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Review

Abstract concepts: Data from a Grey parrot

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ABSTRACT

Do humans and nonhumans share the ability to form abstract concepts? Until the 1960s, many researchers questioned whether avian subjects could form categorical constructs, much less more abstract formulations, including concepts such as same-different or exact understanding of number. Although ethologists argued that nonhumans, including birds, had to have some understanding of divisions such as prey versus predator, mate versus nonmate, food versus nonfood, or basic relational concepts such as more versus less, simply in order to survive, no claims were made that these abilities reflected cognitive processes, and little formal data from psychology laboratories could initially support such claims. Researchers like Anthony Wright, however, succeeded in obtaining such data and inspired many others to pursue these topics, with the eventual result that several avian species are now considered "feathered primates" in terms of cognitive processes. Here I review research on numerical concepts in the Gray parrot (*Psittacus erithacus*), demonstrating that at least one subject, Alex, understood number symbols as abstract representations of real-world collections, in ways comparing favorably to those of apes and young human children. He not only understood such concepts, but also appeared to learn them in ways more similar to humans than to apes.

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1. Introduction

In the early twentieth century, little scientific interest existed in cognitive processes, even in humans. As a consequence, the study of such processes in nonhumans was also not a viable pursuit. Thus, until the so-called "cognitive revolution" of the 1960s, both ethologists and psychologists, with few exceptions (notably in Europe, e.g., Herz, 1928, 1935; Koehler, 1943), were likely to see nonhumans, and particularly birds, as simple automatons, incapable of complex cognitive processing. Indeed, the term "avian cognition" was considered an oxymoron (see review in Pepperberg, 2011).

Ethologists did accept that birds had to have some understanding of divisions such as prey versus predator, mate versus nonmate,

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food versus nonfood, or basic relational concepts such as more versus less, simply in order to survive. Ethological research, however, was mostly interested in issues such as "fixed action patterns" (e.g., Tinbergen, 1951)—innate, instinctual behavioral sequences that seemed indivisible and that, once begun, could not be stopped until they ran to completion. Such sequences were initiated by external stimuli known as "releasers," and even removing these releasers mid-stream had no effect. Moreover, because objects that only approximated the releasers might set the behavior in motion, nonhumans were considered incapable of recognizing substitutions or reacting to change of any sort.

Similarly, psychologists concentrated on issues such as stimulus–response chains, where almost all behavior could be explained in terms of histories of positive or negative conditioning to increase or decrease, respectively, behavior toward some external situation. The rules underlying behavior were thought to be the same whatever the species (Skinner, 1938), and species differences were expected to arise only in the speed and extent of acquisition of these rules (for interesting discussions of these ideas see Bitterman, 1965, 1975). The focus was ostensibly on learning, but not in the sense of information processing, remembering, problem solving, rule and concept formation, perception, or recognition: learning was seen as behavior simply being *shaped* by the association of external stimuli and their consequences. Scientists eschewed discussions of issues such as thought, mental representations, or intentional actions (Pepperberg, 1999, 2011).

By the 1960s, however, researchers began to realize that the behavior patterns of their subjects (human or nonhuman) could not be fully explained by current paradigms (e.g., Breland and Breland, 1961). After realizing that even *human* actions were neither as pre-wired nor as amenable to shaping as once thought, a small group of researchers began to examine nonhumans in the same manner, suggesting a continuum between human and nonhuman abilities (e.g., Hulse et al., 1968). Psychologists such as Herrnstein started examining issues of concept formation in pigeons (e.g., Herrnstein and Loveland, 1964; Herrnstein et al., 1976), and those like Anthony Wright pushed what was then the edge of the envelope to examine so-called "abstract concepts" of same-different (e.g., Premack, 1978); he and his colleagues (Santiago and Wright, 1984; Wright et al., 1984a,b; see also seminal work from the Zentall lab, e.g., Edwards et al., 1983) tried to separate out issues of same-different from those of match-to-sample and nonmatch-to-sample and whether subjects were responding on the basis of novelty or other aspects of the task rather than the abstract concept. Specifically, a subject that understands same/different not only knows that two nonidentical blue objects are related in the same way as are two nonidentical green objects—in terms of color—but also knows that the relations between two nonidentical blue objects and two nonidentical square objects are based on the *same* concept but with respect to a *different* category, and, moreover, can transfer this understanding to *any* attribute of an item (Premack, 1978, 1983). Inspired by the research of scientists like Wright and Zentall, my own studies on Gray parrots showed their capacity to understand concepts of category and of same-different (Pepperberg, 1983, 1987a)—and of the absence of same-different (Pepperberg, 1988)—at levels comparable to those of nonhuman primates.

Once Wright, his collaborators, and colleagues helped demonstrate that abstract concept formation was a legitimate area for study in nonhumans, many of us followed their lead to examine other abstract concepts as well. One path that my laboratory took involved the study of a Gray parrot's number concepts. To succeed on number concepts, the bird would have to reorganize how objects were categorized in its world. Specifically, an object would not only be, for example, something to eat or manipulate, or of a specific color or shape, but also would have to be *labeled* with respect to its membership within a quantifiable set, if exact number competence were to be shown. Could a nonhuman acquire that level of abstract understanding? I was hardly the first to study number concepts in nonhumans or even birds, but was the first to examine whether an avian subject could use human number labels symbolically and referentially, to identify exact quantities (see Pepperberg, 2012b). I likely would not have done so had others like Wright not led the way.

