Anim Cogn (2001) 4:193–199
DOI 10.1007/s100710100086

ORIGINAL ARTICLE

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Use of numerical symbols by the chimpanzee (*Pan troglodytes*): Cardinals, ordinals, and the introduction of zero

Received: 31 July 2000 / Accepted: 29 April 2001 / Published online: 29 June 2001

Abstract An adult female chimpanzee with previous training in the use of Arabic numerals 1–9 was introduced to the meaning of "zero" in the context of three different numerical tasks. The first two were cardinal tasks where the subject was required either to select numerals corresponding to the number of items presented on a computer screen (productive use of numerals) or to match sets of the appropriate size to numerals presented as samples (receptive use). The third task addressed the ordinal meaning of the same symbols where the subject was required to respond to numerals sequentially, arranging them into an ascending series. The subject mastered the recognition of the meaning of zero in all three tasks. However, details of her usage of the symbol revealed that transfer of the meaning between different kinds of tasks was incomplete, suggesting that the level of abstraction characteristic of human numerical ability was not attained in the chimpanzee. Over the course of acquisition leading to the high levels of accuracy eventually observed, the newly introduced zero appeared to shift along the length of a continuous numerical scale toward the lower end, while confusions with 1 remained the most frequently encountered mistakes. Such patterns of error thus suggest that Ai's understanding of the meaning of zero in relation to the rest of the number symbols was not consistent with an "absence of items versus presence of items" scheme.

Key words Numerical competence · Cardinals · Ordinals · Zero · Chimpanzee

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Introduction

The nature and extent of numerical competence in nonhuman animals has been investigated in a variety of species. These include rats (Davis et al. 1989), pigeons (Emmerton et al. 1997; Xia et al. 2000), monkeys (Thomas et al. 1980; Olthof et al. 1997; Brannon and Terrace 1998), and a parrot (Pepperberg 1994). A considerable bulk of the work has concentrated on the chimpanzee (*Pan troglodytes*) whose evolutionary proximity to *Homo sapiens* invites speculation as to the existence of human-like numerical skills. As participants in long-term research projects exploring the cognitive capabilities of chimpanzees, individual test subjects have demonstrated counting and protomathematical skills long thought to be unique to humans (Woodruff and Premack 1981; Rumbaugh et al. 1987; Boysen and Berntson 1989).

To what extent can these subjects be said to possess abstract numerical concepts and what is the range of their numerical abilities? In investigating both of these questions, the number zero deserves special attention. The study of Rumbaugh et al. (1987) of summation in chimpanzees already successfully introduced the concept of "absence of food" (numerical equivalent 0), while the study of Boysen and Berntson (1989) of labeling food items showed that the chimpanzee Sheba had no difficulty in learning to match an empty food tray to the numeral 0. Furthermore, when tested on summation using first food items then cards showing Arabic numerals hidden in various target locations around a room, Sheba successfully solved the addition task when "absence of food" or "zero" was included in the required operation. More recently, Olthof et al. (1997) trained squirrel monkeys on a similar symbolic counting task, first by having them choose one of a pair of Arabic numerals from among 0, 1, 3, 5, 7, and 9, yielding a corresponding number of peanuts as reward. Their subjects then tended to correctly choose the larger of two sums (displayed on two cards, each with one, two, or three Arabic numerals printed on it) when 0 was included among the stimuli used.

Can these subjects be said to indeed possess an understanding of the meaning of zero – a meaning that has puzzled human mathematicians through much of history? The counting model of Gelman and Gallistel (1978) – devised originally for human children – emphasizes the appreciation of the relationship between cardinal and ordinal meanings of number as a hallmark of abstract numerical understanding. In other words, one must be able to arrange into an ascending series the numbers that are used as labels for sets of items based on the relative sizes of these sets. Thus, in order for a subject to demonstrate comprehension of the concept of zero, evidence for transfer between cardinal and ordinal meanings is necessary. Here we report an experiment that is to our knowledge the first attempt at establishing whether a chimpanzee is able to acquire spontaneously the meaning of zero in one domain (ordinal, i.e., “less than one”) through training in the other (cardinal, i.e., “nothing”, “absence”).

