BRIEF REPORTS

Representation of serial order in humans: A comparison to the findings with monkeys (*Cebus apella*)

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In a number of studies, serially organized behavior in humans has been examined using a procedure developed for use with pigeons and monkeys. There have been few direct comparisons, however, between the data collected with humans and that collected with nonhumans, and none with respect to the interesting latency effects noted with nonhumans. The purpose of this experiment was to make this comparison. Human subjects were trained to respond to five simultaneously presented stimuli (A, B, C, D, and E) in a specific order (A→B→C→D→E) and were then tested with all 10 pairwise combinations of the five stimuli, followed by all 10 triplet combinations of the five stimuli. Mirroring the findings with monkeys (*Cebus apella*), humans showed a first-item effect, a missing-item effect, and a symbolic-distance effect. These results suggest that during the course of learning the five-item serial-order task humans form an internal representation of the series and access that representation to guide their behavior.

The ability to acquire serially ordered information and use that information in a flexible manner has been the subject of considerable investigation in pigeons, monkeys, and humans, and it is important for our understanding of many other behaviors such as language, maze learning, timing, motor control, and memory. Of the many types of tasks that tap serially organized behavior, perhaps the one that has enjoyed the greatest success in revealing differences across species is the simultaneous-chaining serial-order paradigm. Originally developed by Terrace for use in pigeons (Straub, Seidenberg, Bever, & Terrace, 1979; Straub & Terrace, 1981) and later adapted for use in New World (*Cebus apella*) monkeys (D'Amato & Colombo, 1988), the procedure is quite simple. At the start of a trial, five stimuli are presented simultaneously. For ease of exposition, they may be referred to as A, B, C, D, and E. In our studies (D'Amato & Colombo, 1988, 1989, 1990), the monkeys were trained to respond to the five stimuli in a specific order—namely, A→B→C→D→E. Although on each trial the stimuli appeared in different spatial positions, the order of correct responding (A→B→C→D→E) remained the same. Any deviation from the assigned response order, such as by skipping over an item that should have been pressed (e.g., A→B→D), or responding to an item that had already been pressed (e.g.,

A→B→C→A), was considered incorrect and terminated the trial.

Once the monkeys had acquired the serial-order task to a level of 75% correct or better over 2 consecutive days, they were given a pairwise test in which only two of the five stimuli were presented on each trial. With these five stimuli, 10 possible pairs could be generated (AB, AC, AD, AE, BC, BD, BE, CD, CE, and DE). We found that the monkeys responded to the stimuli in the pairs in the order in which they appeared in the original sequence. When presented with pair BD, for example, the monkeys first pressed stimulus B and then pressed stimulus D (D'Amato & Colombo, 1988). The high level of performance on this pairwise test suggested that in learning the original serial-order task, the monkeys had formed an internal linear representation of the series. When confronted with a test pair, the monkeys accessed the internal representation at A and then proceeded through the representation until an item in the representation matched an item on the display.

If indeed the monkeys formed and accessed a representation in the manner described, then the latency to respond to the first stimulus of a test pair should increase as a function of whether the first stimulus pressed was A, B, C, or D. For example, the latency to respond to stimulus B in pair BD, which requires accessing only one item (A) prior to B, should be much shorter than the latency to respond to stimulus C in pair CD, which requires accessing two items (A and B) prior to C. This is exactly what we noted. Overall, there was a strong linear relationship between the latency to respond to the first item of a pair
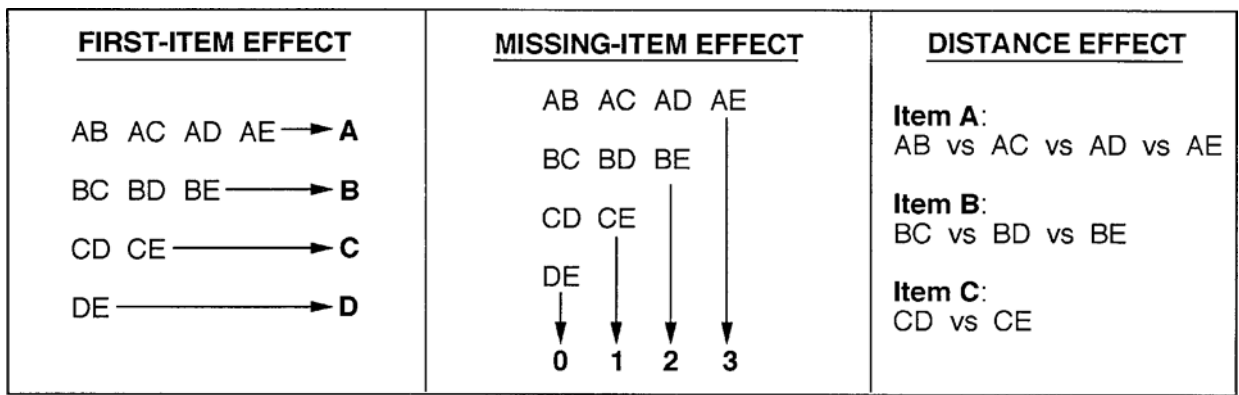
Figure 1. How the first-item (left panel), missing-item (center panel), and symbolic-distance (right panel) effects are generated. For the first-item effect, the latency to respond to the first item of the pair is averaged across all pairs that share the same first stimulus. For the missing-item effect, the latency to respond to the second item of a pair is averaged across all pairs that share the same number of missing items between the first and second stimuli. For the symbolic-distance effect, the latency to respond to the first item of a pair is compared across all pairs that share the same first item. Because only one test pair starts with stimulus D (DE), it is not possible to evaluate the symbolic-distance effect for stimulus D.