Numerical abilities involve many issues. Even for humans, some researchers still disagree on what constitutes various stages of numerical competence; which are the most complex, abstract stages; what mechanisms are involved; and even what is enumerated (for a detailed review, see Carey, 2009). And considerable discussion exists as to the extent to which language—or at least symbolic representation—is required for numerical competence, not only for preverbal children but also for primitive human tribes and nonhumans (e.g., Gordon, 2004; Watanabe and Huber, 2006; Frank et al., 2008). If language and number skills require the same abstract cognitive capacities, then animals, lacking human language and, for the most part, symbolic representation, should not succeed on abstract number tasks; an alternate view is that humans and animals have similar simple, basic number capacities but that only humans' language skills enable development of numerical representation and thus abilities such as verbal counting and addition (see Pepperberg, 2006b; Carey, 2009; Pepperberg and Carey, 2012).

But what if a nonhuman had already acquired a certain level of abstract, symbolic representation? Could such abilities be adapted to the study of numerical competence? Again, with the inspiration and encouragement from colleagues such as Wright, I decided to find out. Here I begin by discussing briefly the background studies with my Gray parrot, Alex, then review the accumulated data that demonstrate the extent of abstract number competence he achieved.

2. Alex's non-numerical capacities

When I first began numerical work with Alex in the 1980s, he had already achieved competence on various tasks once thought limited to young children or at least nonhuman primates (Pepperberg, 1999). Through the use of a modeling technique, roughly based on that of Todt (1975), Alex learned to use English speech sounds to referentially label a large variety of objects and their colors; at the time he could also label two shapes ("3-corner" for triangles, "4-corner" for squares; later he identified various other polygons as "*x*-corner"). He understood concepts of category: that the same item could be identified with respect to material, color, shape, and object name (e.g., "wood", "blue", "4-corner", and "block"). He had functional use of phrases such as "I want X" and "Wanna go Y", X and Y being appropriate object or location labels. He was acquiring concepts of *same*, *different*, and *absence*—for any object pair he could label the attribute ("color", "shape", and "matter") that was same or different, and state "none" if nothing was same or different; he was also learning to view collections of items and state the attribute of the sole object defined by two other attributes—e.g., in a set of many objects of which some were yellow and some were pentagonal, to label the material of the only one that was both yellow *and* pentagonal (Pepperberg, 1999). But could he form an entirely new categorical class consisting of quantity labels?

3. Alex's early numerical abilities

As noted above, to succeed on number concepts, Alex would have to reorganize how he categorized objects in his world. He would have to learn that a new set of labels, "one", "two", "three", etc. represented a novel classification strategy; that is, one based on both physical similarity within a group and a group's quantity, rather than solely by physical characteristics of group members. He would also have to generalize this new class of number labels to sets of novel items, items in random arrays, heterogeneous collections, and eventually to more advanced numerical processes (Pepperberg, 1999, 2006b). If successful, he would demonstrate a *symbolic* concept of number, that is, vocally designate the *exact* quantity of a given array with an appropriate numerical, referential utterance in his repertoire (Pepperberg, 2012b).

3.1. Training and testing methods

Via our standard modeling technique that enabled Alex to produce labels for objects, colors, and shapes, he was initially trained to identify small number sets with English labels (note, however, that he initially used "sih" for six, because he had trouble pronouncing the final /s/; Pepperberg, 1987b). As we will see in detail below, this training was quite different from that experienced by young children. For example, unlike children (Carey, 2009), who learn numbers in the appropriate ordinal pattern (i.e., "one", "two", etc.), he was first trained on sets of three and four, because he already had those labels in his repertoire; he was then taught "five" and "two," then "six" and lastly "one." Training in such a manner also ensured that Alex was building his concept of number solely by forming one-to-one associations between specific quantities and their respective number labels (Pepperberg, 2006b). Unlike children, who seem to learn "one" fairly easily (i.e., "one" versus "many", Carey, 2009), "one" was actually rather difficult for Alex to acquire, because he already knew to label a single item with an object label and had to be trained for quite some time to add the number label. Training details are published elsewhere and will not be repeated (Pepperberg, 1987b). Training was limited to sets of a few familiar objects; testing involved transfer to sets of other familiar and novel exemplars. Various publications describe, again in great detail, testing procedures that ensured against myriad forms of possible external cuing, both with respect to inadvertent human cuing and cues based on nonnumber issues such as mass, brightness, density, surface area, odor, item familiarity, or canonical pattern recognition (Pepperberg, 1987b, 1994, 1999, 2006a,b,c).

3.2. Labeling of basic quantities and simple heterogeneous sets

Initial studies demonstrated that Alex could use English labels to quantify small sets of familiar different physical items, up to six, exactly (78.9%, all trials; Pepperberg, 1987b); that is, he overall made few errors, and his data did not show a peak near a correct response with many errors of nearby numerals, which would have suggested only a general sense of quantity (i.e., an approximate number system). Rather, his most common errors across all sets was to provide the label of the object involved—to respond, for example, "key" rather than "four key", which accounted for almost 60% of his roughly 50 errors in ~250 trials (another ~20% of his errors involved unintelligible responses or misidentifications of the object or material; i.e., 80% of his errors were nonnumerical). Thus Alex indeed had a concept of quantity; he was not, however, necessarily counting, as would a human child who understood, for example, the concept of "five" (Fuson, 1988; Pepperberg, 1999; Mix et al., 2002); that is, who understood the counting principles: that a stable symbolic list of numerals exists, numerals must be applied to individuals in a set to be enumerated in order, they must be applied in 1–1 correspondence, that the last numeral reached in a count represents the cardinal value of the set, and that each numeral is exactly one more than the previous numeral (Gelman and Gallistel, 1986; Fuson, 1988). Even if he was not technically counting, additional tests demonstrated that Alex could quantify even unfamiliar items and those not arranged in any particular (canonical) pattern, such as a square or triangle; he maintained an accuracy of about 75–80% on novel items in random arrays.

