the subject was allowed to take one item. The side on which the peanut appeared (left vs. right window hole) was pseudorandomised, with the constraints that it appeared five times on each side, and it could not appear on the same side in more than two consecutive trials.

Results and discussion

In the preference test, all 19 subjects selected the peanut in 10/10 trials. This suggests that all of the subjects had a strong preference for peanuts over monkey pellets and were thus highly motivated to maximise intake of peanuts. It also demonstrated that subjects were able to visually discriminate between the two food items.

Experiment 1: Inferences from homogeneous populations to samples (baseline condition)

The aim of Experiment 1 was to familiarise subjects with the sampling procedure and to establish their baseline performance in the task when each of the populations consisted of a single type of item (100 % preferred vs. 100 % non-preferred), i.e. when no proportional reasoning was necessary.

Subjects

All 19 subjects participated in Experiment 1 (see Table 1).

Apparatus and procedure

The jars depicted in Fig. 1a were used. Jar A contained 300 peanuts (preferred) and Jar B contained 300 pellets (non-preferred); i.e. the populations were not mixed and each consisted of one type of item.

There were four sessions of six trials (24 trials in total). In session 1 (arms straight; Fig. 2a), items were presented to the subject in the experimenter's closed fists, and once the subject had selected a hand the experimenter opened that hand and the subject could take the item of food from her palm. The item concealed in the unselected hand was not revealed to the subject. Because performance was not as good as we might have expected in this initial session, we made some modifications to this procedure. In sessions 2 and 3 (arms straight), the procedure was the same, except that the experimenter kept the items concealed between her fingers and thumb instead of in her closed fist, so they were still not visible to the capuchin, but the presentation was more similar to the way in which food items are normally handed to the subjects (see video in Online Resource 2; all video captions are in Online Resource 9). In addition, after the subject had made its selection, the experimenter revealed what item was in the unselected hand. In session 4 (arms crossed), the procedure was the same as in sessions 2 and 3, except that after drawing an item from each of the jars, the experimenter crossed her arms over, so that the hand containing the item from Jar A (a peanut) was next to Jar B (containing 100 % pellets) when the subject made their selection.

Results and discussion

Subjects selected the hand containing the item from Jar A (peanut/pellet ratio of 300:0) in 61.0 % of trials (Fig. 3), significantly more than expected by chance [one-sample t test: $t(18) = 3.713$, $P = 0.002$, $d = 0.1.750$].[1]

A repeated measures ANOVA with session (1–4) as a within-subjects factor found no main effect of session on performance [$F(3,54) = 1.619$, $P = 0.196$, partial

[1] All analyses reported in this manuscript were also run using nonparametric tests (Friedman's tests, Wilcoxon signed-rank tests; Mann–Whitney U tests) and produced similar P values in all experiments; see Online Resource 3.

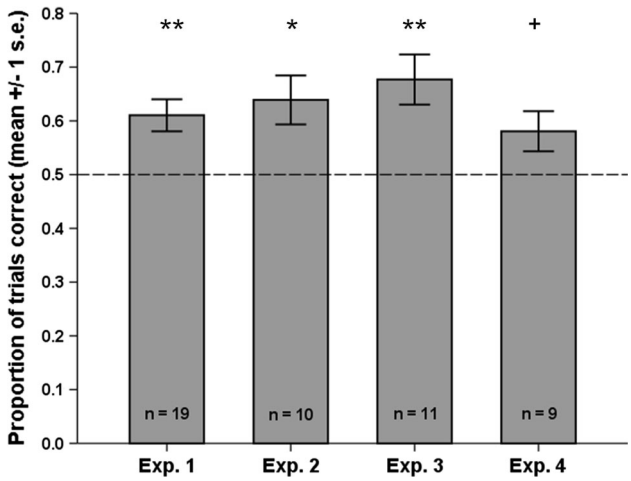

Fig. 3 Mean proportion of trials (±1 SE) in which subjects selected the hand containing the item from Jar A in Experiments 1–4. Experiment 1 had 24 trials and Experiments 2–4 each had 18 trials. All subjects completed Experiment 1 first; the order in which subjects subsequently completed Experiments 2–4 was randomised. $^{**}P < 0.01$, $^{*}P < 0.05$, and $^{+}P < 0.07$ in a one-sample t test. *Dashed line* indicates chance-level performance (half of the trials correct). This *graph* excludes individuals with a 100 % side bias in a given experiment

$\eta^2 = 0.183$], suggesting that subjects did not learn to solve the task over the course of the experiment (performance across trials is shown in Fig. S1a of Online Resource 4) and also that the method of presenting the items (closed fists vs. finger/thumb) did not influence performance. Therefore, in Experiments 2–4, we used the closed fist method, to maximise comparability with the previous ape study (Rakoczy et al. 2014). Trial 1 performance was significantly better than chance, with 16/19 subjects (84.2 %) selecting the hand containing the item from Jar A (binomial test: $P < 0.001$), which further supports an absence of learning across trials. Pooling Trial 1 performance for each of the four sessions of Experiment 1 also revealed above-chance performance [mean = 3.1 trials correct out of 4; one-sample t test: $t(18) = 5.144$, $P < 0.001$, $d = 2.425$]. Performance did not differ significantly between trials in which the experimenter's arms were straight (61.4 % correct) and those in which they were crossed [58.8 %; $t(36) = 0.465$, $P = 0.645$, $d = 0.013$], suggesting that subjects were equally able to solve the task regardless of whether the sample was on the same side as the jar it was drawn from, or on the opposite side, and were not simply reaching towards the jar containing the greater quantity of preferred items.

