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Reasoning Through the Disjunctive Syllogism in Monkeys

Stephen Ferrigno[1,2], Yiyun Huang[2,3], and Jessica F. Cantlon[2,4]
[1]Department of Psychology, Harvard University; [2]Seneca Park Zoo, Rochester, NY; [3]Department of Psychology, Yale University; and [4]Department of Psychology, Carnegie Mellon University

Abstract
The capacity for logical inference is a critical aspect of human learning, reasoning, and decision-making. One important logical inference is the disjunctive syllogism: given A or B, if not A, then B. Although the explicit formation of this logic requires symbolic thought, previous work has shown that nonhuman animals are capable of reasoning by exclusion, one aspect of the disjunctive syllogism (e.g., not A = avoid empty). However, it is unknown whether nonhuman animals are capable of the deductive aspects of a disjunctive syllogism (the dependent relation between A and B and the inference that "if not A, then B" must be true). Here, we used a food-choice task to test whether monkeys can reason through an entire disjunctive syllogism. Our results show that monkeys do have this capacity. Therefore, the capacity is not unique to humans and does not require language.

Keywords
reasoning, inference, logic, disjunctive syllogism, comparative cognition, primates

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Logical reasoning is an important aspect of human learning, reasoning, and decision-making (Rips, 1994). Logical reasoning could be an ancient evolutionary capacity that facilitates effective foraging (Völter & Call, 2017). However, whether logical reasoning is unique to humans has been debated for hundreds of years (Descartes, 1637/1985). Comparative- and developmental-cognition researchers have attempted to address the question of whether nonhuman animals and young children are capable of the type of logic needed for logical inference (Beran & Washburn, 2002; Call, 2004; Premack & Premack, 1994). Comparative researchers have largely used the two-cup hidden-item paradigm (Call, 2004). In this task, a participant is presented with two empty cups. A researcher then hides an item in one of the cups so that the participant does not know which cup it is in. The researcher then shows the participant that one of the cups is empty and tests whether the participant searches for the item in the remaining cup. Children as young as 2 years old and a variety of animal species successfully look in the remaining cup (children: Hill et al., 2012; Mody & Carey, 2016; apes: Call, 2004; Hill et al., 2011; olive baboons and macaques: Petit et al., 2015; Schmitt & Fischer, 2009; lemurs: Maille & Roeder, 2012; birds: Pepperberg et al., 2013; Schloegl et al., 2009).

Although these results are sometimes taken as evidence for inferential reasoning through disjunctive syllogism, there are alternative explanations. Participants may just be avoiding the empty cup or treating the cups as if the probability of each of them containing a treat is independent. Instead of representing the dependent "or" in "if A or B," subjects may represent the task as "maybe A and maybe B" (Mody & Carey, 2016). One recent study in children used a novel four-cup hidden-item paradigm that allowed them to rule out these alternative strategies (Mody & Carey, 2016). The cups were baited in two sets of two (for a similar baiting procedure, see Fig. 1). One of the cups was then shown to be empty, and thus the other cup in that set could be inferred to contain the item. However, this task cannot be successfully completed without representing the dependent relationship between the cups within a set.

Corresponding Author:
Stephen Ferrigno, Harvard University, Department of Psychology
E-mail: sferrigno@g.harvard.edu

They found that 3- to 5-year-olds were successful at this task, whereas 2.5-year-olds were not.

This work converges with a variety of other research showing that children cannot reason through alternative possibilities before the age of 3 or 4 years (Leahy & Carey, 2020; Redshaw et al., 2018; Redshaw & Suddendorf, 2020; Rohwer et al., 2012). One recent study found looking-time evidence consistent with preverbal infants reasoning through a disjunctive syllogism (Cesana-Arlotti et al., 2018). However, the many failures of children until the age of 3 years suggest that this early success might be due to the use of an alternative, noninferential mechanism, such as early object-tracking abilities (Jasbi et al., 2019; for a review, see Leahy & Carey, 2020). The difference seen between 2.5- and 3-year-old children on these other tasks could be due to the development of the verbal label "or" (which develops between the ages of 2.5 and 3 years old; French & Nelson, 1985), due to a slow-developing nonverbal system, or driven by domain-general development such as increased short-term-memory capacity (Mody & Carey, 2016).