Moreover, he could also quantify subsets within heterogeneous sets; that is, in a mixture of X's and Y's, he could respond appropriately to "How many X?", "How many Y?", *or* "How many toy?" (70%, first trials; Pepperberg, 1987b). Here he outperformed some children, who are generally tested on only homogeneous sets (e.g., Starkey and Cooper, 1995) and who, if asked about subsets within a mixed set of toys, usually label the *total* number of items if, like Alex, they have been taught to label homogeneous sets exclusively (see Siegel, 1982; Greeno et al., 1984).

Despite these tests, we still could not identify the mechanism(s) Alex might be using to succeed. Notably, our tests ensured that Alex could not use nonnumerical cues such as mass, brightness, surface area, odor, object familiarity, or canonical pattern recognition (Pepperberg, 1987b, 1999), because we questioned him on a variety of exemplars of various sizes and of both familiar and novel textures and materials (e.g., metal keys versus bottle corks) often presented by simply tossing them in random arrays on a tray. Such controls did not, however, rule out the possibility that, for the smallest collections, Alex had used a noncounting strategy such as subitizing—a perceptual mechanisms that enables humans to quickly quantify sets up to ~4 without counting—or, for larger collections, "clumping" or "chunking"—another form of subitizing (e.g., perception of six as two groups of three; for a review, see von Glasersfeld, 1982). Thus many other tests would be needed to determine the mechanisms that Alex was indeed using.

3.3. Complex heterogeneous sets

Some tests to tease apart subitizing/clumping versus counting issues were initially designed for humans by Trick and Pylyshyn (1989, 1994). In their experiments, subjects had to enumerate a particular set of items embedded within two different types of distractors: (1) white *or* vertical lines among green horizontals; (2) white vertical lines among green vertical *and* white horizontals. The authors argued for subitizing for 1–3 in only the first condition, but counting, even for such small quantities, in the second. When subjects thus must distinguish among various items defined by a collection of competing features (e.g., a conjunction of color *and* shape, where an evaluation cannot be made on the basis of a single attribute, such as "whiteness"; see Pepperberg, 1999), subitizing becomes unlikely. Alex could be examined in a comparable manner, because he already was being tested on conjunction (e.g., being asked to identify the color of an item that was both triangular and wood in a collection of differently shaped objects of various materials; Pepperberg, 1992). He could thus be asked to label the quantity of a similarly defined subset—for example, the number of green blocks in a set of orange and green balls and blocks. Would his numerical capacities match those described by Trick and Pylyshyn for humans? (Note that we now understand even more about the effects of the physical dimensions of various stimuli on number competence; see Rugani et al., 2010 for a discussion.)

Alex turned out to be about as accurate as humans (83.3% on 54 trials, Pepperberg, 1994; see Trick and Pylyshyn, 1989), and analyses suggested that he, like humans, was counting. Had he used perceptual strategies similar to those of humans (e.g., subitizing and clumping), rather than counting, he would have made no errors for 1 and 2, few for 3, and more for larger numbers. His errors, however, were random with respect to number of items to be identified (Pepperberg, 1994) and, importantly, his responses were not simply a close approximation to the correct number label (Pepperberg, 1994), which would be expected had he been subitizing or even estimating. In fact, most of Alex's errors seemed unrelated to numerical competence, but rather were in misinterpreting the defining labels, then correctly quantifying the incorrectly targeted subset. Eight of his nine errors were the correct number for an alternative subset (e.g., the number of blue rather than red keys; in those cases, the quantity of the designated set usually differed from that of the labeled set by two or more items). The problem, however, was that there was no way of knowing whether Alex's perceptual capacities might be more sophisticated than those of humans, allowing him to subitize larger quantities; the data, although impressive with respect to exact number, still did not justify claiming that he was definitively counting. A detailed discussion is in Pepperberg (1994).

In a subsequent study (Pepperberg and Carey, 2012), we further tested Alex's responses concerning exact number. Here we examined how he might process quantities greater than those he could label; we specifically wanted to see if his label "sih" actually referred to exactly six items, or roughly six; that is, to anything he might perceive as large. We showed him, in individual trials under no time constraints, seven, eight, and nine items, asking "How many X?" There were two trials for each quantity, in random order, interspersed with trials on smaller sets and non-number tasks, to ensure that he could switch between sets and objects he could label and those that (potentially) he could not. He was neither rewarded nor scolded whatever his reply, simply told "OK;" we then went to the next query. In trials for sets greater than six, Alex usually initially did not answer, but remained quietly seated on his perch or asked to return to his cage. Only when we continuously badgered him, asking over and over, did he eventually reply "sih." His actions suggested that he knew his standard number answers would be incorrect and he did not, as when was being noncompliant (e.g., see below; Pepperberg, 1992; Pepperberg and Lynn, 2000; Pepperberg and Gordon, 2005), give strings of irrelevant answers, request many treats, or turn his back and preen.

4. Alex's more advanced numerical abilities

En route to determining the mechanism—or mechanisms—Alex used to quantify sets, my students and I examined various other numerical capacities. Thus, Alex was tested on comprehension of numerical labels, on his ability to sum small quantities, and on whether he understood the ordinality of his numbers. The latter task was of particular interest, because, as noted above, unlike children, he had not been trained in an ordinal manner: he had first learned to label sets of three and four, then five and two, then six and one.