and the position of that item in the series (D'Amato & Colombo, 1988). We referred to this as the *first-item* effect, and how this effect is derived is shown in Figure 1 (left panel).

If our analysis of how the monkeys were solving the serial-order task was correct, then the latency to respond to the second stimulus of a pair should be a function of the number of missing items separating the two stimuli. For example, the latency to respond to stimulus D in pair CD (which contains no missing items) should be shorter than the latency to respond to stimulus D in pair AD (which contains two missing items). Again, this is exactly what we noted. There was a strong linear relationship between the latency to respond to the second item of a pair and the number of missing items (D'Amato & Colombo, 1988). We referred to this as the *missing-item* effect, and how it is derived is shown in Figure 1 (center panel).

Finally, monkeys also show evidence of a *symbolic-distance* effect. In humans, this effect refers to the fact that the latency to make a comparison between two items varies inversely with the distance (on some scale) between the two items. This effect has been shown for judging the order of letters in the alphabet (Hamilton & Sanford, 1978; Lovelace & Snodgrass, 1971) as well as judging the larger of two digits (Moyer & Landauer, 1967). In the serial-order task, a symbolic-distance effect would be evident if the latency to respond to stimulus A decreased across pairs AB, AC, AD, and AE (see Figure 1, right panel). The reason is that if the monkeys have formed a linear representation of the five items, then stimuli A and E are farther apart in linear space than stimuli A and B. Hence the latency to respond to stimulus A should be shorter in pair AE than in pair AB. In a similar fashion, we would expect the latency to stimulus B to decrease across pairs BC, BD, and BE, and the latency to stimulus C to decrease across pairs CD and CE. Although the monkeys did not show a symbolic-distance effect for pairs starting with stimulus A, we did note a robust symbolic-distance ef-

fect for pairs starting with stimuli B and C (D'Amato & Colombo, 1990).

Pigeons can also be trained on the serial-order task with five stimuli (Terrace, 1993). In fact, with the exception of small differences in the speed of learning the task, little would distinguish between the terminal serial-order performance of monkeys and of pigeons. Performance on the pairwise test, however, differs dramatically between the two species. In contrast to the monkeys, pigeons perform at chance levels on many of the test pairs, and they fail to show any evidence for the first-item, the missing-item, or the symbolic-distance effect (Terrace, 1993; Terrace & McGonigle, 1994). Rather than form a linear representation of the series, the pigeons seem to learn the task by relying on an inventory of simple discriminative rules such as "always peck A first" and "always peck E last" (Terrace, 1993).

Prompted by the studies with pigeons and monkeys, a number of investigators have begun to look at serial-order behavior in human adults (Stromer & Mackay, 1993) as well as children (Terrace & McGonigle, 1994) and infants (Gulya, Rovee-Collier, Galluccio, & Wilk, 1998). Yet in no case have direct comparisons been made with respect to the data collected with monkeys and pigeons, at least not with regard to the first-item, missing-item, or symbolic-distance effects. The purpose of the present study was to examine the performance of humans on the serial-order task, with particular attention to these latency effects.