The subject of the present study was an adult female chimpanzee with the ability to label sets of up to nine items with the appropriate Arabic numeral (Matsuzawa 1985; Murofushi 1997) as well as order the same symbols according to an ascending numerical scale (Tomonaga et al. 1993; Tomonaga and Matsuzawa 2000; for a review, see Biro and Matsuzawa 2001). The use of a fully computer-controlled apparatus in these tasks has had two main advantages. First, controllability is enhanced as both the number and the location of individual stimuli can be easily varied in a quasi-random pattern from trial to trial, while at the same time completely excluding the possibility of social cueing. Second, using a computer to control automatically all stages of an experimental session also allows accurate measurement of response latency, i.e., the time that elapses between the presentation of stimuli and the subject’s response. Both aspects have proven instrumental in allowing researchers to shed light on cognitive processes underlying the numerical skills (Tomonaga et al. 1993; Murofushi 1997; Biro and Matsuzawa 1999; Kawai and Matsuzawa 2000). Using this objective paradigm, we attempted to expand Ai’s repertoire of numbers by the introduction of zero in two kinds of “dot-counting” tasks. Subsequently, we tested the extent to which the meaning of zero, as trained on these cardinal tasks, transferred to an ordinal task.

Methods

Subject

Subject was a 20-year-old female chimpanzee named Ai. She had been trained on a variety of computer controlled cognitive tasks since the age of 2 years (Asano et al. 1982). Her training in the use of Arabic numerals began at age 5 years, using numbered keys to label sets of items such as pencils and other everyday objects presented to her in a display window (Matsuzawa 1985). The procedure was later modified to transfer both the sample and the comparison stimuli to a touch-sensitive monitor (Matsuzawa et al. 1991; Murofushi 1997). Subsequently, the ordering of numerals was trained (Matsuzawa et al. 1991; Tomonaga et al. 1993; Tomonaga and Matsuzawa 2000), initially through pairs of adjacent numbers, later using successive but non-adjacent series of increasing length. At the start of the present study, Ai was able to label between one and nine items presented on a computer screen, and order up to nine consecutive or four successive but non-consecutive numerals into an ascending series. Ai inhabited an outdoor enclosure shared with nine other chimpanzees throughout the duration of the experiments. She was at no time food deprived and was cared for according to guidelines produced by the Primate Research Institute of Kyoto University.

Apparatus

The subject was tested inside an experimental booth (180×180×200 cm) with acrylic panels as the wall on all four sides. Embedded in one wall of the booth was a 21-inch (53 cm) NEC PC-KH2021 colour monitor equipped with a touch-sensitive panel (Microtouch SMT2). This served both as the output device for stimuli to be presented and the input device for the subject’s response consisting of touches to the screen at particular locations. Stimuli were white dots 1.5 cm in diameter and Arabic numerals (2 cm×3 cm, Helvetica font, white) displayed on a black background. A computer (NEC PC-9821Xn) was used to control stimulus presentation and response evaluation. Data such as trial-by-