4.1. Number comprehension

Although Alex could label numerical sets, he had never been tested on number label comprehension. In general, researchers who teach nonhumans to use a human communication code must ensure the equivalence of label production and comprehension (e.g., Savage-Rumbaugh et al., 1980, 1993), but the issue is particularly important in numerical studies: even a young child who successfully labels the number of items in a small set ("Here's X marbles") might fail when shown a very large quantity and asked "Can you give me X marbles?" That is, the child might not really understand the relationship between the number label and the quantity (Wynn, 1990). If labeling indeed separates animal and human numerical abilities (see above; Watanabe and Huber, 2006; Pepperberg, 2012b; Pepperberg and Carey, 2012), such comprehension-production equivalence would be necessary to demonstrate nonhuman numerical competence (Fuson, 1988).

To test Alex's comprehension abilities, we used a variation of the previous task. Here we simultaneously presented several sets of different quantities of different items—for example, X red blocks, Y yellow blocks, Z green blocks, or X blue keys, Y blue wood, and Z blue pompons, with X, Y, and Z being different quantities. Alex was then queried, respectively, "What color Z?" or "What matter X?" (Pepperberg and Gordon, 2005). He received no training on this task prior to testing. To succeed, he had to comprehend the auditorially presented numeral label (e.g., X = "four") and use its meaning to direct a search for the cardinal amount specified by that label (e.g., four things), that is, know exactly what a set of "X" items is, even when intermixed with other items representing different numerical sets (Fig. 1). We again controlled for contour, mass, etc. by using objects of different sizes, within or across trials so that comprehension of the number label was the only way to perform correctly (Pepperberg and Gordon, 2005). To respond correctly, he also had to identify the item or color of the set specified by the numerical label. Some or all this behavior likely occurred as separate steps, each adding to task complexity (Premack, 1983).

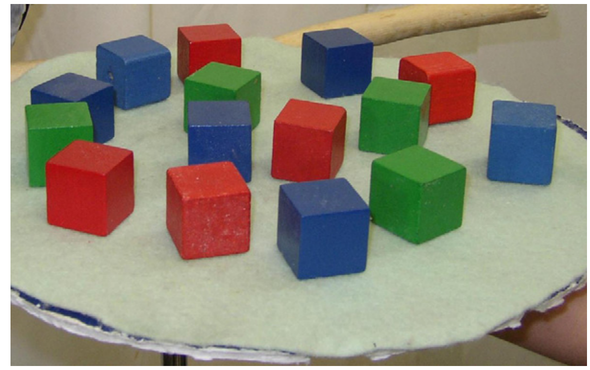

Fig. 1. Alex's comprehension task. Trials with blocks were the only ones in which all the objects were exactly the same size; these trials tested whether accuracy improved with same-sized objects.

Alex's overall score was again impressive (statistically significant 87.9% on 66 trials), with no errors on the first 10 trials (Pepperberg and Gordon, 2005). Interestingly, errors increased with time, suggesting lack of focus or inattention as testing proceeded. He may have been like keas (Gajdon et al., 2011) or large-billed crows (Izawa and Watanabe, 2011) that will, after succeeding on various tasks, often later employ other, less successful or simply different methods, possibly from boredom (e.g., to engender more interesting responses from trainers; Pepperberg, 2012c) or maybe to find other possible solutions. In any case, he understood the meaning of his number labels somewhat better than young children (see above, Fuson, 1988; Wynn, 1990, 1992), and, most importantly, he had little difficulty with numbers differing by small amounts, suggesting that his number sense was exact and not approximate. Most of his errors appeared to involve color perception or phonological confusion, not numerical misunderstanding: he sometimes erred in distinguishing orange from red or yellow, a consequence of differences in parrot and human color vision (Bowmaker et al., 1994, 1996); he also sometimes confused "wool" and "wood", or "truck" and "chalk"; he pronounced the last label a bit like "chuck" (Pepperberg and Gordon, 2005).

4.2. Use of "none"

The comprehension study was notable for another reason: Alex's spontaneous transfer of use of "none"—learned as a response to the queries "What's same/different?" with respect to two objects when no category (color, shape, or material) was same or different (Pepperberg, 1988)—to the absence of a set of a particular quantity. After responding appropriately for several trials of the standard comprehension task, Alex reacted in a manner quite different from the norm. When, on one particular trial, he was asked "What color three?" to a set of two, three, and six objects, he replied "five"; obviously no such set existed and his response made little sense. The questioner asked twice more, each time he replied "five." He was obviously refusing to answer the question posed, but, unlike his usual responses when he was being noncompliant (e.g., Pepperberg and Lynn, 2000)—that is, when he refused to maintain his gaze on the tray, but instead endlessly preened, made requests to be returned to his cage or for treats he then discarded, or uttered strings of irrelevant labels (e.g., colors not on the tray and thus not possible response choices), here he was providing the label of a *number* that was *not* being tested and *consistently* repeating it. The response seemed irrelevant, but was different enough from noncompliance that, finally, the questioner said "OK, Alex, tell me, what color 5?", to which he immediately responded "none" (Pepperberg and Gordon, 2005). The response came as a complete surprise, as he had never been taught the concept of absence of quantity nor to respond to absence of an exemplar. He had, previously, spontaneously transferred use of "none" from the same-different study to "What color bigger?" for two equally sized items in a study on relative size (Pepperberg and Brezinsky, 1991), but that use of "none" still referred to the absence of difference in an attribute. "None," or a zero-like concept, is advanced, abstract, and relies on the violation of an expectation of presence (Bloom, 1970; Hearst, 1984; Pepperberg, 1988). Of additional interest was that Alex not only had provided a correct, novel response, but had also manipulated the trainer into asking the question he apparently wished to answer, which suggested other levels of abstract processing (Pepperberg and Gordon, 2005). Alex also correctly answered additional queries about absent sets of one to six items, showing that his behavior was not a chance response.