Although these possibilities are hard to disentangle in children, nonhuman animals offer a unique opportunity to differentiate between them. Monkeys have been shown to have short-term visuospatial memory abilities similar to or better than those of 4- to 5-year-old children (spatial span of monkeys is three to four items, see Fagot & De Lillo, 2011; spatial span of 4- to 5-year-old children is ~3 items, see Orsini et al., 1987); however, monkeys will never acquire verbal labels for the logical operators "or" and "not." If monkeys can use disjunctive syllogism to find hidden objects instead of simpler alternative strategies, this would suggest that verbal labels are not needed to represent these logical operators in a flexible and abstract way.

Statement of Relevance

Which cognitive capacities are unique to humans and which are shared with nonhuman primates? Humans have been pondering this question for centuries. One potentially unique domain is logical reasoning—for example, solving disjunctive syllogisms: Given that A or B is true, if not A is true, then B is true. If this form of reasoning is dependent on verbal labels for logical operators, it should not be possible in nonhuman animals. We gave nonhuman primates disjunctive syllogism problems that they could solve to earn a favored food, grapes. A subset of the animals was quite successful at the task, earning grapes almost 75% of the time. How widespread this ability is at the population level is unknown. However, the observation that even one nonhuman primate can engage in this logical operation is proof of the existence of the cognitive capacity in nonverbal, nonhuman primates. This finding adds to the growing body of research showing what types of logic are possible in the absence of language.

Method

Participants

Nine adult baboons (*Papio anubis*; mean age = 10 years, range = 7–14 years) participated in the training phase of the study; however, only four subjects passed all of the training phases (see below). All subjects were socially housed at the Seneca Park Zoo in Rochester, New York. All of the animals that were willing to sit throughout the testing procedure were tested. Thus, the maximum number of subjects possible was tested. Because this study is about the existence of a cognitive capacity in a nonhuman animal, showing that even one animal has this capacity is sufficient evidence (i.e., an existence proof). Animals received primate chow, fruits, and vegetables every morning, and water was available ad libitum. All procedures were approved by the Seneca Park Zoo Research Committee.

Apparatus

The apparatus consisted of a short rectangular table (75-cm long × 35-cm deep × 17-cm high) that was a comfortable height for a seated baboon. The front of the apparatus was shielded Plexiglas and had five equally spaced ports for subjects to indicate their choice. Experimental manipulations were conducted on a sliding panel (75-cm long × 17-cm deep) that sat atop the table. When the sliding panel was pushed forward, subjects could reach through a port in the Plexiglas and indicate their choice. Four identical, opaque, polyvinyl-chloride cylinders were placed on the sliding board in front of corresponding ports. To occlude which of the two cylinders in each set was baited, we used a piece of corrugated plastic that blocked the subject's sight of the two cylinders from both the front and sides. After items were dropped into the cylinders, the items were hidden from the subject.

Familiarization training

To familiarize subjects with the testing procedure, we first tested them with the two-cup task (Call, 2004). For this task, two baiting cylinders were placed on the testing apparatus. At the beginning of each trial, the experimenter placed the occluder in front of the baiting cylinders. The experimenter then showed a grape above the occluder in the center between the two baiting