Performance in Experiment 1 was poorer than expected overall, given the subjects' strong motivation to obtain peanuts rather than pellets as evidenced by the preference trials. Many subjects exhibited significant side biases (though there were no 100 % side-biased individuals, unlike in Experiments 2–4; see Table S1 in Online Resource 1), compared with in the preference trials where none of the subjects were side-biased. Interestingly, recent evidence suggests that making inferences about samples drawn from homogeneous populations can be a non-trivial task, even for 3-year-old children (Girotto et al. 2016). Given that this task did not require subjects to reason about probabilities, this suggests that the sampling procedure, i.e. the experimenter randomly drawing a single item from each population and keeping it hidden in her hand while subjects make their selection poses additional demands (cognitive and/or non-cognitive) that impair performance. This requires knowledge of object permanence (to understand that there were items in the experimenter's hands that were currently out of sight); short-term memory (for which jar each sample was drawn from); and inhibitory control (to prevent impulsive reaching to a side for which the subject has an inherent preference). While apes have not been tested in a comparable baseline task, there is some evidence that apes outperform capuchins in tests of object permanence, short-term memory and inhibitory control (Amici et al. 2008, 2010), and we return to this in the General Discussion.

Experiment 2: Inferences from heterogeneous populations to samples

The aim of Experiment 2 was to investigate the ability of capuchins to make an inference about which of two single-item samples drawn from two populations differing in their distributions of preferred to non-preferred items is more likely to consist of a preferred item.

Subjects

Seventeen subjects participated in Experiment 2 (see Table 1). Two subjects did not participate due to a lack of motivation to come into the testing cubicles for sufficient sessions to complete the experiment.

Apparatus and procedure

The jars depicted in Fig. 1b were used. Both jars contained the same total number of items (300) but Jar A contained a 4:1 distribution of peanuts to pellets, and Jar B contained a 1:4 distribution of peanuts to pellets. The samples drawn always consisted of a peanut from Jar A and a pellet from Jar B (the majority item, as in Rakoczy et al. 2014). Items were presented to the subject in closed fists, and once they had taken the selected item, the alternative item was revealed to them (see video in Online Resource 5). There were three sessions of six trials (18 trials in total).

Results and discussion

Of the seventeen subjects that participated in Experiment 2, seven exhibited a 100 % side bias (they chose the sample on the same side in all 18 trials), suggesting that their behaviour was independent of the populations in the jars, and thus uninformative with regards to our experimental question. Therefore, we excluded these subjects from our analyses, an approach that has previously been used with young children (e.g. Austin et al. 2014), capuchins (e.g. de Waal et al. 2008; Schrauf et al. 2008), and other animal species (e.g. Tauzin et al. 2015) in two-alternative forced choice tasks. We followed this procedure for the remainder of the experiments reported in this paper (results of analyses with 100 % side-biased individuals included are available in Online Resource 6).

The ten subjects that were not 100 % side-biased selected the hand containing the item from Jar A (peanut/pellet ratio of 240:60) in 63.9 % of trials (Fig. 3); significantly more than expected by chance [one-sample t test: $t(9) = 3.049$, $P = 0.014$, $d = 2.03$]. A repeated measures ANOVA, with session (1–3) as a within-subjects factor and arms configuration (straight or crossed) as a between-subjects factor found no main effect of session [$F(2,16) = 1.869$, $P = 0.186$, partial $\eta^2 = 0.108$], suggesting that subjects did not learn to solve the task over the course of the experiment (see also Fig. S1b in Online Resource 4). There was also no effect of arms configuration [$F(1,8) = 0.055$, $P = 0.820$, partial $\eta^2 = 0.021$], suggesting that subjects were equally able to solve the task whether the experimenter's arms were straight or crossed. There was no interaction between session and arms configuration [$F(2,16) = 0.486$, $P = 0.624$, partial $\eta^2 = 0.052$].

In Trial 1 of the experiment, only 5/10 subjects (50.0 %) selected the hand containing the item from Jar A (binomial test: $P = 1.00$). However, pooling Trial 1 performance for each subject across the three sessions of Experiment 2 to increase power revealed performance that was significantly better than chance [mean = 2.1 trials correct out of 3; one-sample t test: $t(9) = 3.343$, $P = 0.009$, $d = 2.229$].