A subsequent study (Pepperberg and Carey, 2012) further emphasized Alex's number comprehension and made use of his knowledge of absence. Here we again tested him with sets larger than he could label: he saw four trays with sets of various numbers of items, including 7 or 8 but omitting 6 (e.g., 3 yellow wool, 4 blue wool, 7 green wool), and was asked "What color six?" to see if he would reply "none" (Pepperberg and Gordon, 2005)—would he require exactly six or accept the set that was roughly six (here, say "green")? These questions tested whether he knew that "six" meant *exactly* six and not approximately six, that is, whether he truly understood that his labels referred to very specific sets. He was also asked about an existing set for two arrays to ensure he did not learn to respond "none." Thus he had six queries: two probing an existing set (one for a 3-item set, one for 5) and four for which the correct response was "none" if "six" meant exactly six. Alex responded "none" on all four trials involving quantities above six. On trials for colors of sets that were present, he gave the appropriate labels (respectively, "yellow" and "green" to 3- and 5-item sets).

A critical issue was that Alex's initial use of "none" was spontaneous, unlike that of the chimpanzee, Ai, who had to be trained to use the label "zero" (Biro and Matsuzawa, 2001). But our data did not demonstrate whether he really understood the overall *concept* of zero. How similar was his understanding to that of a young child or an adult human? Only additional studies could provide that information.

4.3. Addition of small quantities

Although I had always wanted to determine if Alex could perform the same kind of small number addition as did chimpanzees (Boysen and Berntson, 1989), I had started to focus on other areas of cognitive processing (e.g., research on optical illusions, Pepperberg et al., 2008) at this time. Thus studies on addition (Pepperberg, 2006a), like those on "zero," were unplanned, and came about as follows. Alex, who routinely interrupted the sessions of a younger parrot, Griffin, with phrases like "Talk clearly" or with an appropriate answer, appeared to sum the clicks over the individual trials that we were using to train Griffin on sequential auditory numbers (training to respond to, e.g., three computer-generated clicks with the vocal label "three"). Given how difficult it would be to demonstrate true summation auditorially, I chose to replicate, as closely as possible, the object-based addition study of Boysen and Berntson (1989) on apes, and to use the experiment to study further Alex's understanding of zero (Pepperberg, 2006a).

I chose the Boysen and Bernston procedure because it was a formal test of addition—having a subject observe two (or more) separate quantities and provide the *exact* label for their total (Dehaene, 1997)—that is, it required both summation *and* symbolical labeling of the sum by a nonhuman. Most additive and subtractive studies on nonhumans required the subject to choose the larger amount of two sets, not label final quantity (review in Pepperberg, 2006a). Specifically, when the correct response involves choice of relative amount, no information is obtained on whether the subject has "...a digital or discrete representation of numbers" (Dehaene, 1997, p. 27; see also Carey, 2009, for a discussion of how such responses can rely on an approximate number system). In contrast to most other addition studies, moreover, I avoided use of only one token type of a standard size (e.g., whole marshmallows), which could allow evaluations to be based on contour and mass, not number (note Mix et al., 2002).

The procedure was as follows: Alex was presented with a tray on which two upside down cups had been placed (Fig. 2); prior to presentation, a trainer had hidden items such as randomly shaped nuts, bits of cracker, or differently sized jelly beans under each cup, with items in the same cup less than 1 cm from each other. We occasionally used identical candy hearts to see if accuracy was higher when mass/contour cues were available (Pepperberg, 2006a). After bringing the tray up to Alex's face, the experimenter lifted the cup on his left, showed what was under the cup for 2–3 s in initial trials, replaced the cup over the quantity; then replicated the procedure for the cup on his right. For reasons described below, in trials comprising the last third of the experiment, Alex had ~6–10 s to view items under each cup before everything was covered. The experimenter then made eye contact with Alex, who was asked, vocally, and without any training, to respond to "How many total?" He saw collections with all possible addends, totaling to every amount from 1 to 6, plus trials with nothing under both cups to see if he would generalize use of "none" without instruction. No objects other than the cups were visible during questioning. To respond correctly, Alex had to remember the quantity under each cup, perform some combinatorial process, then produce a label for the total amount. He had no time limit in which to respond, given that his

Fig. 2. Alex's addition task.

response time generally correlated with his current interest in the items being used in the task, rather than the task itself (Pepperberg, 1988). Appropriate controls for cuing and tests for interobserver agreement were, as usual, in place (Pepperberg, 2006a).

For sets of countable objects, Alex had a statistically significant accuracy of 85.4% on 48 first trial responses (Pepperberg, 2006a), and his accuracy did not improve on trials with identical tokens. He had trouble with one set of trials, however. Interestingly, when given only 2–3 s, he always erred on the 5 + 0 sum, consistently stating "6"; when given ~6–10 s, however, his accuracy went to 100%. Differences in accuracy between the shorter and longer interval trials was significant only on 5 + 0 trials (Fisher's exact test, $p = 0.01$). Such data suggest that he used a counting strategy for 5: only when beyond the subitizing range of 4 did he, like humans, need time to label the set exactly (for a detailed discussion, see Pepperberg, 2006a). Overall, his data are comparable to those of young children (Mix et al., 2002) and, because he added to six, are more advanced than those published on apes (Boysen and Hallberg, 2000).