METHOD

Subjects and Apparatus

Fifty-six undergraduate students, ranging between 17 and 19 years of age, served as subjects. All were enrolled in an introductory course in psychology and were required to participate in experiments as partial fulfilment for their course grade. They were informed that at any time they could terminate their participation in the present experiment with no penalty incurred.
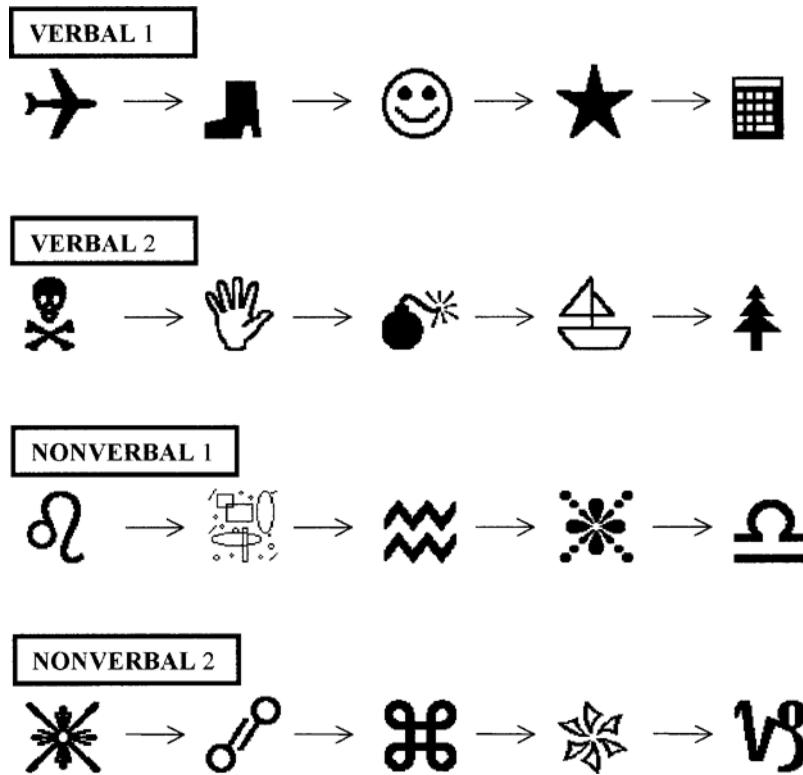
Figure 2. The two verbal (top) and two nonverbal (bottom) sequences. The stimuli appeared as white figures against the black background of the computer monitor.

The students sat in front of a ViewSonic monitor (Model E655) with a touch sensitive screen (MicroTouch Systems, Inc.) inside a sound-attenuating room. A 300-MHz Pentium II computer controlled the presentation of the stimuli and recorded all the data.

Behavioral Procedure

The stimuli consisted of a variety of common and abstract pictures (see Figure 2). All appeared as white shapes against the black background of the computer monitor and measured approximately 18×18 mm. At the start of a trial, the five stimuli were presented on the screen at the four corners and midpoint of a 140×100 mm rectangle centrally located on the monitor. Although the spatial arrangement of the five stimuli varied from trial to trial, a correct trial consisted of pressing the stimuli in the order A→B→C→D→E. A correct press to each stimulus resulted in the presentation of a 100-msec high-frequency (5000-Hz) feedback tone, whereas an incorrect press resulted in the presentation of a 100-msec low-frequency (300-Hz) feedback tone.

A correct trial was defined as pressing all five stimuli in the correct order, which resulted in the display of the word CORRECT in the middle of the monitor for 2 sec, followed by a 1-sec intertrial interval. An incorrect trial could result from committing either a forward error (e.g., A→B→D) or a backward error (e.g., A→B→C→A). Such responses terminated the trial and resulted in the presentation of the word INCORRECT in the middle of the monitor for 2 sec, followed by a 1-sec intertrial interval.

The subjects were divided into four equal size groups. Because of the importance of verbal mediation in human cognition, and because we were interested in whether such mediation would have an influence on the processing of serial-order information, half of our subjects were trained with one of two "verbal" sequences and the other half with one of two "nonverbal" sequences (see Figure 2). The

subjects were initially trained to play the serial-order task with only one stimulus (A), then two stimuli (A→B), three stimuli (A→B→C), four stimuli (A→B→C→D), and finally all five stimuli (A→B→C→D→E). Following 6 consecutive correct trials on the ABCDE series, the subjects were given a 20-trial pairwise test followed by a 20-trial triplet test. The pairwise test and triplet test consisted of two presentations of each of the 10 possible pairs (AB, AC, AD, AE, BC, BD, BE, CD, CE, and DE) and triplets (ABC, ABD, ABE, ACD, ACE, ADE, BCD, BCE, BDE, CDE) of stimuli that could be generated from the ABCDE series. Response latencies were measured to an accuracy of 1 msec (Emerson, 1988).

For comparative purposes, the human data were compared with data that we had collected previously with monkeys (D'Amato & Colombo, 1988, 1990). We made every attempt to model the procedures in the present experiment on those used with monkeys. Naturally, there were some differences. In the case of the monkey studies, the stimuli consisted of simple geometric shapes (circle, plus, dot, vertical line, and an hourglass shape) and a red disk. Procedurally the tasks were identical, with the exception that the monkeys worked for a food reward (banana pellets), and the spacing between trials was 15 sec. The training and testing protocols were also identical with the exception that the monkeys were trained until they satisfied a criterion of 30/40 correct responses over two consecutive sessions on the ABCDE series.