While the results of Experiment 2 suggest that capuchins may be capable of rudimentary probabilistic reasoning, probability and quantity were confounded in this experiment, because more numerous also meant more probable (Denison and Xu 2014). Given that previous work has shown that capuchins are capable of comparing quantities of items and selecting the larger of the two (e.g. Addessi et al. 2008; Evans et al. 2009; VanMarle et al. 2006), it is possible that subjects succeeded by using a quantity heuristic such as "select the sample from the jar containing the most peanuts" without considering the proportions in each jar. Therefore, the findings from Experiment 2 replicate results in the animal numerical reasoning literature and extend it, as the monkeys were asked to indicate one of two hidden samples, rather than choose between the distributions themselves, suggesting some understanding of *sampling* and not straightforward numerical comparison. Returning to the question of heuristics, the aim of Experiment 3 was to directly address this possibility.

Experiment 3: Ruling out a choice heuristic based on absolute quantity of preferred items

In this experiment, we pitted absolute quantity of preferred items against probability. If subjects base their selection on the sample from the jar containing the larger absolute quantity of peanuts rather than reasoning about relative proportions, then they should select the sample from Jar B more often than expected by chance.

Subjects

Fifteen subjects participated in Experiment 3 (see Table 1). The other four subjects did not participate due to a lack of motivation to participate in sufficient sessions to complete the experiment.

Apparatus and procedure

The jars depicted in Fig. 1c were used. Jar A contained 32 peanuts and 8 pellets (4:1), and Jar B contained 60 peanuts and 240 pellets (1:4). As in Experiment 2, the samples always consisted of a peanut from Jar A and a pellet from Jar B. Items were presented to the subject in closed fists and once they had taken the selected item the alternative item was revealed to them (see video in Online Resource 7). There were three sessions of six trials (18 trials in total).

Results and discussion

Of the fifteen subjects that participated in Experiment 3, four exhibited a constant side bias) and so were excluded from our analyses. The eleven subjects that were not 100 % side-biased selected the hand containing the item from Jar A (peanut/pellet ratio of 32:8) in 67.7 % trials correct [$t(10) = 3.791$, $P = 0.004$, $d = 2.40$]. A repeated measures ANOVA, with session (1–3) as a within-subjects factor and arms configuration (straight or crossed) as a between-subjects factor found no main effect of session [$F(2,18) = 0.10$, $P = 0.990$, partial $\eta^2 = 0.001$], suggesting that subjects did not learn to solve the task over the course of the experiment (see also Fig. S1c in Online Resource 4). There was also no effect of arms configuration [$F(1,9) = 0.003$, $P = 0.955$, partial $\eta^2 = 0.000$],

suggesting that subjects were equally able to solve the task whether the experimenter's arms were straight or crossed. There was no interaction between session and arms configuration [$F(2,9) = 1.573$, $P = 0.241$, partial $\eta^2 = 0.149$].

In Trial 1 of Experiment 3, 7/11 subjects (63.6 %) selected the hand containing the item from Jar A (binomial test: $P = 0.549$). Pooling Trial 1 performance for each subject across the three sessions of Experiment 3 to increase power revealed performance that was significantly better than chance [mean = 2.0 trials correct out of 3; one-sample t test: $t(10) = 2.622$, $P = 0.026$, $d = 1.658$].

The results of Experiment 3 further support the idea that capuchins are capable of rudimentary probabilistic reasoning, as they were able to make accurate inferences about samples drawn from populations that were not based on the absolute quantity of preferred items, as has been demonstrated with infants (Denison and Xu 2014) and apes (Rakoczy et al. 2014). However, there are two additional heuristics that capuchins could still potentially have used to make decisions in Experiments 2 and 3, and which infants and apes could have used in previous studies, which are impossible to tease apart from probabilistic inference given the distributions used in those experiments. First, the possibility remains that capuchins could have succeeded in both experiments by avoiding the sample from the jar containing the larger absolute quantity of non-preferred items; e.g. by using a heuristic such as "select the sample from the jar containing the fewest pellets"; a possibility previous work with other species does not address, though Rakoczy et al. (2014) do discuss it. This alternative would allow them to avoid comparing the *ratio* of peanuts to pellets in Jar A to the *ratio* of peanuts to pellets in Jar B and allow them instead to compare the absolute quantities of pellets across jars. Alternatively, subjects could have used a different heuristic, one slightly more complex than the avoidance strategy but still a shortcut to engaging in true comparison of proportions. In both Experiments 2 and 3, capuchins were faced with a decision between a sample drawn from a jar containing a larger quantity of peanuts than pellets versus a sample from a jar containing a larger quantity of pellets than peanuts. They could avoid comparing the ratios in each jar to one another by simply marking any jar that has a larger number of peanuts than pellets a "good" jar, and any jar that has a larger number of pellets than peanuts a "bad" jar. In this case, comparison of ratios across jars is unnecessary, as subjects can simply select the sample drawn from the good jar (or avoid the sample from the bad jar) rather than compare ratios (Denison and Xu 2014). We address both of these potential heuristics in Experiment 4. Jar A contained 100 peanuts and 200 pellets, and Jar B contained 22 peanuts and 200 pellets. This addresses the first heuristic based on avoiding pellets, as the jars have equal absolute quantities of pellets. Thus if capuchins use absolute quantity estimations to avoid pellets, they will perform at chance. It addresses the second heuristic because, if a subject were simply labelling jars as "good" or "bad", he would have to label both of these jars as "bad", as they both contain more pellets than peanuts, and they would not know which sample to select, again performing at chance. If they instead can compare the ratios of peanuts to pellets, then they should be more likely to select the sample from Jar A. Experiment 4 thus represents a particularly challenging case that no species, including human infants, has yet been shown to solve.