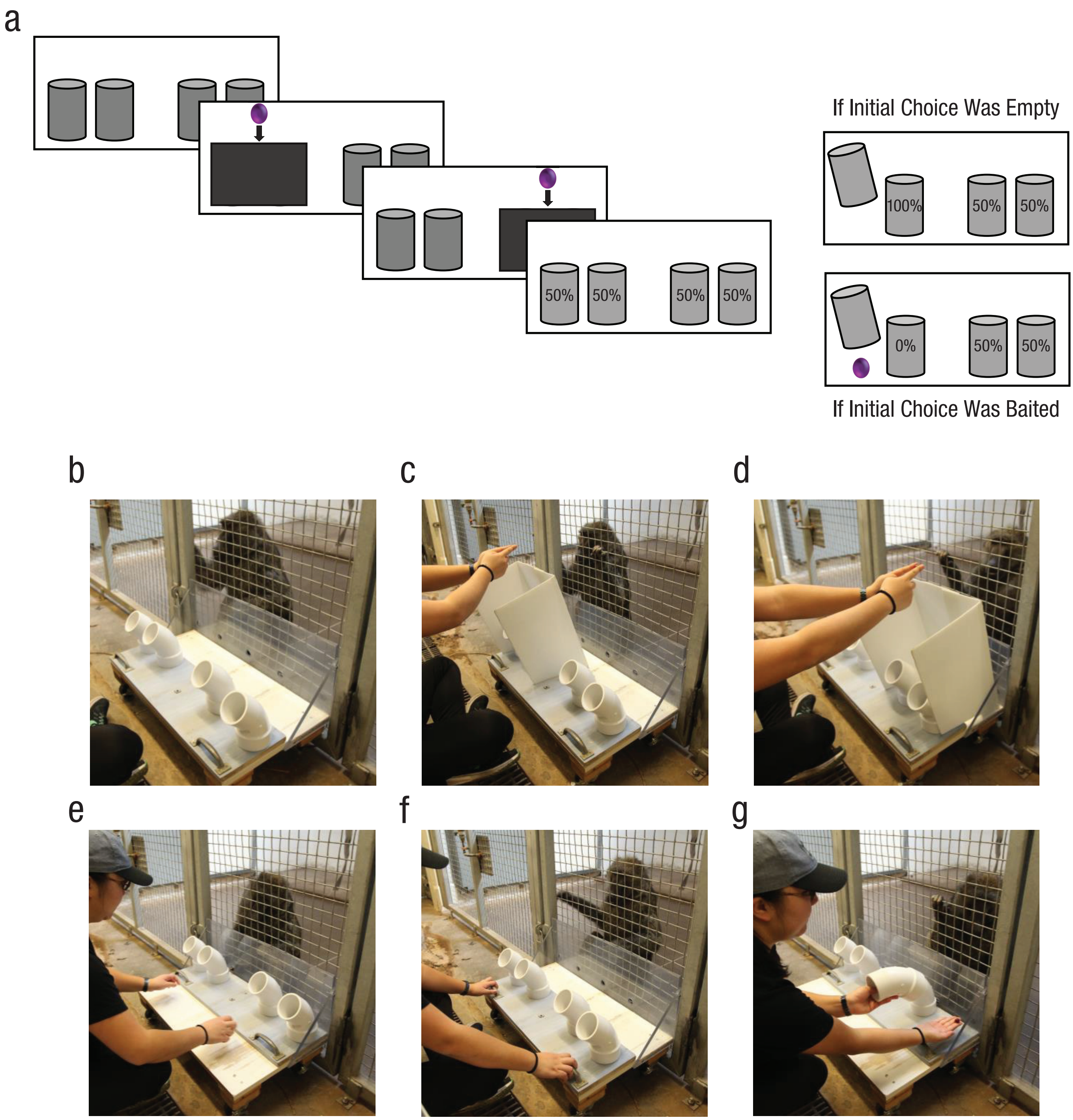

Fig. 1. A schematic of the testing procedure and a sample trial sequence. On each trial (a), there were two sets of two baiting cylinders each. The experimenter placed an occluder in front of one of the sets and then showed a grape above it before placing the grape in one of the two occluded cylinders. This process was repeated for the other two baiting cylinders, and then the occluder was removed. The monkey could then select any of the cylinders, after which the experimenter revealed whether the monkey had found a grape. The chances that can be deduced via disjunctive syllogism are listed here on the cylinders, both for when the first choice was correct and for when it was not. The photos illustrate moments in a sample trial. First, a grape is shown to the monkey (b) and then placed in one of two cylinders in the left set behind the occluder (c). The experimenter repeats this process with the right-hand set of cylinders (d). The board is then pushed forward. The monkey chooses a cylinder by putting a finger through the port and receives the contents of the cylinder (e). The board is then pulled back (f) before it is pushed forward again to allow the monkey to make the second choice (g).

locations. The grape was brought down behind the occluder and then placed in one of the two baiting locations. Then the experimenter removed the occluder, lifted the empty cylinder, and showed that the location was empty. To reduce the possibility of enhancement effects of alternative cues, the experimenter also touched but did not lift the baited cylinder. The experimenter then pushed the wooden platform forward so the baboons could indicate their choice by reaching through a port in the Plexiglas.

Each session consisted of 24 trials. The criterion that subjects needed to reach to move to the next stage was choosing the baited cylinder 17 out of 24 trials in two consecutive sessions (minimum of two sessions per subject). Five of nine monkeys passed this stage of training, which aligns with previous findings that approximately half of monkeys pass the two-cup version of this task (Schmitt & Fischer, 2009). For the five monkeys that passed, the number of sessions needed to meet the training criterion was highly variable. Two of five monkeys (Jefferson and Olive Oil) reached the criterion in the minimum number of sessions and performed above chance levels (17/24) from the first day tested. The remaining three monkeys that passed took on average 10 sessions of 24 trials to reach the criterion of 17 of 24 correct on two consecutive sessions.