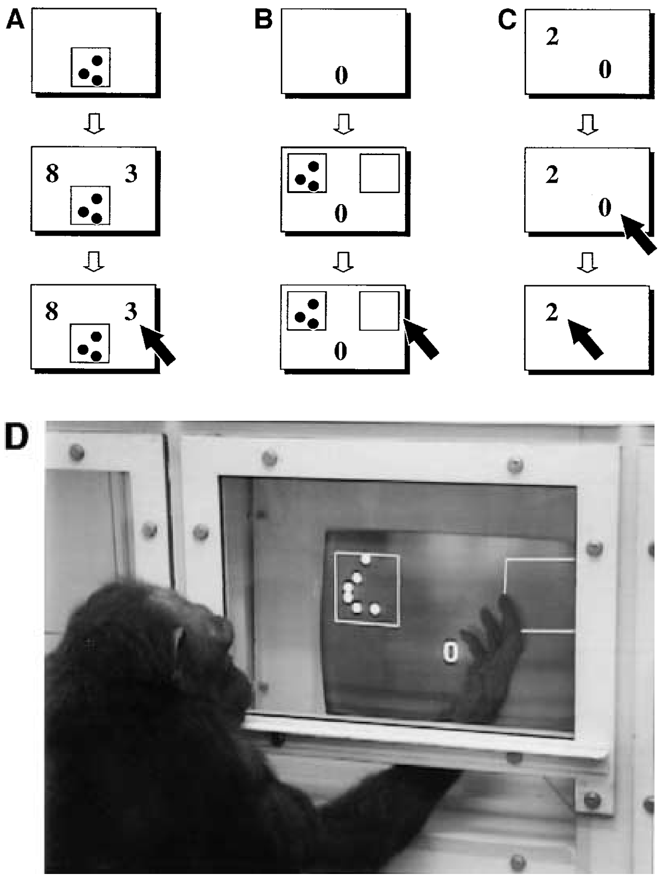

Fig. 1A–D Summary diagrams (**A–C**) of the three types of numerical task used in the experiment. **A** Dot-to-numeral (DN) matching. Sample is *set of dots* inside the *central frame*; comparison stimuli are two *Arabic numerals* in *top left and right corners*. **B** Numeral-to-dot (ND) matching. Sample is *Arabic numeral* in the *centre*; comparison stimuli are *top left and right*. **C** Ordering, two-units. **D** Subject performing the numeral-to-dot matching task, here correctly selecting the *frame containing zero dots* in response to the presentation of the symbol *0*

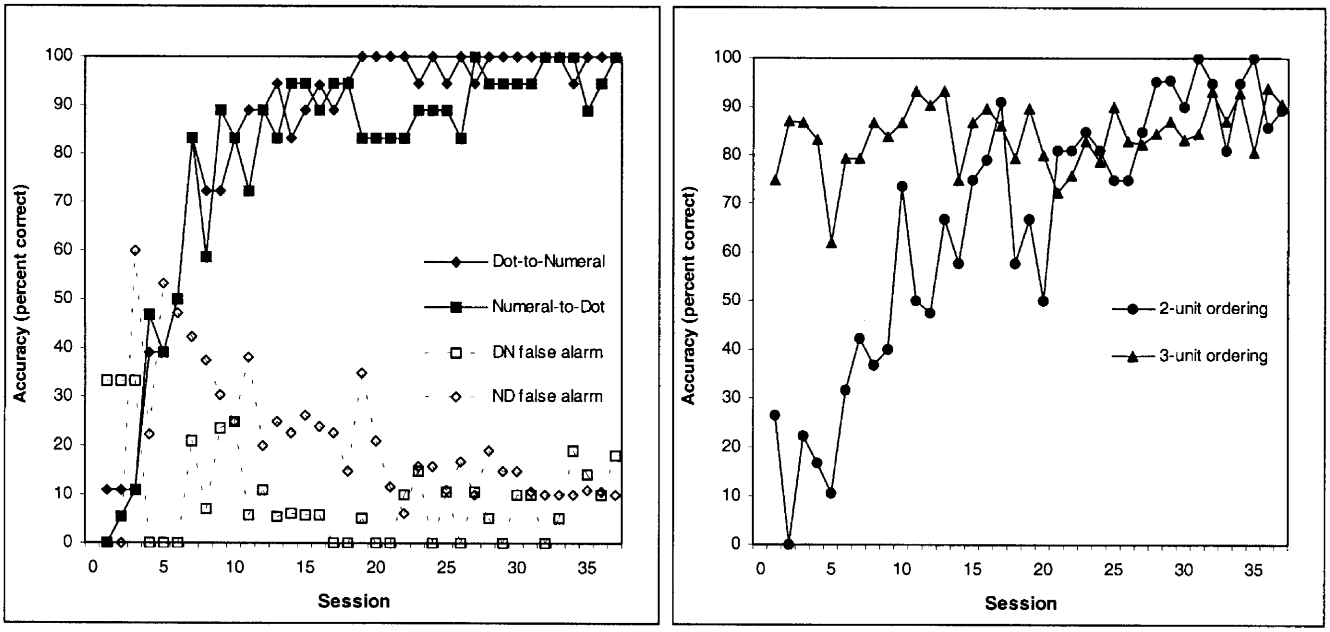

Fig. 2 Progress of accuracy in all tasks. *Solid lines* indicate performance in trials where zero served as the sample. *Dotted lines* trace "false alarms", i.e., erroneous use of zero as the label for non-zero samples in DN and ND matching

trial records of accuracy were also stored by the computer. A digital video camera (Sony Handycam DCR-VX1000) was used to videotape all sessions.