Experiment 4: Ruling out a choice heuristic based on avoiding the larger absolute quantity of non-preferred items, or labelling jars as "good" and "bad"

Experiment 4 was a novel experimental condition that infants and apes have not previously been tested on, which aimed to investigate, for the first time, whether individuals might potentially be using an alternative heuristic (as opposed to choosing on the basis of the greater quantity of preferred items, which has been ruled out by Experiment 3) when solving this type of task. In this experiment we kept the absolute quantity of non-preferred items the same in both jars, and also in the majority, so both jars would be "bad" jars. Therefore, if subjects were basing their selection on avoiding the jar containing the greater absolute quantity of non-preferred items, or were simply labelling jars as "bad" and avoiding them, they would be expected to perform at chance-level (50 % of trials correct).

Subjects

Sixteen subjects participated in Experiment 4 (see Table 1). The remaining three subjects did not participate due to a lack of motivation to participate in sufficient sessions to complete the experiment.

Apparatus and procedure

The jars depicted in Fig. 1d were used. Jar A contained 100 peanuts and 200 pellets, and Jar B contained 22 peanuts and 200 pellets. Unlike in Experiments 1–3 where Jar A always contained a greater quantity of peanuts than pellets, whereas the reverse was true for Jar B, in Experiment 4 both jars contained a greater quantity of pellets than peanuts. Therefore, we chose to manipulate the sample drawn from Jar A so that unlike in Experiments 1–3 it did not consist of a peanut in every trial; instead, a peanut was drawn from Jar A in 2/6 trials, and a pellet in the remaining

4/6 trials (to match the probability of the population). The order in which the different items were drawn out of Jar A for the different sessions was the same for each monkey and as follows: session 1: pellet, peanut, pellet, pellet, peanut, pellet; session 2: peanut, pellet, pellet, peanut, pellet, pellet; session 3: pellet, pellet, peanut, pellet, pellet, peanut. A pellet (the majority item) was always drawn out of Jar B. Items were presented to the subject in closed fists and once they had taken the selected item, the alternative item was revealed to them (see video in Online Resource 8). There were three sessions of six trials (18 trials in total).

Results and discussion

Of the 16 subjects that participated in Experiment 4, seven exhibited a constant side bias and so were excluded from our analyses. The nine subjects that were not 100 % side-biased selected the hand containing the item from Jar A (peanut/pellet ratio of 100:200) in 58.0 % of trials (Fig. 3), and while performance was in the same direction as the other experiments, it was only marginally significant [one-sample t test: $t(8) = 2.163$, $P = 0.063$, $d = 1.53$]. A repeated measures ANOVA (corrected using Greenhouse-Geisser estimates of sphericity), with session (1–3) as a within-subjects factor and arms configuration (straight or crossed) as a between-subjects factor found no main effect of session [$F(1.123,7.862) = 0.758$, $P = 0.425$, partial $\eta^2 = 0.098$], suggesting that subjects did not learn to solve the task over the course of the experiment (see also Fig. S1d in Online Resource 4). There was also no effect of arms configuration [$F(1,7) = 0.012$, $P = 0.916$, partial $\eta^2 = 0.002$], suggesting that subjects were equally able to solve the task whether the experimenter's arms were straight or crossed. There was no interaction between session and arms configuration [$F(1.123,7.862) = 0.408$, $P = 0.645$, partial $\eta^2 = 0.055$].

In Trial 1 of Experiment 4, 3/9 subjects (33.3 %) selected the hand containing the item from Jar A (binomial test: $P = 0.508$). Pooling Trial 1 performance for each subject across the three sessions of Experiment 4 to increase power revealed performance that did not differ significantly from chance [mean = 1.67 trials correct out of 3; one-sample t test: $t(8) = 0.577$, $P = 0.580$, $d = 0.408$].

Although capuchins' performance in Experiment 4 was only marginally above chance and Trial 1 performance did not differ from chance, additional factors unrelated to probabilistic reasoning may have contributed to making the task presented in Experiment 4 more challenging than Experiments 1–3. First, the populations in Jar A and B were more difficult to discriminate visually than in the other experiments since both contained a majority of pellets (see Online Resource 10). Second, the reward schedule implemented differed from that used in the other experiments (as described in the "Apparatus and Procedure" section for Experiment 4). In Experiments 1–3, the sample always consisted of the more probable item from each jar (as in Rakoczy et al. 2014), which in each case was a peanut from Jar A and a pellet from Jar B. Therefore subjects were always rewarded for selecting the hand containing the sample from the "correct" jar. In Experiment 4 however, because the most probable item from each jar would have been a pellet on every trial, we manipulated the sample drawn from Jar A to match the probability of the population, such that it consisted of a peanut in 2/6 trials. This reward schedule would be less likely to result in reinforcement-based learning and may have led to reduced motivation. However, Trial 1 performance in Experiment 4 (33.3 % correct) was also lower in this experiment than overall performance, and lower than Trial 1 performance in Experiments 1–3, which cannot be explained by the different reinforcement schedule.