Before moving to the four-cylinder version of the task, we first wanted to make sure that subjects were familiar with all four possible response ports in the testing apparatus. Four cylinders were placed on the testing apparatus and an experimenter placed one grape in one of the four cylinders while the subject watched. The experimenter then pushed the wooden platform forward, and the subject could make a choice. Again, each session was 24 trials long, and the criterion to move to the next stage was choosing the baited cylinder in 17 out of 24 trials in two consecutive sessions. All five monkeys passed this training.

Lastly, we wanted to familiarize the subjects with the procedure of having two opportunities to respond on each trial. To do this, the experimenter placed a grape in two of the four cylinders on the testing apparatus without the use of an occluder. The wooden platform was then pushed forward, and the monkey could make a first choice. After the animal was given what was in the baiting location, the board was pulled back and then pushed forward again, indicating that the monkey could make another choice. The subject could then make a second choice and would receive what was in the chosen baiting location. If a subject did not respond within 5 s, the trial ended and no response was counted. The criterion for proceeding to the testing phase was choosing two different baiting locations for 19 of 24 trials in a session with a minimum of two sessions (increased from the previous 17/24 trials because chance was higher in this training condition; chance = 75%). Four monkeys passed this criterion and continued to the testing phase.

Testing Phase 1

During the testing phase, the apparatus was set up in the same configuration as in the final training phase. There were four cylinders placed on the sliding wooden response board on the testing apparatus. Before each trial, the experimenter lifted all four cylinders to show the subjects they were empty before the trial started. The experimenter then placed the occluder in front of two of the four baiting cylinders (either the left two or right two). The treat was then shown above the occluder and was placed in one of the two cylinders behind the occluder so that the monkey could not know which location the grape was in. The occluder was then moved in front of the other two baiting cylinders, and the baiting process was repeated. The occluder was then removed, and the response board was slid forward, indicating that the monkey could make a first choice by touching the response port in front of one of the cylinders. The monkey was given the grape if it was under the chosen location or was shown that the location was empty if it was not there. The response board was then pulled away from the monkey and then pushed back toward the monkey after 2 s, indicating that the subject could make the next response. As before, whatever was hidden in the chosen location was given to the monkey (for a schematic of the trial procedure, see Fig. 1; for example trials, see Video S1 in the Supplemental Material available online).

Responses were live coded by a second experimenter, and all sessions were video recorded and coded off-line by a separate researcher. To control for accidental experimenter cuing, we used visors to cover the experimenter's eyes and face during all training and testing sessions. Monkeys received 10 sessions of 24 trials per session. One monkey left the testing area before completing an entire session and thus received only 21 trials for one of her sessions. Additionally, a small number of trials were excluded because of experimenter errors (n = 5), no response from the subject (n = 12), and subjects choosing the same cylinder two times in a row (n = 74, ~8% of trials). The trials in which the animal chose the same cylinder two times in a row were excluded because the results from the previous training session had already shown that these subjects can reliably avoid a cylinder they have seen to be empty. Furthermore, the number of repeated cylinder choices was far less than chance would predict (chance = 25%, monkeys = 8%). We not only excluded these trials but also removed the option when calculating chance performance. Thus, excluding this (rarely chosen) option made our analysis more conservative because we were able to compare our results with a more rigorous chance level. When these trials were included, the results were qualitatively similar (logistic regression predicting switching behavior using whether the first cylinder was empty or not as a predictor: $\beta = 0.19$, $p < .001$).

Testing Phase 2: cylinder distance control and prepointing behavior

The animals who succeeded in the initial testing phase ($n = 3$) were then given 10 more testing sessions of 24 trials per session (one monkey received only nine additional testing sessions because she refused to continue to participate). This second phase of testing began on average 44 days after the end of Phase 1 of testing for each subject. In the second testing phase, we positioned the four cylinders so that they had an equal distance within a set and between sets.

Additionally, during the initial testing phase, the experimenters noticed a spontaneous "prepointing" behavior. On some trials, the monkeys would point to a choice before it was time to make their second choice, either while the experimenter showed the contents of the first cylinder or while the experimenter pulled the board away from the subject. To investigate this further, we placed a camera directly above the testing board to clearly show exactly when the monkeys pointed to an option during this phase. The number of prepointing behaviors was coded off-line by two experimenters who did not participate in those testing sessions. A prepointing behavior was counted only when an animal put a finger through the choice holes after making the first choice but before the experimenter began pushing the board forward a second time to allow the monkey to make a second choice (between Figs. 1e and 1f). We excluded any trials that were noted as unclear by either off-line coder (9%) and any trials on which the coders disagreed (9%).