Procedure

The three numerical tasks used were designed to test the comprehension of the numeral 0 in three different contexts: the receptive use of numerals, the productive use of numerals, and the ordering of numerals. The first two thus addressed the cardinal meaning of the novel symbol (i.e., absence of items), while the latter focused on the ordinal meaning (i.e., less than 1). Testing on the two cardinal tasks was conducted in parallel; then, once acquisition had taken place, training in the ordinal task commenced. Sessions were carried out 6 days a week between October and December 1997, with the subject receiving 600–700 trials daily.

Dot-to-numeral matching (DN)

Each trial commenced with the presentation of a small white circle near the lower edge of the screen. The subject was required to respond to this "start key" by touching the screen directly above, thus initiating the presentation of the sample stimulus in the centre of the lower half of the screen. The sample stimulus consisted of a thin white frame (15 cm×15 cm) containing between zero and nine dots randomly positioned within a 7×7 invisible matrix inside the frame. Touching the sample stimulus led to the presentation of two Arabic numerals as comparison stimuli in the left and right corners of the upper half of the screen. Choice by the subject of the numeral corresponding to the number of items inside the white frame constituted a correct response and was followed by a chime and the delivery of food reward. Incorrect responses were accompanied by a buzzer sound, no food reward, and a 3-s timeout before the next trial could commence. Sessions consisted of 180 trials over which all dot numbers were presented as stimuli equal numbers of times, and the corresponding numerals were pitted against each of the remaining nine exactly twice. Order of presentation was random, and the position of the correct alternative was counterbalanced between left and right for all dot numbers. Accuracy in labeling different numbers of sample dots was recorded. A schematic outline of the task is shown in Fig. 1A.

Numeral-to-dot matching (ND)

In this reverse version of the dot-to-numeral task, the subject was required to match an Arabic numeral as the sample stimulus to one of two alternative sets of white dots displayed inside two frames in the top left and right corners of the screen (Fig. 1A, D). In all other aspects, the procedure in this task was identical to that used in dot-to-numeral matching.

Ordering

In the initial phase of this task, the subject was shown two numerals taken from the range zero to nine and displayed at random locations within an invisible 5×8 matrix on screen. She was required to respond to both according to an ascending numerical scale (Fig. 1C). If she touched the lower of the two numerals first, it disappeared immediately, leaving only the higher of the two on screen. Responding to the latter now completed a correct trial and was rewarded by a chime and the delivery of food reward. However, touching the larger of the two numerals first resulted in the automatic clearing of the whole screen and an incorrect response was scored, accompanied by a buzzer, no food delivery, and a 3-s timeout before the next trial. Sessions consisted of 90 trials over which all ten numerals were paired with all of the remaining nine exactly twice, hence both consecutive and successive but non-consecutive combinations were tested.

In the second phase of this task, three numerals were presented. Again the subject was required to order them according to an ascending numerical scale. Consecutive as well as successive but non-consecutive three-unit combinations were used. Incorrect responses at any point during a trial caused the immediate clearing of the screen; the subject was only allowed to proceed through a trial if she chose the lowest numeral available on screen at each stage. Sessions were 120 trials long, with all possible three-unit combinations from 0→1→2 to 7→8→9 presented once. Accuracies in selecting the first and second (and third, if available) items were recorded.