In a subsequent study (Pepperberg, 2012a), Alex showed that he could perform with equal accuracy when asked to sum three sets of sequentially presented objects—that is, collections of variously sized objects now hidden under three cups. Here he had to maintain numerical accuracy under what could be an additional memory load, because the protocol required two updates in memory rather than one. His first trial score was 8/10 correct, 80%, $p < 0.001$ (binomial test, chance of either ¼ or 1/6; 1/6 represented a guess of all possible number labels, ¼ represented a guess of using one of the three addends as well as their sum). For all trials, his score was 10/12 correct or 83.3%. Occasionally, one cup contained no objects, but even if only those trials are considered in which all three cups contained items, Alex's first trial score was 4/5 correct, $p = 0.015$ (chance of ¼; for chance of 1/6, $p < 0.01$); his all trials score was 5/6 or, again, 83.3%. In this three-cup task, all of the addends were within subitizing range (Boysen and Hallberg, 2000; Pepperberg, 2006a); thus Alex could easily have tracked these without specifically counting. However, he still would have needed to remember the values under each of the three cups, for several seconds for each cup, and update his memory after seeing what was under each cup, even if nothing was present. Again, because he added up to 6, his competence surpassed that of an ape similarly tested (Sheba: Boysen and Hallberg, 2000).

Interestingly, in the two-cup task, Alex did not respond "none" when nothing was under any cup (Pepperberg, 2006a; NB: such trials were not present in the three-cup task). He either looked at the tray and said nothing (five trials) or said "one" (three trials). He never said "two," showing that he understood that the query did not correspond to the number of *cups*. On trials in which he did not respond, his lack of action suggested that he knew his standard number answers would be incorrect. Again, he did not react as he did when noncompliant (see above, Pepperberg and Lynn, 2000). His behavior somewhat resembled that of autistic children (Diane Sherman, personal communication, 2005), who simply stare at the questioner when asked "How many X?" if nothing exists to count. As for his response of "one," he may, despite never having been trained on ordinality and having learned numbers in random order (see above), have inferred that "none" and "one" represented the lower end of the number spectrum and conflated the two labels. Such confusion was demonstrated by the chimpanzee Ai (Biro and Matsuzawa, 2001). Alex's inability to use "none" here might have arisen because he was asked to denote the total absence of labeled *objects*; previously, he was responding to the absence of an attribute. Specifically, these data confirmed that Alex's use of "none" was merely *zero-like*: he did not use "none", as he did his number labels, to denote a specific numerosity (Pepperberg, 1987b). In that sense, he was like humans in earlier cultures, or young children, who seem to have to be ~4 years old before achieving full adult-like understanding of the label for zero (e.g., Wellman and Miller, 1986; Bialystok and Codd, 2000).

4.4. Ordinality and equivalence

As noted above, despite having learned his number labels out of order—quite unlike children—Alex may have deduced something about ordinality, that is, about an exact number line. He had a concept of bigger and smaller (Pepperberg and Brezinsky, 1991) and, without explicit training, may have organized his number labels in that manner. Such behavior would be important for two reasons. First, even for apes that referentially used Arabic symbols, ordinality did not emerge but had to be trained (e.g., Matsuzawa et al., 1991; Boysen et al., 1993; Biro and Matsuzawa, 2001); if Alex understood ordinality without training, his concepts would be more advanced than those of a nonhuman primate. Second, ordinality is intrinsic to *verbal* counting (e.g., Gelman and Gallistel, 1986; Fuson, 1988). To count, an organism must produce a standard sequence of number tags and know the relationships among and between these tags; for example, that "three" (be it any vocal or physical symbol) not only comes before "four" in the verbal sequence but also represents a quantity less than "four." An understanding of ordinality, therefore, would help support our possible claims for counting.

Notably, ordinality is not a simple concept. Children acquire ordinal–cardinal abilities in steps. They learn cardinality, slowly, usually over the course of over a year, for very small numbers (<4) and a general sense of "more versus less" while acquiring a meaningless, rote ordinal number series. Only around the time that they acquire an understanding of "fourness" do they connect their knowledge of quantity in the small sets with this number sequence to form 1:1 correspondences that can be extended to larger amounts for both cardinal and ordinal accuracy (e.g., Carey, 2009; see also Mix et al., 2002). Children may give the impression that they have full understanding of cardinality before they actually do, by learning associative rules (i.e., respond correctly to "How many?" but fail on "Give me X"; see above) but cannot act in that manner with ordinality (e.g., Teubal and Guberman, 2002; Bruce and Threfall, 2004).

To test what Alex might know about ordinality and compare his abilities to those of children would require first that he learn to label Arabic numerals, so that he could be tested abstractly; that is, in the absence of physical sets of objects. If, after learning English labels for Arabic numerals (production and comprehension) in the absence of the physical quantities to which they refer, Alex could—without any training—use the commonality of these English labels to equate quantities (sets of physical objects) and Arabic numerals, then I could use a task involving these equivalence relations (Pepperberg, 2006c): I could ask him which of two Arabic numerals was bigger or smaller. To ensure that I could repeat the trials enough times to gain statistical significance without Alex learning rote responses to specific pairs, the task would be to identify the *color* of one of a pair of Arabic numbers (e.g., a green 2, a yellow 5, next to each other on a tray; Fig. 3) that was *numerically* (not physically) bigger or smaller. He already answered "What color/matter bigger/smaller?" for object pairs and responded "none" for same-sized pairs (Pepperberg and Brezinsky, 1991). To succeed on this new task, he would have to use deductions and inferences: deduce that an Arabic symbol has the same numerical value as its *vocal label*, compare *representations* of quantity for which the labels stand, infer rank ordering based on these representations, then state the result *orally* (Pepperberg, 2006c). Unlike the tasks used in other nonhuman studies (e.g., Olthof et al., 1997; Olthof and Roberts, 2000), the question would not always be about the larger set, and specific stimuli within pairs would not be associated with reward of the corresponding number of items.