Results

To examine whether olive baboons exhibited inferential updating, we looked at the relationship between subjects' first-choice accuracy and their behavioral response type. Figure 2a shows the proportions of the two different types of responses made by the subjects (switched to the other baiting set vs. stayed in the same set), separately for whether they first chose the cylinder that was baited or not baited. We saw that subjects made different responses on the basis of whether they chose a baited cylinder or empty cylinder first. Specifically, when subjects chose an empty location first, they were more likely to stay in the same baiting set and choose the other cylinder in the set (59% of trials, 271/463) than switch to the other set (41% of trials, 192/463). Conversely, when subjects chose a cylinder containing a grape for their first choice, they were more likely to switch to the other baiting set and choose either one of the two cylinders (66% of trials, 267/403) than stay in the same set (34% of trials, 136/403).

To verify whether this pattern of data is robust, we conducted a Fisher's exact test. This test was used because our goal was to determine whether there was a significant difference in the proportion of switches between the different trial types (when the first cylinder was empty vs. full). This allowed us to control for any bias that the monkeys might have in their switching behavior. We found a significant contingency between first-choice accuracy and response type (Fisher's exact test, two-tailed: $n = 866$, $p < .001$; see Fig. 2b). Furthermore, we conducted a logistic regression using whether or not the first cylinder was empty as a predictor of switching behavior. Our results showed a significant effect of the first-cylinder results on subjects' switching behavior (first cylinder empty vs. first cylinder full: $\beta = 0.25$, $p < .001$). Thus, subjects flexibly modified their second-choice responses on the basis of inferential updating from their first choice, consistent with using disjunctive syllogisms.

We also examined the individual performance of the four baboons. We found that three of the four subjects made more logical responses (staying in the baiting set when an empty cylinder was chosen first or switching to the other set when a baited cylinder was chosen first: Olive Oil: 72%, Pepperella: 72%, Jefferson: 56%, Sabina: 47%; see Fig. 2a). To test whether the effect of first choice on switching behavior was significant, we ran individual Fisher's exact tests comparing whether the first cylinder was baited and whether the monkeys switched to the other baiting set or not. We found a significant dependence in three of four subjects; the subjects switched between baiting sets more often when they chose a baited cylinder first and stayed in the same set more often when they chose an empty cylinder first (Olive Oil: $n = 229$ trials, $p < .001$; Pepperella: $n = 219$ trials, $p < .001$; Jefferson: $n = 213$ trials, $p = .033$; Sabina: $n = 185$ trials, $p = .86$). Thus, three of the animals showed a pattern of inferential updating based on the first choice.

To further investigate the animals' success on this task, we broke down each of the trial types and analyzed them separately. Firstly, we looked at the trials in which an empty cylinder was chosen first (the trials that were similar to those used by Mody & Carey, 2016).

