AUDITORY DELAYED MATCHING IN THE BOTTLENOSE DOLPHIN¹

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A bottlenose dolphin, already highly proficient in two-choice auditory discriminations, was trained over a nine-day period on auditory delayed matching-to-sample and then tested on 346 unique matching problems, as a function of the delay between the sample and test sounds. Each problem used new sounds and was from five to 10 trials long, with the same sound used as the sample for all trials of a problem. At each trial, the sample was projected underwater for 2.5 sec, followed by a delay and then by a sequence of two 2.5-sec duration test sounds. One of the test sounds matched the sample and was randomly first or second in the sequence, and randomly appeared at either a left or right speaker. Responses to the locus of the matching test sound were reinforced. Over nine, varying-sized blocks of problems, the longest delay of a set of delays in a block was progressively increased from 15 sec initially to a final value of 120 sec. There was a progressive increase across the early blocks in the percentage of correct Trial 1 responses. A ceiling-level of 100% correct responses was then attained over the final six blocks, during which there were 169 successive Trial 1 responses bracketed by two Trial 1 errors (at 24- and 120-sec delays). Performance on trials beyond the first followed a similar trend. Finally, when the sample duration was decreased to 0.2 sec or less, matching performance on Trial 1 of new problems dropped to chance levels.

The bottlenose dolphin has previously been shown capable of one-trial learning of two-choice auditory discrimination problems (Herman and Arbeit, 1973). This degree of learning efficiency was in keeping with expectations based on the large and complex brain of this species (Flanigan, 1972; Jansen and Jansen, 1969).

In the present experiment, the dolphin's capability for delayed matching-to-sample was studied, in order to test its short-term memory capacity and to explore further its ability to form learning sets. In the typical delayed matching procedure, a sample stimulus is presented, and then removed. Following a vari-

able delay interval generally two test stimuli are presented in the form of a nonspatial, simultaneous discrimination. A response to the test stimulus matching the sample is reinforced.

Delayed matching has been studied previously in the monkey (*e.g.*, D'Amato and O'Neill, 1971; D'Amato and Worsham, 1972; Jarrard and Moise, 1971) and pigeon (*e.g.*, Berryman, Cumming, and Nevin, 1963; Smith, 1967), so that comparative data are readily available. In these studies, pigeons have generally approached chance matching levels after delays as short as 7 to 10 sec. In contrast, responses of three capuchin monkeys were from 75 to 96% correct after 60-sec delays and from 56 to 80% correct after 120-sec delays (D'Amato and O'Neill, 1971). With subsequent extended practice, the performance of one of these monkeys rose to approximately 88% correct after 120 sec, 94% after 180 sec, and then fell to 70% after 240-sec delays (D'Amato and Worsham, 1972). These appear to be among the best delayed matching skill levels reported for monkeys thus far.

Visual test stimuli have been used in all prior delayed matching studies. Because the auditory system of the bottlenose dolphin is

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highly developed (e.g., Norris, 1969) and because auditory discriminations are readily attained by this species (e.g., Herman and Arbeit, 1973), the present experiment used auditory test stimuli.

METHOD

Subject

A female, adult Atlantic bottlenose dolphin, *Tursiops truncatus* (Montagu), was tested. She was the subject (Keakiko) used, successively, in the studies of Herman and Arbeit (1973) and Herman and Arbeit (1972). She was 8 to 9 yr old, 2.4 m long, and weighed 140 kg. Her daily diet was 7 kg of smelt, a normal intake for an adult, captive bottlenose dolphin. Most of this ration was given during testing.

Apparatus

The 15.2-m diameter circular tank in which the animal lived and was tested, and the apparatus configuration within the tank were, with slight modification, as reported previously (Herman and Arbeit, 1973). The apparatus was suspended underwater from overhead beams projecting up to 3.5 m into the tank in the horizontal plane. Two pairs of vertically suspended weighted ropes defined the left and right sides of a 0.9-m wide, 0.5-m long channel leading to a listening area. At 1.0 m beyond the channel exit and in line with the center of the channel was a start paddle. The region between this paddle and the channel exit was the listening area, and all of the underwater speakers were pointed towards this area. At 45° to the left and right of the start paddle, at 2-m radial distance, were the two stimulus speakers (Chesapeake J9 underwater sound projectors), used to project the sample and test sounds. Slightly to the side and front of each stimulus speaker was a response paddle.

A control speaker (University MM-2PPS) was positioned 2 m beyond the start paddle, between the two stimulus speakers, and projected sounds for controlling entry into the channel and listening area and exiting from the listening area. It also provided a sound following a correct response on the left or right response paddle. Before the start of this study, control of exiting from the listening area was transferred from a previously used

light stimulus to a sound from the control speaker.

Test Sounds

A subset of 17 of the 28 sound-pair types described by Herman and Arbeit (1973, Table 1) was used to form pairs of test sounds. Reference should be made to that study for details of the acoustic variables within the sound-pair types, and for the method of their generation, calibration, and underwater projection. Basically, a sound-pair type described a pair of sound classes, e.g., two pure tones or a pure tone and a frequency modulated sound. A given sound-pair type was used in multiple problems, but without repeating the same pair of sounds, e.g., the specific values of the two pure tones were changed for each use. Each delayed matching problem was therefore unique, in that the specific pair of sounds used was different from those in any other problem.