Fig. 3. Alex's ordinality task.

To ensure that Alex really did understand not only ordinality but also the meaning of the Arabic numerals, he was tested on several related tasks (Pepperberg, 2006c). Trials on identical numerals of different colors but of the same size (e.g., 6:6) tested if Alex would, as expected, reply "none" to the query as to which was bigger or smaller. To determine if he might be tricked into responding based on the physical appearance of the numerals rather than their meanings, he was queried about numerals of the same value but different colors and different sizes (e.g., 2:2). By mixing Arabic symbols and physical items, I could determine whether he really did understand that, for example, one numeral (an Arabic 6) was bigger than five items (or an Arabic 2 as the same as two items) and cleanly separate mass and number.

Alex did indeed succeed on the equivalence task and, as a consequence, demonstrated that, without direct, explicit training, he inferred the ordinality of his number labels (Pepperberg, 2006c). Notably, he had never been trained to recite the labels in order nor to associate any Arabic numeral with any specific set of objects. Nevertheless, for trials on two different Arabic numbers of the same physical size, his first trial score was 63/84, or 75% ($p < 0.01$, binomial test, chance of ½). If his occasional responses of the Arabic number label rather than the requested color (technically correct, but not with respect to the actual query) were not counted as errors, his score was 74/84, or 88.1% ($p < 0.001$, binomial test, chance of ½). As in previous studies, errors sometimes involved yellow-orange-red confounds. When numerals were the same value-same size, his accuracy was 10/12, or 83.3%, $p < 0.01$ (binomial test, chance of 1/3; answers could be one of the two colors or "none"). Importantly, statistical comparisons on his first and final trials for all these sets showed no significant differences in accuracy, suggesting that no training was occurring. For the same value—different size trials, counting as correct either "none" or the color label of the physically targeted number, his accuracy was 12/12, or 100%, $p < 0.01$ (binomial test, chance of 2/3, a color or "none"). Seven times he gave the correct color of the physically targeted number, five times he said "none," but gave colors most often in earlier trials and "none" most often in later trials, as if he shifted after experience with responses based on symbolic value, even though he had initially been rewarded for responses based on physical size (Pepperberg, 2006c).

Alex's responses to trials that mixed objects and numerals were intriguing. For arrays in which object sets were paired with a single Arabic number representing a quantity larger than or equal to the array (incongruent trials) and in which the single Arabic number represented a quantity less than the array (congruent trials), his accuracy was 16/21, or 76.2%, $p < 0.01$. However, in five trials in which a *single* object was paired with a *single* Arabic number that represented a larger quantity, Alex consistently replied "none." Only here did the physical set consistently overwhelm symbolic responses.

Overall, Alex did appear to exhibit numerical understanding far closer to that of children than other animals. However, he differed from humans and was like other nonhumans in that he had demonstrated no savings in his learning of larger numerals. Once children learn ordinality and the successor function—that each digit in their number line is one more than the previous digit—they no longer need to be taught the values of each individual digit for digits greater than 4 (Carey, 2009). Why was Alex unlike children in this instance? Might the issue be Alex's difficulty in learning to produce the English sounds? In order to produce any given English label, Alex had to learn to coordinate his syrinx, tracheal muscles, glottis, larynx, tongue height and protrusion, beak opening, and even esophagus (Patterson and Pepperberg, 1998); might there be a way to dissociate vocal and conceptual learning to test this possibility?

4.5. An exact integer system

To test whether such a dissociation existed, colleagues and I devised the following experiment. Initially, I would teach Alex to identify vocally the Arabic numerals 7 and 8 in the absence of their respective quantities, divorcing the time needed to learn the speech patterns from any concept of number. Only after the labels were being produced clearly would I train him to understand that $6 < 7 < 8$, that is, where the new numerals fit on the number line. He could then be tested as to whether he understood the relationships among 7 and 8 and his other Arabic labels. If he inferred the new number line in its totality, he could be tested on whether, like children, he could *spontaneously* understand that "seven" represented one more physical object than "six", and that "eight" represented two more than "six" and one more than "seven", by labeling appropriate physical sets on first trials (Pepperberg and Carey, 2012). Nothing in his training at this point would provide specific information about the value of 7 and 8; they could refer to ten and twenty items, respectively. The question was whether, all other numerals having been taught as either +1 or −1 than those he already knew (that is, after learning "3" and "4", he was taught "5" and "2", then "6" and "1", Pepperberg, 1987b, 1994), he could use past and present information to induce the cardinal meaning of the labels "seven" and "eight" from their ordinal positions on an implicit count list.

Over the course of the study, Alex did indeed learn to label the novel Arabic numerals, to place them appropriately in his inferred number line, and to label appropriately, on first trials, novel sets of seven and eight physical items. Detailed data is presented in the published paper (Pepperberg and Carey, 2012); the conclusion was that Alex, like children, and unlike nonhuman primates tested so far, created a representational structure that allowed him to encode the cardinal value expressed by any numeral in his count list (Carey, 2009), that is, to understand the successor function.