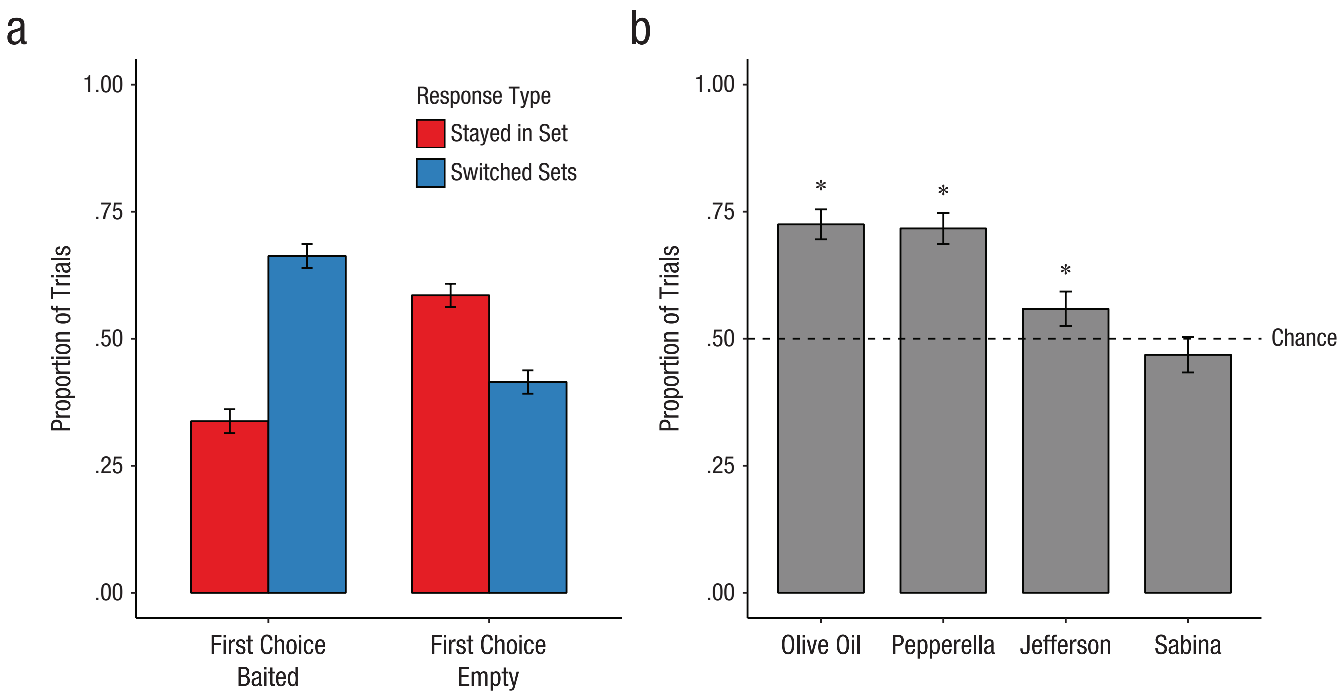

Fig. 2. Results. The proportion of trials in which subjects stayed in the baiting set and switched sets (a) is shown separately for when their first choice was the baited cylinder and for when it was the empty cylinder. The proportion of trials on which logical responses (stay when first cylinder was empty and switch when first cylinder was baited) were made by each subject is shown in (b). Asterisks indicate significant results ($p < .05$), as determined by a Fisher's exact test of the contingency between first choice and response type (stay in set or switch sets). Error bars in both panels indicate standard errors.

On these trials, there were significantly more choices to the cylinder that had to contain the grape in the same set compared with the other two cylinders (binomial test: chance = 33%, average of four monkeys = 58%, $p < .001$). Three of the four monkeys chose the cylinder that had to contain the grape more often than chance (binomial test: chance = 33%; Olive Oil: n = 113/123 trials, $p < .001$; Pepperella: n = 82/110 trials, $p < .001$; Jefferson: n = 53/119 trials, $p = .007$). The animal that showed no bias based on the outcome of the first choice, Sabina, had a strong bias to switch baiting sides regardless of whether the first cylinder was baited or not (mean switch rate = 79%). Her performance on these trials was significantly below chance (binomial test: chance = 33%; Sabina = 23/111, $p = .002$).

Next, we tested whether the monkeys performed above chance on trials in which the first cylinder chosen was baited. We found that their performance was not significantly above chance (binomial test: chance = 66%, average of four monkeys = 66%, $p = .74$). This is likely because of the monkeys not attending on every trial (because of the group housing atmosphere where the testing took place) and the very high level of chance on these trials. Even in the trials in which the monkeys were very successful (when the first cylinder was empty), their performance levels never reached 66%. Thus, this is likely ceiling performance. It is currently unknown whether young children could pass these types of trials because only trials in which the first cylinder was empty were included in previous work testing young children (Mody & Carey, 2016).

To investigate whether baboons could have succeeded in this task by associative learning, we examined changes in performance over time. If subjects learned the task by associating an empty cylinder with a "stay" response and a baited cylinder with a "switch" response, they would show chance performance during the beginning of training and improved performance over time. To test whether this was the case, we ran a logistic regression using trial number to predict the probability of making a logical response (0 for illogical and 1 for logical) across the three subjects who had successfully passed the task. We excluded the subject who failed to pass the task after 10 sessions (below-chance performance on trials in which the first cylinder was empty and no difference in performance based on the outcome of the first cylinder) because this analysis was meant to test whether associative learning could account for the performance of the monkeys who were successful on this task. We can already conclude that this one animal did not use any successful strategy (associative or not) to pass the task.