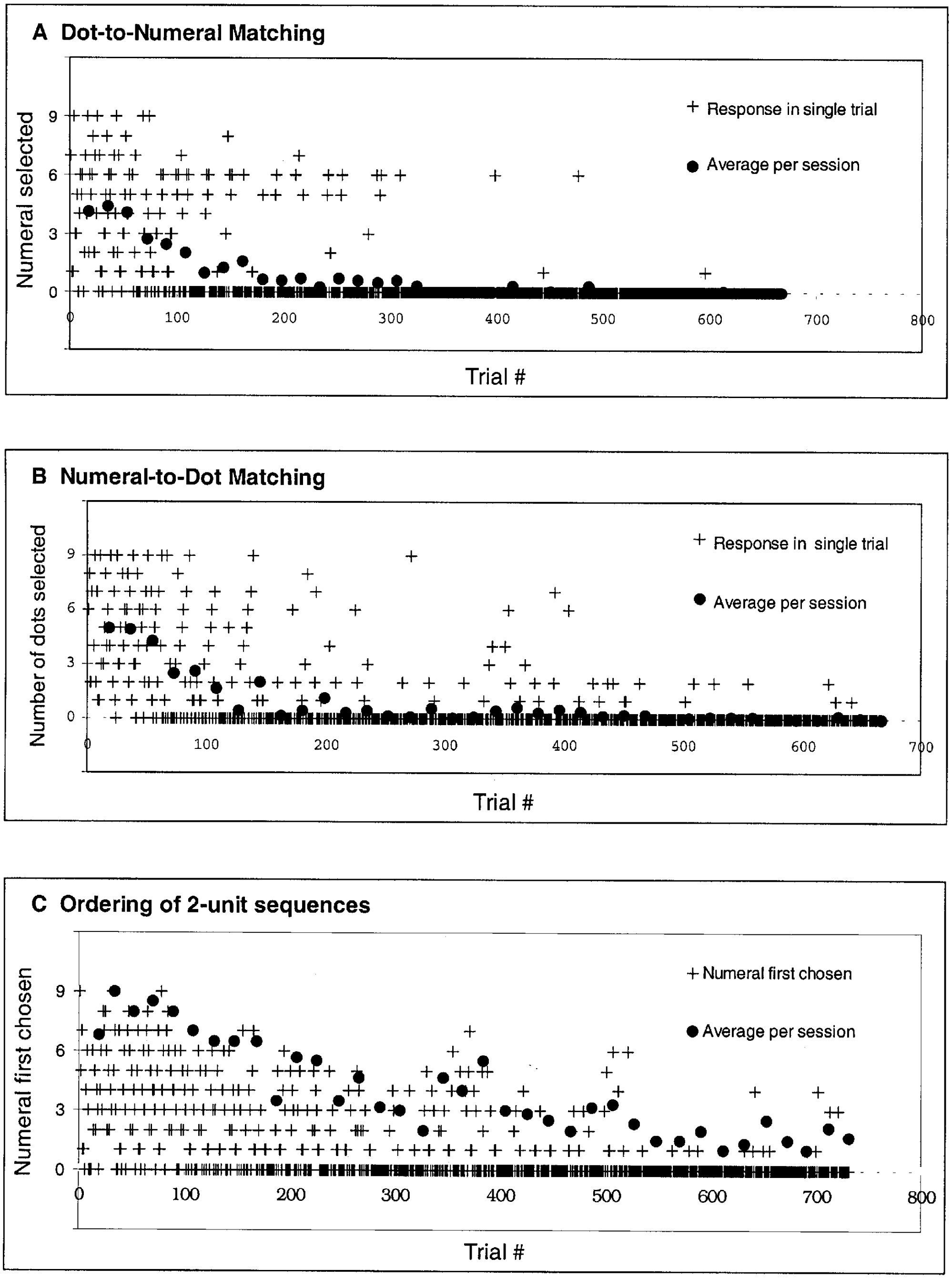

Fig. 3A–C Trial-by-trial history of acquisition of zero in three types of numerical tasks. *Crosses* indicate choices in individual trials, while *solid circles* show the "virtual" value of zero in a given session, calculated using the pattern of Ai's responses to the presentation of zero as the sample

Results

Our subject mastered the meaning of "zero" in all three numerical tasks examined. Accuracy in trials involving zero reached 99.4% in the final ten sessions of DN, 96.1% in ND, 92.7% in two-unit ordering, and 87.7% in three-unit ordering (Fig. 2). The number of sessions required to reach criterion of three consecutive sessions with at least 80% accuracy was 12, 14, 23, and 4 in the four tasks, respectively. However, to address the question of transfer between the cardinal and ordinal tasks, it is necessary to trace early performance in particular, and attempt to identify different phases of acquisition in all four tasks.