RESULTS

Preliminary analyses across all of the effects described below indicated no significant differences between the sex of the participants, the type of sequence (verbal or nonverbal), or the interaction of sex and sequence. Therefore,
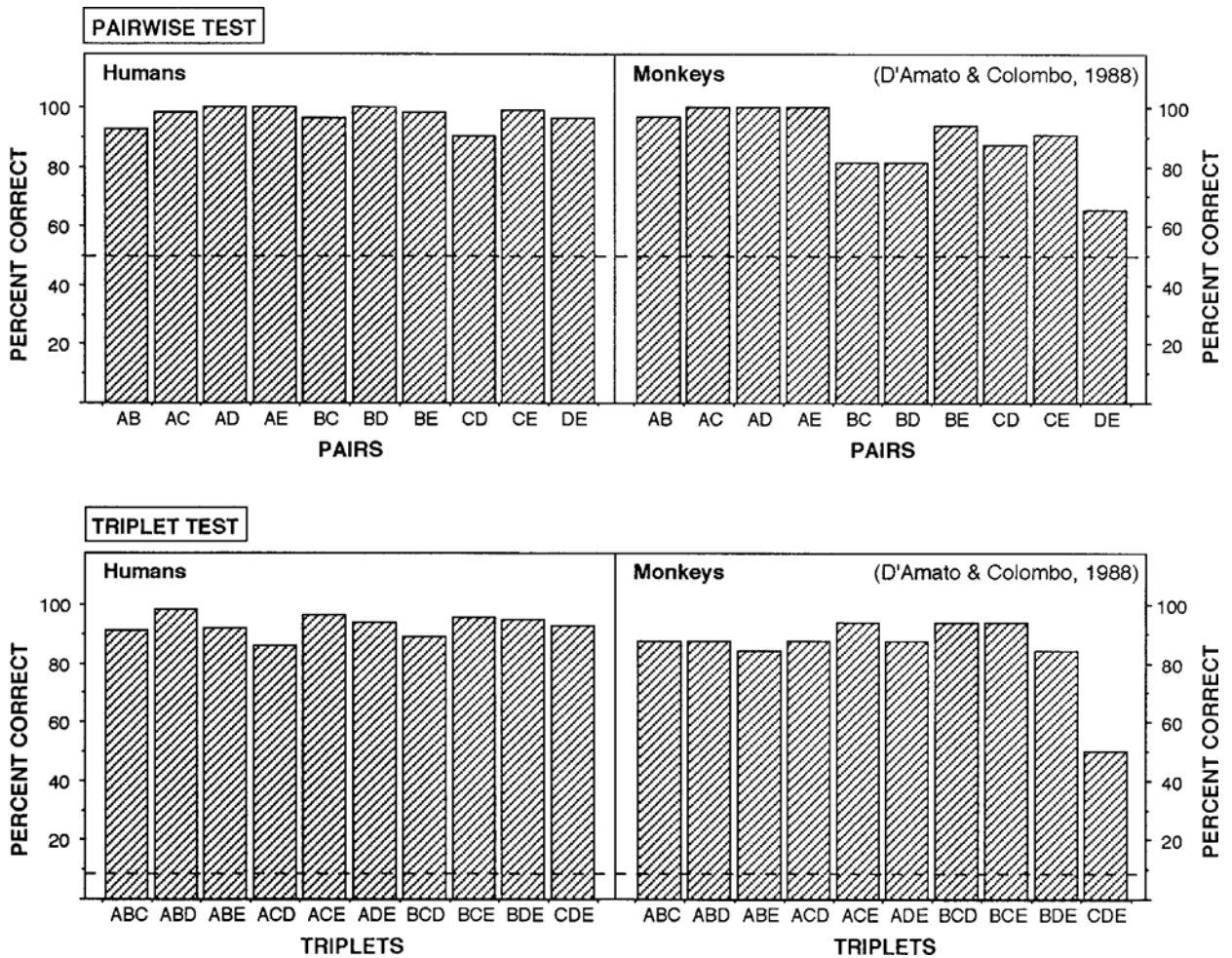
Figure 3. Mean performance on the pairwise test (top) and triplet test (bottom) for humans and monkeys. The dashed line represents chance level of performance. The monkey (*Cebus apella*) data, shown on the right, are redrawn from D'Amato and Colombo (1988).

the data have been collapsed across these variables. For comparative purposes, we present the monkey data alongside the human data.

Errors

The performance on the pairwise test and triplet test is shown in Figure 3. Overall, performance was uniformly high, and ranged from 90.2% to 100% correct on the pairwise test, and from 85.7% to 98.2% correct on the triplet test. The data for the monkeys are shown next to the human data. Like humans, monkeys also performed significantly above chance levels on all 10 test pairs and all 10 test triplets.

First-Item Effect

The latency to press the first item as a function of the position of the item in the series is shown in Figure 4 for both the pairwise test (top panel) and the triplet test (bottom panel). There was a significant first-item effect for both the pairwise test $[F(3,141) = 23.83, p < .001]$ and

the triplet test $[F(2,94) = 87.66, p < .001]$, with a significant linear component accounting for 87.2% and 96.6% of the variances, respectively. Thus, human subjects showed a strong first-item effect, with an increase in latency to respond to stimuli farther along in the series. This is the exact same finding that we noted with monkeys, whose data are shown next to the human data.