General discussion

The results of these experiments suggest that some capuchin monkeys, like human infants (Denison and Xu 2010, 2014) and great apes (Rakoczy et al. 2014), are capable of making probabilistic inferences from populations to samples, and success was not due to learning across trials. In particular, Experiment 3 ruled out the possibility that capuchins succeeded by using a heuristic based on comparing absolute quantities of preferred items in the two populations,[2] though relatively poor performance in Experiment 4 suggests that capuchins (and possibly infants and apes) may rely on quantity-based heuristics in certain situations. Our experiments show that at minimum capuchins do not solve these tasks by using one simple heuristic that even school-aged children have been shown to rely on in some more explicit probabilistic inference tasks (Falk et al. 2012): selecting the item from the population containing the greatest absolute quantity of preferred items. The possibility remains that individuals of any of the taxa tested to date could be flexibly using a combination of different heuristics in different tasks (e.g. in our study "select sample from population with greatest absolute quantity of peanuts" in Experiments 2 and 4, and "avoid sample from population with greatest absolute quantity of pellets" in Experiment 3). However, we believe

[2] It should be noted that it is not possible to say *how* capuchins were estimating proportions, i.e. whether they computed probabilities over numerical representations or continuous quantities, and this question has not yet been examined in either infants or apes. While this is an interesting avenue for future research, computing proportions is about considering relative amounts, regardless of format.

that probabilistic inference is a more parsimonious explanation for our data. Taken together, our results provide some evidence to suggest that the capacity for rudimentary intuitive statistics may be evolutionarily ancient, given that humans and capuchins shared a common ancestor over 30 million years ago (Fragaszy et al. 2004; though it is also possible that this capacity evolved convergently in capuchins and apes, Reader et al. 2011).

Despite some methodological differences between species (e.g. number of subjects, number of trials, exact quantities of items in populations), it is possible to draw meaningful comparisons between the results of the current capuchin study and previous data from infants and apes. Infants, apes and capuchins were all presented with a task where the total number of items in the two populations was the same, but the proportions of preferred to non-preferred items were reversed (4:1 vs. 1:4 for all three species; total number of items in the populations varied between species). Infants were only presented with a single trial (Denison and Xu 2010); therefore, their performance can be compared with Trial 1 performance for apes and capuchins. Because side-bias data were not available for the previous ape study, here we discuss our own data with all capuchins included, to facilitate valid comparison. Twenty-five out of 32 infants (78 %) succeeded in their single trial (Denison and Xu 2010), compared with correct Trial 1 performance by 20/28 apes (71 %; Rakoczy et al. 2014: Experiment 1). In our study (Experiment 2), 10/17 capuchins (59 %) chose correctly in Trial 1, with 7 of those individuals subsequently exhibiting a 100 % side bias (5 who chose correctly and 2 incorrectly in Trial 1). Pooling data for all trials, both capuchins and great apes performed above chance-level, though capuchins succeeded in fewer trials (58 % correct with completely side-biased individuals' data included; Experiment 2 of this study), than apes (71 % correct; Rakoczy et al. 2014: Experiment 1).

All three species were also presented with a task in which absolute quantity was pitted against probability (as in Experiment 3 of this study), such that the population that was more likely to produce a preferred-item sample contained the smaller absolute quantity of preferred items (though again total numbers of items in the populations varied between species). Nineteen out of 24 infants (79 %) succeeded in their single trial (Denison and Xu 2014: Experiment 2), compared with correct Trial 1 performance by 20/26 apes (77 %, Rakoczy et al. 2014). In our Experiment 3, 9/15 capuchins (60 %) chose correctly in Trial 1, with 4 of these individuals (2 that chose correctly and 2 incorrectly) subsequently exhibiting a 100 % side bias. Across all trials, apes succeeded in 63 % (Rakoczy et al. 2014: Experiment 6), which was the same as capuchins' success rate (63 % of trials correct with completely side-biased individuals' data included; Experiment 3 of this study), providing evidence of an ability to reason about *relative* frequencies of preferred and non-preferred items within populations and to draw inferences about random single-item samples drawn from these populations.