In both DN and ND matching, "zero" as a response was initially avoided. For several sessions, the presentation of zero as the sample (zero dots or the numeral 0) repeatedly elicited labeling with the non-zero comparison stimulus, irrespective of the identity of the latter. Soon, however, correct responses began to appear, particularly when large numbers served as comparison. At the same time, we noted a sharp rise in the frequency of so-called "false alarms", where the zero label was applied erroneously to non-zero samples. Gradually, these false alarms disappeared almost

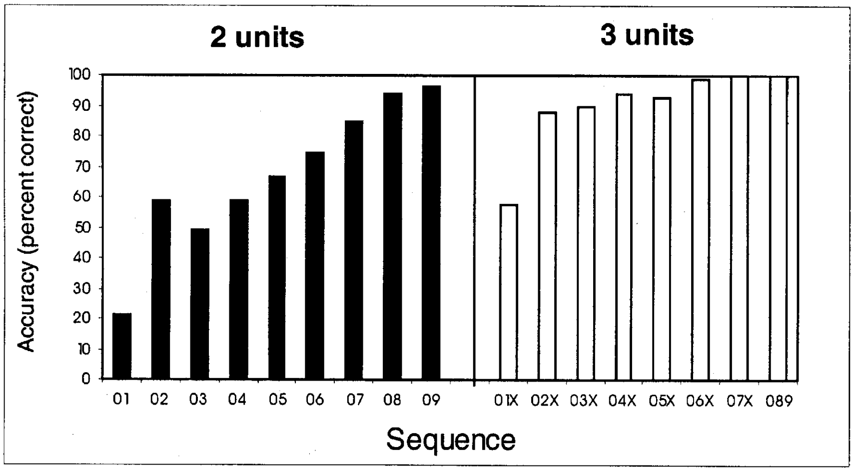

Fig. 4 Effects on accuracy of numeral following 0 in the ordering task. Data from both two-unit and three-unit tasks are shown, calculated from a total of 37 sessions each (3330 and 4440 trials, respectively)

completely, and zero was labeled correctly when pitted against progressively smaller alternatives. Eventually, Ai's performance approached near-perfect levels, although occasional errors remained both in applying incorrect labels to zero and in using zero as the label for non-zero samples.

How the meaning Ai assigned to the symbol 0 changed over the course of the experiment is illustrated in Fig. 3A, B. For each session, a 'virtual' value for zero was calculated from the pattern of Ai's responses to the presentation of zero as the sample; in other words, the average value of labels that she matched to the zero stimulus. The graphs show this virtual value gradually approaching the lower end of the scale, through the reduction of errors involving large numbers as comparison. Some errors, however, appear more or less persistent: for instance, the numeral 6 as the label for zero dots (not seen in the final ten sessions), one or two dots as responses to 0 as the sample (until the end of the testing period), 0 as the response to one dot as the sample (on every occasion in the last 16 sessions).

In the two-unit ordering task, a similar sequence of events was noted (Fig. 3C). Initially, the presentation of zero in combination with most other numerals elicited selection of the non-zero stimulus first, resulting in the termination of the trial and the scoring of an incorrect response. The exceptions to this pattern were the numerals 8 and 9, which were, from the start, correctly identified as items following 0 in the numerical sequence. Five sessions later, the numeral 7 similarly began consistently to appear in correct trials, and gradually, the same was achieved for progressively smaller numbers. Again, therefore, the virtual value of zero – as calculated from combinations of stimuli that were judged to precede or follow 0 in the numerical sequence – approached the lower end of the scale, with levels of accuracy rising accordingly. However, a persistent mistake was the selection of 1 before 0: an error that we continued to encounter until the end of the testing period.

The three-unit ordering task – tested after extensive training with two units – further confirmed the assimilation of zero into Ai's numerical ordering skills. Accuracy in trials involving zero was above 70% from the very first three-unit session, and exceeded 90% by the 11th session. Nevertheless, although performance in zero-trials was thus highly accurate overall, sequences with 0 and 1 as the first two items were solved correctly at a rate only slightly above chance level (58.5%). The recurring error of selecting 1 before 0 was evident until the end of the testing period.

Figure 4 shows accuracy in trials involving zero in the two- and three-unit ordering tasks as a function of the numeral that was to follow zero in the correctly identified sequence. In both cases, accuracy increases with larger numbers following zero in the series. As the data were pooled from all 37 sessions, the effect appears more pronounced in the two-unit condition which incorporates the early training phase where small numbers were repeatedly chosen before zero.