Missing-Item Effect

The latency to press the second item in the pairwise test as a function of the number of missing items is shown in Figure 5 (top panel). There was no significant missing-item effect for humans $[F(3,144) = .46, p = .71]$. In contrast, monkeys showed a robust missing-item effect on the pairwise test.

We suspected that the reason for the absence of a missing-item effect on the pairwise test in humans was that after pressing the first stimulus of the pair, the humans simply made a default response to the second stimulus. Unlike on the pairwise test, it is not possible to re-
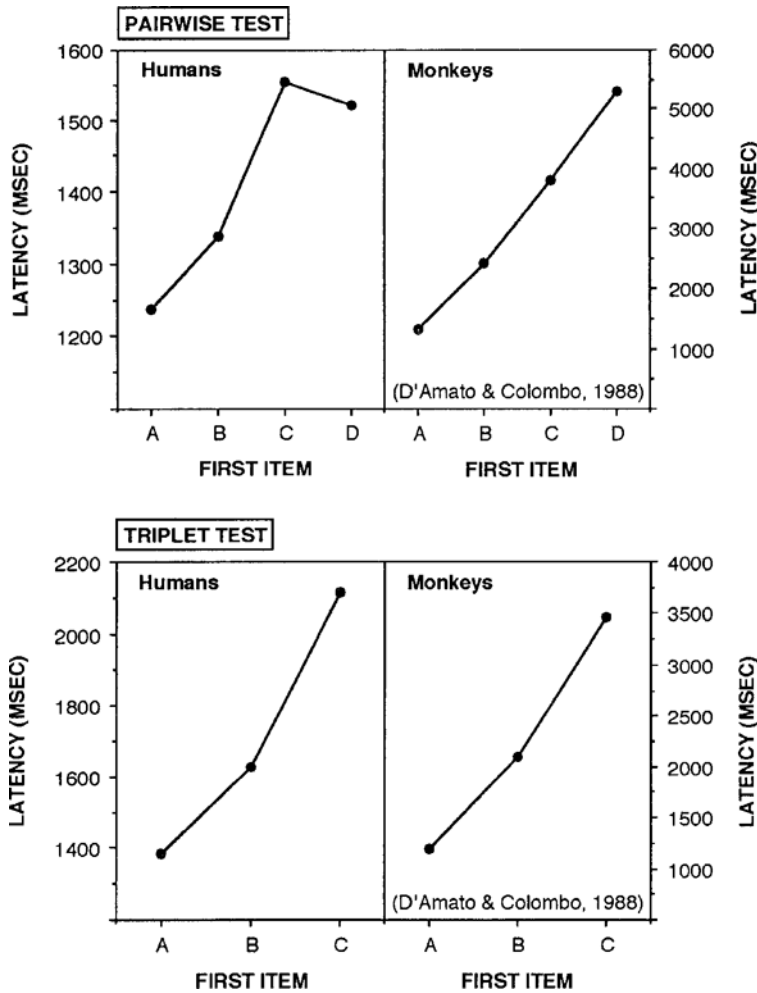
Figure 4. The first-item latency effect for the pairwise test (top) and triplet test (bottom). The monkey (*Cebus apella*) data, shown on the right, are redrawn from D'Amato and Colombo (1988).

spond by default to the second stimulus on the triplet test. The reason, of course, is that there is still a third stimulus that must be pressed. On the other hand, once the second stimulus has been pressed, it is once again possible to respond by default to the third stimulus of the triplet test. If the absence of a missing-item effect on the pairwise test was the result of a default strategy, we would expect to see a missing-item effect on the second press (i.e., second latency) of the triplet test but not the third press (i.e., third latency) of the triplet test. This is exactly what we noticed, and the results are shown in the middle and bottom panels of Figure 5. Humans showed a significant missing-item effect on the second latency of the triplet test [$F(2,94) = 14.35, p < .001$], with the significant linear component accounting for 86.0% of the variance, but not on the third latency [$F(2,94) = .75, p = .48$], when a default strategy was again possible. Thus humans show a robust missing-item effect, but only when they were unable to respond in a default manner. In contrast, mon-

keys did not avail themselves of a default strategy, showing a missing-item effect under all testing conditions.

Distance Effect

The latency to press the first item of a pair as a function of the distance between the first and second stimuli is shown in Figure 6. Humans showed a significant symbolic-distance effect for stimulus B [$F(2,96) = 4.10, p < .05$], as well as stimulus C [$F(1,48) = 34.63, p < .001$], with the linear component accounting for 79.2% of the variance in the case of stimulus B. (Because there are only two points in the case of stimulus C, the linear component naturally accounts for 100% of the variance.)