In our Experiment 4, which was a novel condition unexamined in previous work done with infants and apes, capuchins were presented with a task in which the total number of non-preferred items was held constant in the two populations, and also outnumbered the preferred items in both jars (i.e. both jars were unlikely to yield a preferred item, but one was more unlikely than the other). This meant that subjects could not succeed by avoiding the sample drawn from the population containing the greater quantity of non-preferred items, or by marking one Jar As "bad" and one Jar As "good". Capuchins' performance was marginally different from chance across all trials (58 % of trials correct overall). Trial 1 performance did not differ from chance (3/9 subjects, 33 %, correct), even when Trial 1 of each session was pooled to increase power (56 % of first trials correct). Apes were not tested in a task where the quantity of non-preferred items was equal in the two populations (Rakoczy et al. 2014) and infant performance was only marginally significant in an analogous task in which both populations were likely to yield a preferred object but one was more likely (Denison and Xu 2014: Experiment 4), which suggests that there may be something more difficult about this task. One possibility (in addition to the different reinforcement schedule mentioned in the Experiment 4 "Results and discussion" section) is that the ratio between ratios (defined as the ratio of preferred to non-preferred items in the favourable population, divided by the ratio of preferred to non-preferred items in the unfavourable population; Drucker et al. 2016) of the populations in Experiment 4 [(100/200)/(22/200) = 4.55] was lower than in Experiment 2 [(240/60)/(60/240) = 16] and Experiment 3 [(32/8)/(60/240) = 16]. Drucker et al. (2016) found that macaques were better able to select the "favourable" of two arrays (greater ratio of positive to negative stimuli) on a touch screen when the ratio between ratios was higher. It also leaves open the possibility that at least some subjects may have used a strategy that involved avoiding the population containing the greatest absolute quantity of non-preferred items (not possible in Experiment 4 as both populations contain the same number of non-preferred items), or by marking each Jar As "good" or "bad" (both jars would be "bad" in this task).

A critic could argue that capuchins solved the tasks presented in our study due to a "Clever Hans" effect; that is, by using subtle behavioural cues from the human experimenter. However, we think this is unlikely for the following reasons. First, Rakoczy et al. (2014) demonstrated that apes still solved this type of task when Clever Hans effects were controlled for in an intricately designed

experiment involving two experimenters and special equipment (which we were unfortunately unable to replicate due to testing setup constraints), and their performance did not differ from the original experiment without the Clever Hans controls. Second, non-human primates are notoriously poor at understanding even deliberate human communicative cues such as pointing (e.g. Bräuer et al. 2006; but see e.g. Hopkins et al. 2013 for evidence that chimpanzees can utilise human pointing as a cue in a modified object-choice task), and capuchins specifically were found to be unable to use experimenter gaze direction to locate a food reward hidden under one of two objects, even after receiving 510 trials (Anderson et al. 1995). Finally, as described in the "Methods" section, the experimenter was aware of the potential for unintentional cueing and implemented several measures to control for this possibility.

It could also be argued that capuchins solved the tasks by using olfactory cues from the items concealed in the experimenter's hands; however, we also think this is unlikely. Capuchins rely on visual information more than olfactory cues to locate food (Fragaszy et al. 2004), and free-ranging capuchins did not succeed in using olfactory cues to locate food concealed in containers (Bolen and Green 1997). Our experimental set-up also made it difficult for capuchins to exploit olfactory cues. The cubicle doors were polycarbonate windows with small arm holes (as opposed to more open wire mesh), and at the time of choice the samples were held at such a distance that the capuchins had to fully extend an arm out of the window to reach one of the experimenter's hands (see videos in Online Resources 2, 5, 7 and 8) meaning that it was not possible to sniff the samples directly, making the detection of odour cues was unlikely. Additionally, the latex gloves worn by the experimenter at all times had a strong odour, and all testing sessions started with the test individual being handed both sunflower seeds and raisins, adding further scents to the experimenter's gloved hands.

As mentioned earlier (see Experiment 1 Results and Discussion), capuchins performed more poorly than we expected in the baseline condition, which did not require subjects to reason probabilistically. Any factors limiting performance in Experiment 1 would also apply to Experiments 2–4 where subjects were additionally required to reason about proportions and therefore could also have been responsible for limiting performance in these test conditions. Is there any evidence that apes perform better in tasks designed to test object permanence, short-term memory or inhibitory control that might explain capuchins' relatively lower success rate in some of the sampling tasks?

Amici et al. (2008, 2010) compared the performance of several ape and monkey species in a battery of physical cognition and inhibitory control tasks. Chimpanzees and bonobos outperformed capuchins in a short-term memory task (though capuchins still performed above chance-level), and capuchins were outperformed by chimpanzees, bonobos and gorillas in a single invisible displacement task (Amici et al. 2010). Similarly, capuchins performed significantly worse than chimpanzees and bonobos in a series of inhibitory control tasks (Amici et al. 2008; but see MacLean et al. 2014 for evidence of capuchins performing comparably to great apes in two inhibitory control tasks).

Interestingly, Girotto et al. (2016) recently presented 3-year-old children with a task comparable to our Experiment 1, where one population consisted of 100 % of one type of item, and the second population consisted of 100 % of another type of item. Children were presented with a single trial, and unlike for our capuchins, the samples were never crossed over (so the task was arguably more straightforward). In one of these tasks (Study 2, Task A; the one that was most similar to our Experiment 1), only 33 out of 48 3-year-olds selected the sample drawn from the favourable population (69 % correct), compared with capuchins' Trial 1 performance of 16/19 (84 %) correct. This finding suggests that making inferences from homogeneous populations to samples can be a non-trivial task, even for 3-year-old children, and the authors posit that this may be due to inhibitory control limitations resulting in a working memory overload (Girotto et al. 2016).