The results from the logistic regression show that, overall, subjects were more likely to make a logical response from the first trial (predicted probability at Trial 1 = ~60%, intercept: β = 0.415, p = .011). Additionally, we found a small but significant effect of trial number; as testing progressed, subjects were slightly more likely to make logical responses (β = 0.003, p = .043). We also ran this analysis on each individual animal. We found that all three animals were directionally more likely to make a logical response from the first trial, although this reached significance in only one of three animals (Olive Oil = ~60%, intercept: β = 0.35, p = .22; Pepperella = ~65%, intercept: β = 0.59, p = .044; Jefferson = ~58%, intercept: β = 0.33, p = .23). The predicted probabilities above 50% suggest that the spontaneous success from the start of testing was not being driven by one specific subject. Furthermore, only one of three animals showed a significant effect of trial number, which suggests that associative learning cannot account for our data (Olive Oil: β = 0.005, p = .015; Pepperella = ~65%, β = 0.59, p = .20; Jefferson: β = −0.001, p = .68).

Lastly, to measure whether associative learning accounts for the animals' success specifically on the trials that can be directly compared with those reported by Mody and Carey (2016), we ran a logistic regression using test trial number as the predictor of success on the subset of trials in which the monkeys chose the empty cylinder first. We found no evidence that the animals improved as testing progressed. Instead, we found a small but negative effect of trial number; the monkeys got slightly worse on these trials as testing progressed (β = −0.001, p = .015).

We also ran a series of logistic regressions to test whether any of the familiarization periods might have led to the animals learning an associative strategy. We first looked at the two-cylinder familiarization trials. Two of the three animals who succeeded on the four-cylinder task did not show any evidence of learning on the two-cylinder task (logistic regression; Jefferson: β = 0.058, p = .11; Olive Oil: β = −0.037, p = .51; Pepperella: β = 0.008, p = .004). We also analyzed the four-cylinder familiarization trials. We found that for two of the three monkeys, there was no evidence that trial number had an effect on whether they made two different choices per trial (logistic regression; Jefferson: β = −0.175, p = .09; Olive Oil: β = −0.008, p = .74). The third monkey did show improvement in this training. As training progressed, she was more likely to choose two different cylinders in a given trial (Pepperella: β = 0.04, p < .001). However, this provides evidence only that she could have learned that the same cylinder could not contain a grape after she chose it, not the correct contingencies between the cylinders.

Lastly, to test whether the monkeys were learning something about the structure of the cylinder contingencies (only one item per set), we tested whether there was an increase in logical switches (staying after finding an empty cylinder or moving after finding a food item) during the familiarization. We again found no evidence of learning in two animals (logistic regression; Jefferson: β = −0.086, p = .14; Olive Oil: β = 0.044, p = .051). The third animal showed some improvement across the familiarization trials (Pepperella: β = 0.022, p = .009). But it is ambiguous whether this is because of needing familiarization with the task itself to pass this training or learning of some type of noninferential heuristic. However, the evidence from the other two animals suggests that this type of heuristic cannot account for all of our data.

Although experimenter cuing was controlled for by occluding the experimenter's face during testing, it was possible that subjects could have used some other type of experimenter cue that was not controlled for. To test this possibility, we looked at the first choice made by the three monkeys who passed the four-cylinder task. For the first choice, it is possible that the subjects could make any inference on the location of the baited cylinders. Any results above chance would indicate the presence of experimenter cuing. We found that on the monkeys' first choice, they were not more likely to choose a baited cylinder than an empty cylinder (binomial test: chance = 50%, monkeys = 47%, 310/662, p = .95). Thus, the monkeys were not using experimenter or extraneous cues to infer the location of the baited cylinders.

It is possible that the animals' success on the subset of trials in which the first item chosen was empty might be due to a strategy such as tracking an item and choosing the closest cylinder to the one shown to be empty in order to find the tracked item. To test whether this type of strategy could account for our results or whether there was any decrease in performance for the control condition, we compared the overall performance between Testing Phase 1 (when the two sets of cylinders had additional space between them) and the control condition (when the two sets of cylinders were as far apart as the cylinders within a set), including all trials regardless of which cylinder was chosen first. We found no decrease in performance across conditions (three successful monkeys; Testing Phase 1 = 67% logical, control condition = 73% logical). Furthermore, when we analyzed only the trials in which the first choice was one of the middle cylinders and that cylinder was empty, we found that the monkeys more often switched to the cylinder that was within that baiting set, even though it was equally distant from another option in the other set (binomial test: choice of cylinder in set = 67%, chance = 50%, $p < .001$). Thus, their success was not due to the strategy of choosing the closest cylinder after finding an empty cylinder.