The case for a symbolic-distance effect for stimulus A in humans was somewhat ambiguous. Although there was a significant difference in the latency to respond to stimulus A in pairs AB, AC, AD, and AE [$F(3,144) = 9.73, p < .001$], the linear component accounted for only 55.1% of the variance, with the cubic component account-
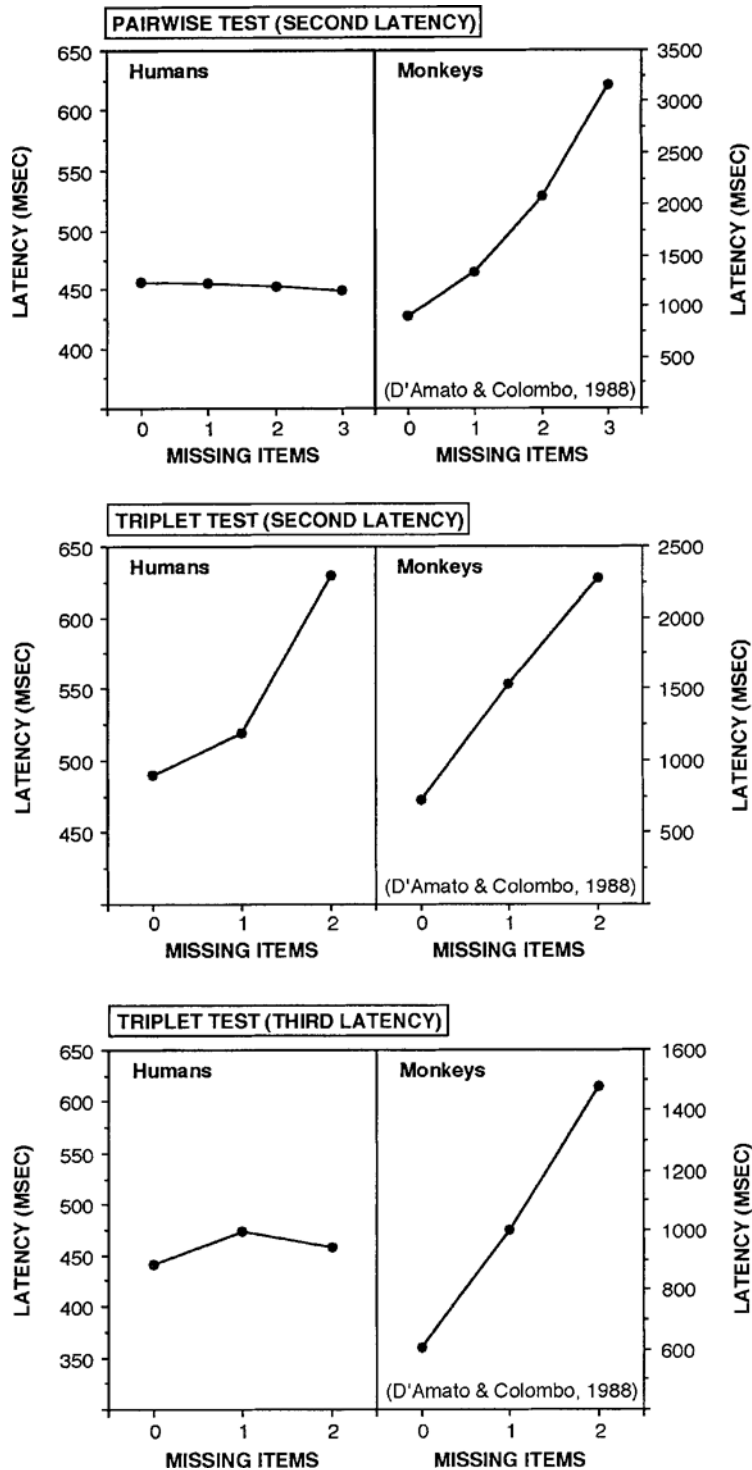
Figure 5. The missing-item latency effect for the pairwise test (top) and triplet test (middle and bottom). In the case of the triplet test, two missing-item effects can be generated, one for the second latency and one for the third latency. The monkey (*Cebus apella*) data, shown on the right, are redrawn from D'Amato and Colombo (1988).
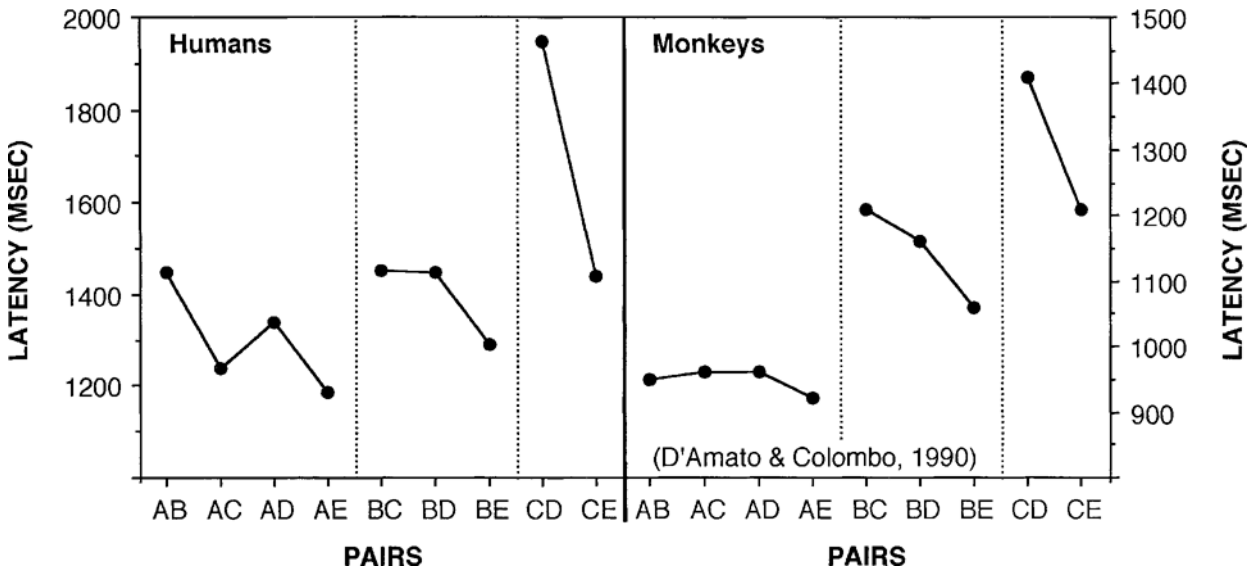
Figure 6. The symbolic-distance effect for pairs beginning with stimuli A, B, or C. The monkey (*Cebus apella*) data, shown on the right, are redrawn from D'Amato and Colombo (1990).