Discussion

Our experiment aimed to elucidate the extent to which a subject trained on both cardinal and ordinal numerical tasks was able to comprehend and use abstract numerical symbols. We introduced the novel concept of "zero" in tasks illustrating the two types of meaning the symbol carries (i.e., "absence of items" and "less than 1") which provided us with an opportunity to examine spontaneous transfer of the meaning of a newly-acquired numerical symbol between the cardinal and ordinal domains. Our results showed that although the use of zero reached near-perfect levels in all tasks tested, there was no evidence of transfer. Furthermore, the processes of acquisition that led up to the eventual high levels of accuracy eventually observed were characteristic in pattern and worth examining in themselves. To summarize, the following distinct phases were encountered:

1. Complete or near complete avoidance of zero as a response. Zero as the sample stimulus is matched to every alternative between 1 and 9.

2. Correct responses begin to appear in trials where large numbers serve as comparison.
3. Zero is selected with progressively smaller numbers as comparison, while there is an sharp rise in "false alarms", i.e., incidents of 0 being erroneously chosen in response to the presentation of samples between 1 and 9.
4. Highly accurate performance; "false alarms" disappear almost completely; but errors with small numbers remain.

The early avoidance of zero as a response in the cardinal tasks may be explained in terms of the subject's unfamiliarity with the novel stimuli: the symbol 0 in DN matching and the empty frame in ND matching had never before been encountered in Ai's training. However, the same reluctance in the two-unit ordering task shows that zero was still considered unfamiliar, as it had not appeared previously in the context of an ordering task. In fact, Ai's initial response to zero in the serial response task was reminiscent of a wild-card effect (D'Amato and Colombo 1989; Tomonaga and Matsuzawa 2000). The probability of Ai correctly selecting zero as the lower of a pair was a function of the serial position of the other numeral, with small numbers being more likely to be selected before zero and large numbers after. Thus, while in the very first ordering session Ai identified 0 as being positioned somewhere between 6 and 7, in later sessions correct responses began to appear when 0 was presented with 6, then 5, 4, and so forth. Eventually, errors with comparison numerals higher than 1 disappeared completely. However, the confusion between 0 and 1 continued to be a prominent feature of Ai's performance, with accuracy in these trials hovering just above 50%.

Performance in the three-unit task was highly accurate from the start, demonstrating that transfer from the two-unit task was successful. However, accuracy in zero-trials still appeared to be influenced by the identity of the numeral next in the series, evidence of a symbolic distance effect (D'Amato and Colombo 1990; Tomonaga and Matsuzawa 2000). In particular, trials with 0 and 1 were a persistent problem, where 0 was correctly selected as the lower of the two in just under 60% of cases.

Such confusions between zero and small numbers were prominent features of the cardinal tasks as well. Here, the training of zero represented a sharp contrast to Ai's previous number training. For all numbers between 1 and 9, each new number was added on to her already existing repertoire successively, in ascending order. This is analogous to a child's learning of numbers (Gelman and Gallistel 1978). The training of zero therefore represented a novelty, as it was the first to join the series at the low end of the scale, severely disturbing the sovereignty of "one" as the lowest number. This fact may help to explain why comparisons of 0 and 1 caused so much difficulty for the chimpanzee, both in cardinal and in ordinal number problems. How chimpanzees may solve "counting" tasks of this kind is not the subject of the present paper (see Murofushi 1997), but if Ai was using a form of relative magnitude estimation (relative numerousness judgment, Thomas et al. 1980) rather than "true" counting, then a sample of the numeral 1 may have prompted selection of the least number of dots available, i.e., none.

The present results thus show that the chimpanzee is able to use the numerical symbol 0 appropriately in both cardinal and ordinal contexts. However, transfer between the meanings of zero in the two domains has been found to be incomplete, and details of our subject's usage of the symbol reveal that her representation of the meaning of zero may not be analogous with that of humans. Ai's understanding of zero in relation to the rest of the number symbols is not consistent with an "absence of items vs. presence of items" scheme. Instead, the newly-introduced zero appears to have shifted along the length of a continuous numerical scale, gradually approaching the lower end, yet ultimately still contiguous with, adjacent to, and often confused with one.

Acknowledgements This study was supported by Grants-in-Aid for Scientific Research, Ministry of Education, Science, and Culture, Japan (Nos. 04551002, 04651017, 05044066, 12002009, 07102010 and 10CR2005). The authors wish to thank S. Nagumo, K. Kumazaki, and N. Maeda for their assistance.

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