Lastly, if the monkeys were correctly inferring that the remaining cylinder in the set must contain a grape, then there may have been indications in their behavior of this confidence. During the initial testing, the experimenters noticed a prepointing behavior. On some trials, the monkeys would point to a cylinder before it was time to make their second choice (for a similar behavioral measure using speed of searching to indicate understanding of a disjunct, see Watson et al., 2001). To investigate whether this behavior might indicate increased confidence, we analyzed when these prepointing behaviors happened on 10 additional sessions of testing in the three successful animals (the original 10 testing sessions could not be coded because of the camera angle).

We found that the monkeys were more likely to point to a response before the experimenter pushed the board forward more often when the first choice was empty and the location of a remaining grape could be confidently inferred (72% of these trials) compared with when the first cylinder was baited and no remaining baited location could be inferred (9% of trials; $z = 15.79$, $p < .001$). Furthermore, within a trial, when subjects pointed early, the animals were pointing to a correct grape location 79% of the time. One potential confound of this measure is that on the baited-first trials, the monkeys had just received a reward, which may have decreased the pointing behavior. Although it is possible that this affected their prepointing, we think that it is unlikely because of the size of the food reward (1/4 grape). The reward was small enough that it was eaten immediately after receiving it. The monkeys would continue to finish the trial and make a second choice regardless of whether they just received a reward or not. There was only a single trial in the control experiment (when the prepointing behaviors were analyzed) in which a subject did not make a second choice. This provides additional evidence that the monkeys updated the probability of which cylinder must contain the food item on the basis of the evidence they received from their first choice.

Discussion

Our results provide evidence that nonhuman primates can reason using disjunctive syllogisms to reliably deduce the location of hidden food items. To date, this has been shown only in children of at least 3 years old (Mody & Carey, 2016) and in a single African gray parrot (Pepperberg, Gray, Mody, Cornero, & Carey, 2019). In contrast, 2.5-year-olds were not capable of inferring which location must contain the hidden object in this four-cylinder task. The capacity for a nonlinguistic animal to successfully complete this task suggests that having verbal labels for the logical operators "or" and "not" is not a prerequisite for reasoning logically through a disjunctive syllogism. In contrast, 2.5-year-old children did not reliably infer which location must contain the hidden object, and performance did not reach above 50% until the age of 4 years. This failure of young children could be due to a lack of nonlinguistic modal concepts (see Leahy & Carey, 2020; for a more complete discussion of these topics, see Redshaw & Suddendorf, 2020). The success of monkeys on this task suggests that monkeys not only are capable of representing a possible outcome (a minimal representation of possibility) but also can compare multiple possibilities. This modal representation of possibility is beyond that which has been attested in young children until the age of 4 years.

Overall, our results show that nonhuman primates have the capacity to represent the abstract, combinatorial, or logical thought required to reason through a nonverbal disjunctive syllogism. However, it is unknown how widespread this ability is at the population level, a question that should be addressed in future research. Furthermore, the precise mechanism by which animals reason through a nonverbal disjunctive syllogism requires detailed study. Some researchers have argued that the underlying mechanism is analogous to symbolic logic in that it may require explicit logical operators such as "not" and "or" (Mody & Carey, 2016), whereas others have argued that the mechanism may be implicit and tied to primitive object-tracking mechanisms or nonlinguistic but fully languagelike structures (Cesana-Arlotti et al., 2018); still other researchers have suggested that Bayesian reasoning could describe the behavior (Rescorla, 2009). Whatever the mechanism, the slow developmental trajectory of disjunctive reasoning and the continuity between primates and older children on nonverbal disjunctive syllogisms suggest a role for higher level nonverbal cognition in its solution.

Transparency

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Author Contributions
All the authors developed the study concept and design. S. Ferrigno and Y. Huang conducted testing and data collection. All authors analyzed and interpreted the data under the supervision of J. F. Cantlon. All the authors wrote the manuscript and approved the final manuscript for submission.
Declaration of Conflicting Interests
The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Open Practices

All data and materials are available from the corresponding author on request. The design and analysis plans for the study were not preregistered.

ORCID iD

Stephen Ferrigno https://orcid.org/0000-0002-8021-1662

Supplemental Material

Additional supporting information can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797620971653

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