ing for 43.1% of the variance. Thus there was not a consistent decrease in latency to stimulus A across pairs AB, AC, AD, and AE, which would be expected in the case of the symbolic-distance effect. Interestingly, the results for the monkeys were almost identical to those obtained with the humans. Monkeys showed a symbolic-distance effect for stimuli B and stimulus C, and no evidence for a symbolic-distance effect for stimulus A.

DISCUSSION

To summarize the findings from the present study, humans performed at high levels on all test pairs and all test triplets, and they displayed a first-item effect, a missing-item effect (when defaulting was not possible), and a symbolic-distance effect. These latency effects occurred irrespective of whether the serial-order task was learned with a verbal or a nonverbal sequence. Whether this indicates that the subjects were engaging verbal mediation for the nonverbal lists, or whether it indicates that in the context of the present task verbal and nonverbal lists were processed in the same fashion, is a matter for further investigation.

Overall, the findings that we obtained with humans were very similar to those obtained with monkeys (*Cebus apella*). We had suggested that in learning a list of five items, monkeys formed a linear representation of the list and accessed that information to guide their behavior (D'Amato & Colombo, 1988, 1989, 1990). The findings of the present study suggest that humans also formed and implemented a similar linear representation of the five items and used that representation to solve the pairwise and triplet tests.

One obvious difference between the human and monkey latency data concerns the missing-item effect. Hu-

mans clearly adopted a default strategy during the terminal response—that is, during the second response on the pairwise test or the third response on the triplet test. In fact, there was no reason for not doing this. Once the first stimulus is pressed on the pairwise test, and once the first and second stimuli are pressed on the triplet test, the final response can be made with little concern for the nature of the last stimulus. In fact, it is interesting that the monkeys did not adopt this strategy. Although some forms of defaulting may be within the capacity of monkeys (Terrace, 1993), it is likely that defaulting on the terminal response reflects a logical formulation that may be beyond the capacity of monkeys, at least as tapped by the present serial-order procedure. Whether this defaulting strategy is a by-product of our linguistic abilities, or whether it is the result of some other process, is unclear. Nevertheless, given that language training seems to go hand-in-hand with the expression of certain cognitive abilities in apes, at least according to Premack (1976, 1983; but see Roberts, 1983, and Roitblat, 1983, for differing opinions), it might be interesting to compare, with reference to the missing-item effect, the serial-order behavior of language-trained and non–language-trained chimpanzees. Would they adopt a default strategy similar to that of humans, or would they continue to access their linear representation and solve the problem in a manner like that for the monkeys?