The presence of significant side biases throughout this study, and evidence from comparative studies that apes outperform capuchins in tasks that rely on abilities related to our choice-based dependent variable (e.g. object permanence, short-term memory and inhibitory control; Amici et al. 2008, 2010) suggest that it was not having to reason about probabilities that was more challenging for the capuchins than the infants and apes previously tested using this paradigm. This is further supported by the fact that capuchins' performance in Experiments 2 and 3 of this study did not differ from their performance in Experiment 1 (baseline condition), which did not involve probabilistic reasoning. One way to investigate this further would be to test capuchins on looking-time versions of our experiments. If capuchins performed better in this version than in our current action-based version (i.e. they reliably looked longer at unlikely samples), then this would bolster the claim that it is these other aspects of the task, not reasoning about probabilities, that limits capuchins' performance.

In conclusion, we found evidence that at least some capuchins, like human infants and apes, were able to make inferences about single-item samples randomly drawn from heterogeneous populations (Experiment 2), and this was achieved by reasoning about relative as opposed to absolute frequencies of preferred and non-preferred items within populations (Experiment 3). This is the first evidence for intuitive probabilistic inference in a monkey

species, suggesting that the ability to reason about probabilities may be evolutionarily ancient. However, given that sophisticated cognitive abilities may have evolved convergently in capuchins and great apes (Reader et al. 2011), additional primate species would need to be tested to establish just how widespread the capacity for probabilistic inference is. As performance was relatively poor in Experiment 4—our novel experimental condition that goes beyond the work previously done with either apes or infants—further research is required to establish whether some capuchins might use strategies that involve avoiding non-preferred items or marking the populations as "good" and "bad"; and whether the same might be true for apes and/or infants. Given the broad ecological relevance of reasoning about proportions, future research should also aim to investigate whether probabilistic inference is an ability that is also shared with non-primate species.

Acknowledgments We would like to thank the RZSS Living Links staff who gave permission to conduct research and provided invaluable support and assistance. Thanks to Keith Haynes at the University of St Andrews for constructing the cubicle window. Thanks also to Natalia Robert-Nunez for secondary coding of data.

Funding This study was funded by an Economic and Social Research Council Future Research Leaders Grant (ES/K009540/1) to D.B.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest

Human and animal rights All procedures were in accordance with UK law and the ASAB Guidelines for the Treatment of Animals in Behavioural Research and Teaching. The study was approved by the University of St Andrews School of Psychology and Neuroscience Ethics Committee and the Research Committee at Living Links.

References

Addessi E, Crescimbene L, Visalberghi E (2008) Food and token quantity discrimination in capuchin monkeys (*Cebus apella*). Anim Cogn 11:275–282

Albiach-Serrano A, Call J (2014) A reversed-reward contingency task reveals causal knowledge in chimpanzees (Pan troglodytes). Anim Cogn 17(5):1167–1176

Amici F, Aureli F, Call J (2008) Fission-fusion dynamics, behavioural flexibility, and inhibitory control in primates. Curr Biol 18:1415–1419

Amici F, Aureli F, Call J (2010) Monkeys and apes: are their cognitive skills really so different? Am J Phys Anthropol 143:188–197

Anderson JR, Sallaberry P, Barbier H (1995) Use of experimenter-given cues during object-choice tasks by capuchin monkeys. Anim Behav 49:201–208

Austin K, Theakston A, Lieven E, Tomasello M (2014) Young children's understanding of denial. Devel Psychol 50(8):2061–2070

Beran MJ, Decker S, Schwartz A, Schultz N (2011) Monkeys (*Macaca mulatta* and *Cebus apella*) and human adults and children (*Homo sapiens*) compare subsets of moving stimuli based on numerosity. Front Psychol 2:61

Bolen RH, Green SM (1997) Use of olfactory cues in foraging by owl monkeys (*Aotus nancymai*) and capuchin monkeys (*Cebus apella*). J Comp Psychol 111:152–158

Bräuer J, Kaminski J, Riedel J, Call J, Tomasello M (2006) Making inferences about the location of hidden food: social dog, causal ape. J Comp Psychol 120:38–47

Brosnan SF, de Waal FBM (2003) Monkeys reject unequal pay. Nature 425:297–299

Brosnan SF, Schiff HC, de Waal FBM (2005) Tolerance for inequity may increase with social closeness in chimpanzees. Proc R Soc B Biol Sci 272:253–258

Bryant P, Nunes T (2012) Children's understanding of probability: a literature review (full report). A report to the Nuffield Foundation. Retrieved on 20 May 2015 from: http://www.nuffieldfoundation.org/sites/default/files/files/Nuffield_CuP_FULL_REPORTv_FINAL.pdf

Cronin KA, Snowdon CT (2008) The effects of unequal reward distributions on cooperative problem solving by cotton-top tamarins (*Saguinus oedipus*). Anim Behav 75:245–257

de Waal FBM, Leimgruber K, Greenberg AR (2008) Giving is self-rewarding for monkeys. Proc Nat Acad Sci 105:13685–13689