4.6. The final study

Once Alex had acquired the numerals through 8, we went back to the addition task to determine if he could, like apes (Boysen and Berntson, 1989) sum the Arabic numerals that had been hidden under cups (Pepperberg, 2012a). Such a task would demonstrate further knowledge of the representational nature of the numerals. As in the addition experiment with sets of items, he was sequentially shown two Arabic numerals initially hidden under cups and, in their subsequent absence, was asked to vocally produce a label to indicate their sum. In a separate small set of trials, he was shown the same stimuli in the same manner, but was simultaneously presented with various Arabic numerals of different colors, and asked for the color of the numeral representing the sum; colors changed on each trial. The second set of trials ensured that Alex could not learn a particular pattern over time (e.g., "if I see X + Y, I say Z"). Alex's passing precluded completion of this latter task, but had he lived longer, this procedure, with its additional step, would have allowed testing the same sums many more times without training him to produce a specific response, unlike tasks given other nonhuman subjects (see discussion in Pepperberg, 2012a).

For the Arabic numeral task requiring a numerical response, Alex demonstrated some competence in summing two Arabic numerals, each representing quantities less than or equal to 5, to a total of 1–8. His first trial score was 9/12 (75%), $p = 0.004$ (chance of 1/3; $p = 0.001$ for chance of 1/8). His all trials score was 12/15 (80%). Although the study did not contain enough trials to test all possible sums and combinations of addends or to repeat most queries, Alex was given at least one trial for each sum from 1 to 8. The lack of replication of the various sums over trials, however, emphasizes the first trial nature of the results and shows that no training could have been involved. Notably, if the numerals had only approximate meanings, Alex's errors would likely have exhibited a range close to the correct response. In contrast, such was the case only once (Pepperberg, 2012a); the other errors were to state "eight" when the sums were five and four. He thus seemed to have some fixation on producing the label "eight," which was his newest. Overall, his data surpassed what would be expected if he were using the kinds of systems employed by most nonhumans or preverbal infants—for example, analog magnitude systems or object files, which cannot represent any positive integer above 4 exactly (see Carey, 2009, for a review).

Because of his death, he had only three trials on queries requiring a color response; his first trial score, 2/3 (66%), was too low for statistical significance ($p = 0.07$), but the small number of trials preclude real statistical power. His all trials score was 3/4 (75%). These data do, however, suggest a capacity for exact number representation: conceivably, his one error, on the first trial, may have represented a misunderstanding of the task. His response, which labeled the numeral representing "two," suggests he might have responded to the number of objects under the cups (i.e., the two numerals) rather than their values, given that no training of any sort had preceded questioning on this novel task, and all previous queries did refer to the number of objects. Note, however, that he did not persist in this response but was correct when asked a second time and responded appropriately on the next two trials. Overall, Alex, like Sheba, had had no training on summing the Arabic numerals, and, like Sheba, spontaneously transferred from summing items to summing symbols. His data on the color response task (although extremely limited)—a task somewhat like that of Sheba's, in that possible responses were available from which to choose—tended toward significance. In contrast to Sheba, however, he had to indicate the label not just for the sum but also for the color of the numeral that represented the correct numerical sum (an additional step), and the total summed quantity on which he was tested could reach 8.

5. Summary

The above data demonstrate the extent to which a nonhuman, nonprimate, nonmammalian subject can form complex, abstract concepts and, specifically, that one particular subject, Alex, understood the cardinal representation of his vocal number labels and their corresponding Arabic numerals. He succeeded at levels that, on occasion, went beyond those of nonhuman primates and approached those of children.

Other nonhumans have, of course, succeeded on related numerical tasks, but none yet, like Alex, have deduced the successor function. For example, nonhumans can represent ordinal relations among arbitrary stimuli, even among Arabic digits, but without necessarily having knowledge of these symbols' cardinal values (e.g., Emmerton et al., 1997; Harris et al., 2007; Beran et al., 2008; Matsuzawa, 2009). Nonhumans also use an analog magnitude system to evaluate more/less for sets of items and transfer to new set sizes, but their data are constrained by Weber's Law (e.g., Brannon and Terrace, 1998, 2000; Emmerton and Renner, 2009; Scarf et al., 2011; note Dehaene, 2009); that is, their evaluations are not precise but center around the correct response, unlike Alex's results. Similarly, some nonhumans engage in approximate addition and subtraction (e.g., Rugani et al., 2009), and have even mapped numerals to approximate quantities, but these latter results could be related to hedonic value or reward probablility (e.g., Beran et al., 2008; note Olthof et al., 1997). Only those nonhumans that *symbolically* map numerals to *exact* cardinal values of sets (notably, Matsuzawa's Ai, Boyen's Sheba, and Alex), seem able to engage in several types of *precise* numerical computations, especially for quantities above 4.

Finally, Alex was not the only avian subject to succeed on many cognitive tasks. Other Gray parrots have succeeded on tasks involving exclusion (e.g., Mikolasch et al., 2011), corvids are considered "feathered primates" (e.g., Emery and Clayton, 2004), Vallortigara and colleagues have shown advanced abilities in chicks (Vallortigara, 2012) and Wright's work and those of his colleagues (see many papers in this special edition) demonstrate advanced cognitive abilities in pigeons. We have come a long way from the 1960s, and much of our progress was inspired by Anthony Wright, who was among the first to challenge the status quo and argue that nonhumans should be tested for the same types of abstract concept formation as humans.

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