From a comparative perspective, other than differences in the speed with which the task was acquired, there is little that would distinguish between the terminal performance levels of humans, monkeys, and pigeons on the five-item serial-order task. On the other hand, the types of representations that are formed differ dramatically. The latency data from the pairwise and triplet tests indi-

cate that humans and monkeys form an internal representation of the series. In contrast, pigeons show no evidence of a first-item effect, missing-item effect, or symbolic-distance effect, and they appear to solve the serial-order task by means of discriminative mechanisms that do not require elaborate internal representations (D'Amato & Colombo, 1988; Terrace, 1993). For example, pigeons may learn that the onset of the stimulus display serves as a discriminative stimulus to respond to stimulus A. Likewise, responding to stimulus A serves as the discriminative stimulus to respond to stimulus B, and so on. In the absence of any of the stimuli, such as on the pairwise and triplet tests, and in the absence of an internal representation to guide their behavior, pigeons are often lost with respect to what stimulus should be pressed. Whether the capacity to form an internal linear representation is a feature exclusive to mammals, or whether it is an ability restricted to primates, remains to be seen.

We do not wish to imply that what humans and monkeys extract from learning a list of items is identical under all circumstances. For example, we have argued that the first-item and missing-item latency effects suggest that monkeys form an associative representation of the five-item list (D'Amato & Colombo, 1988), and the distance effect data suggest that they also form a spatial representation of the list (D'Amato & Colombo, 1989, 1990). The associative representation allows the monkeys to progress in a linear fashion through the list, whereas the spatial representation allows the monkeys to extract ordinal information without having to scan each individual item progressively in the list. The data from the present experiment suggest that humans form both associative and spatial representations as well. Interestingly, the distance effect in monkeys emerges only after special training with just the adjacent pairs AB, BC, CD, and DE (D'Amato and Colombo, 1990), whereas for humans it emerges without this special training. Thus, humans and monkeys may differ in the weights that they assign to each of these two modes of processing serially organized information. Alternatively, humans may be more adept at shifting between these two strategies as a function of task demands. Nevertheless, it will be experiments of this sort that will ultimately determine the dimension along which human serial-order behavior differs from that in monkeys. In this way, we can begin to construct the phylogeny and ontogeny of serial-order behavior.

REFERENCES

D'AMATO, M. R., & COLOMBO, M. (1988). Representation of serial order in monkeys (*Cebus apella*). *Journal of Experimental Psychology: Animal Behavior Processes*, **14**, 131-139.

D'AMATO, M. R., & COLOMBO, M. (1989). Serial learning with wild card items by monkeys (*Cebus apella*): Implications for knowledge of ordinal position. *Journal of Comparative Psychology*, **103**, 252-261.

D'AMATO, M. R., & COLOMBO, M. (1990). The symbolic distance effect in monkeys (*Cebus apella*). *Animal Learning & Behavior*, **18**, 133-140.

EMERSON, P. L. (1988). TIMEX: A simple IBM AT C language timer with extended resolution. *Behavior Research Methods, Instruments, & Computers*, **20**, 566-572.

GULYA, M., ROVEE-COLLIER, C., GALLUCCIO, L., & WILK, A. (1998). Memory processing of a serial list by young infants. *Psychological Science*, **9**, 303-307.

HAMILTON, J. M. E., & SANFORD, A. J. (1978). The symbolic distance effect for alphabetic order judgements: A subjective report and reaction time analysis. *Quarterly Journal of Experimental Psychology*, **30**, 33-43.

LOVELACE, E. A., & SNODGRASS, R. D. (1971). Decision times for alphabetic order of letter pairs. *Journal of Experimental Psychology*, **88**, 258-264.

MOYER, R. S., & LANDAUER, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, **215**, 1519-1520.

PREMACK, D. (1976). *Intelligence in ape and man*. Hillsdale, NJ: Erlbaum.

PREMACK, D. (1983). The codes of man and beasts. *Behavioral & Brain Sciences*, **6**, 125-167.

ROBERTS, W. A. (1983). Doubts about the importance of language training and the abstract code. *Behavioral & Brain Sciences*, **6**, 154-155.

ROITBLAT, H. L. (1983). Does language training affect the code used by chimpanzees? Some cautions and reservations. *Behavioral & Brain Sciences*, **6**, 155-156.

STRAUB, R. O., SEIDENBERG, M. S., BEVER, T. G., & TERRACE, H. S. (1979). Serial learning in the pigeon. *Journal of the Experimental Analysis of Behavior*, **32**, 137-148.

STRAUB, R. O., & TERRACE, H. S. (1981). Generalization of serial learning in the pigeon. *Animal Learning & Behavior*, **9**, 454-468.

STROMER, R., & MACKAY, H. A. (1993). Human sequential behavior: Relations among stimuli, class formation, and derived sequences. *Psychological Record*, **43**, 107-131.

TERRACE, H. S. (1993). The phylogeny and ontogeny of serial memory: List learning by pigeons and monkeys. *Psychological Science*, **4**, 162-169.

TERRACE, H. S., & McGONIGLE, B. (1994). Memory and representation of serial order by children, monkeys, and pigeons. *Current Directions in Psychological Science*, **3**, 180-185.