Denison S, Xu F (2010) Twelve- to 14-month-old infants can predict single-event probability with large set sizes. Dev Sci 13:798–803

Denison S, Xu F (2014) The origins of probabilistic inference in human infants. Cognition 130:335–347

Drucker CB, Rossa MA, Brannon EM (2016) Comparison of discrete ratios by rhesus macaques (*Macaca mulatta*). Anim Cogn 19:57–89

Evans TA, Beran MJ, Harris EH, Rice DF (2009) Quantity judgments of sequentially presented food items by capuchin monkeys (*Cebus apella*). Anim Cogn 12:97–105

Falk R, Yudilevich-Assouline P, Elstein A (2012) Children's concept of probability as inferred from their binary choices—revisited. Educ Stud Math 81:207–233

Fontanari L, Gonzalez M, Vallortigara G, Girotto V (2014) Probabilistic cognition in two indigenous Mayan groups. Proc Nat Acad Sci 111:17075–17080

Fragaszy DM, Visalberghi E, Fedigan LM (2004) The complete capuchin: the biology of the genus *Cebus*. Cambridge University Press, Cambridge

Girotto V, Fontanari L, Gonzalez M, Vallortigara G, Blaye A (2016) Young children do not succeed in choice tasks that imply evaluating chances. Cognition 152:32–39

Hanus D, Call J (2014) When maths trumps logic: probabilistic judgements in chimpanzees. Biol Lett 10:20140892

Hopkins WD, Russell JL, McIntyre J, Leavens DL (2013) Are chimpanzees really so poor at understanding imperative pointing? Some new data and an alternative view of canine and ape social cognition. PLoS ONE 8(11):379338

Jordan KE, Brannon EM (2006) Weber's Law influences numerical representations in rhesus macaques (*Macaca mulatta*). Anim Cogn 9:159–172

Judge PG, Evans TA, Vyas DK (2005) Ordinal representation of numeric quantities by brown capuchin monkeys (*Cebus apella*). J Exp Psychol Anim Behav Process 31:79–94

Leonardi R, Buchanan-Smith HM, Dufour V, MacDonald C, Whiten A (2010) Living together: behaviour and welfare in single and mixed species groups of capuchin (*Cebus apella*) and squirrel monkeys (*Saimiri sciureus*). Am J Primatol 72:33–47

MacLean EL, Hare B, Nunn CL et al (2014) The evolution of self-control. Proc Nat Acad Sci 111:E2140–E2148

Piaget J, Inhelder B (1975) The Origin of the Idea of Chance in Children. Routledge and Kegan Paul. Translation of original work (1951)

Rakoczy H, Clüver A, Saucke L, Stoffregen N, Gräbener A, Migura J, Call J (2014) Apes are intuitive statisticians. Cognition 131:60–68

Range F, Horn L, Zs Viranyi, Huber L (2009) Effort and reward: inequity aversion in domestic dogs? Proc Nat Acad Sci 106:340–345

Reader SM, Hager Y, Laland KN (2011) The evolution of primate general and cultural intelligence. Phil Trans R Soc B 366:1017–1027

Reznikova Z, Ryabko B (2011) Numerical competence in animals, with an insight from ants. Behaviour 148:405–434

Rugani R, Vallortigara G, Regolin L (2015) The use of proportion by young domestic chicks (*Gallus gallus*). Anim Cogn 18:605–616

Rugani R, McCrink K, de Hevia MD, Vallortigara G, Regolin L (2016) Ratio abstraction over discrete magnitudes by newly hatched domestic chicks (*Gallus gallus*). Sci Rep 6:30114

Schmitt V, Fischer J (2011) Representational format determines numerical competence in monkeys. Nat Commun 2:257

Schrauf C, Huber L, Visalberghi E (2008) Do capuchin monkeys use weight to select hammer tools? Anim Cogn 11:413–422

Tauzin T, Csík A, Kis A, Topál J (2015) What or where? The meaning of referential human pointing for dogs (Canis familiaris). J Comp Psychol 129(4):334

Teglas E, Girotto V, Gonzalez M, Bonatti LL (2007) Intuitions of probabilities shape expectations about the future at 12 months and beyond. Proc Nat Acad Sci 104:19156–19159

Teglas E, Vul E, Girotto V, Gonzalez M, Tenenbaum JB, Bonatti LL (2011) Pure reasoning in 12-month-old infants as probabilistic inference. Science 332:1054–1058

Vallortigara G (2014) Foundations of number and space representations in non-human species. In: Geary DC, Bearch DB, Mann Koepke K (eds) Evolutionary origins and early development of number processing. Elsevier, New York, pp 35–66

VanMarle K, Aw J, Mccrink K, Santos LR (2006) How capuchin monkeys (*Cebus apella*) quantify objects and substances. J Comp Psychol 120:416–426

Wilson ML, Hauser MD, Wrangham RW (2001) Does participation in intergroup conflict depend on numerical assessment, range location, or rank for wild chimpanzees? Anim Behav 6:1203–1216

Xu F, Garcia V (2008) Intuitive statistics by 8-month-old infants. Proc Nat Acad Sci 105:5012–5015