Training

Training for delayed matching made use of the prior skill of the animal in two-choice auditory discriminations (Herman and Arbeit, 1972, 1973). The two sounds of a two-choice discrimination problem were redefined as test sounds and a response to one of them (S+) was reinforced. Responses to the other sound (S-) were not reinforced, and no correction was given following errors. Over successive discrete trials, with responding to S+ maintained, the sample sound (S+) and the delay interval were gradually introduced before the pair of test sounds, by progressively increasing their durations over trials.

A total of 21 unique problems was given at the rate of two to three per day over a nine-day period. All but three problems were 50 trials long (total trials = 934). Each trial began with a tone of 10-sec maximum duration from the control speaker. In its presence, the animal entered the channel, passed into the listening area and briefly pressed the start paddle, turning the tone off. The sample sound was projected 1.5 sec later *simultaneously* from the two stimulus speakers, so that there was no unique association between the sample and either speaker. Following the delay interval, the two test sounds were projected *sequentially* from the stimulus speakers. Except on Trial 1, the test sounds were each of

2.5-sec duration, separated by a 0.5-sec silent interval. On Trial 1, the S— was 0.5 sec long, while the S+ was 2.5 sec. This was the Trial-1 cueing method described by Herman and Arbeit (1973), in which the animal was trained to respond on Trial 1 to the longer duration (S+) sound. Following a Trial-1 response to S+, the probability of continued responding to S+ was very high, while the probability of responding to S+ after an initial response to S— was somewhat lower (Herman and Arbeit, 1973, Experiment 5).

The sequential order of the two test sounds was random (either S+/S— or S—/S+). One test sound appeared at the left stimulus speaker and the other at the right, with the mapping of the sounds onto the speakers randomized over trials independently of the randomization of the order of the sounds. When the two test sounds ended, a second tone was projected from the control speaker. The animal then exited the listening area and pressed either the left or right response paddle, ending the tone and beginning 2.5 sec of playback of the test sound selected, *i.e.*, the test sound that had been projected from the adjacent stimulus speaker. Playback of S+ (the match sound) was followed by a third tone, of 0.5-sec duration, from the control speaker and then by a thrown fish reinforcer and a 7-sec intertrial interval. Playback of S— was followed only by the intertrial interval. Playback was shown previously to assist substantially in the acquisition of auditory discriminations, given the sequential presentation of a pair of sounds (Herman and Arbeit, 1973, Experiment 2). The chain described was also developed in that study and was used to maintain the animal within the listening area during presentation of the auditory discriminanda and to regulate the intertrial interval.

The sample duration was increased from 0.2 to 2.5 sec within each of the first 12 problems. The trial number at which the sample was first given and the number of trials taken to reach the final duration of 2.5 sec were progressively reduced over problems until, at Problem 13 and thereafter, the duration remained at 2.5 sec for all trials.

The delay interval was increased from 0.2 to 1.5 sec within each of the first three problems, with progressively fewer trials taken at each problem to complete the fade-in schedule. From Problem 4 through 12 the delay

remained at 1.5 sec for all trials. Beginning with Problem 13, sets of five to eight different delays were given in random sequence over blocks of trials. Over successive problems, longer delays were progressively introduced into the sets, while still retaining a sampling of the shorter delays. By Problem 17, delays of 18 sec, the longest used during training, were occasionally presented. The use of sets of delays within problems was continued during the testing given following training.

Because of the use of the Trial-1 cueing method, an unconfounded measure of the probability of a correct Trial-1 response as a function of the sample sound was not obtained, *i.e.*, a correct Trial-1 response could be controlled by the different test sound durations. For all problems given after training, however, the Trial-1 cue was deleted (S+ and S— were each 2.5 sec) so that the probability of a correct Trial-1 response then solely indexed the degree of control of a response to the matching test sound by the preceding sample sound.

Testing

There were 346 delayed matching problems, given over a four-week period. Four additional problems given were deleted because of equipment failure on Trial 1. Generally, there were 20 problems daily, with 5 to 10 min between problems, plus a 1- to 2-hr break after the tenth problem.

The problems were grouped into nine blocks of varying numbers of problems each. Each block used a different set of delay values (Table 1). The general plan was to increase the duration of the longer delays in the set over blocks while still maintaining a sampling of the shorter delays as a control, until an upper limit of performance at the longer delays was reached.

For Blocks 1 to 6 (Problems 1 to 257), the number of delay values in a set was five. Problems 13 through 257 were five trials each, and the trial number at which a given delay value occurred was balanced every five problems by 5×5 Latin squares. Problem 1 to 12 were 10 trials each, and each of the five delay values appeared twice per problem (once over Trials 1 to 5 and once over Trials 6 to 10). Ten trials were used in these initial problems to provide a more gradual transition from the 50 trials per problem given in training.

Table 1

The number of trials and errors at each delay value for the nine blocks of problems. The problem numbers are shown at the top of each block. The data not in parentheses are for Trial 1 only and the data within parentheses are for the combined trials beyond the first (Trials 2-N). For blocks eight and nine, the maximum delay was given only on Trial 1, and the dash in the error column in these blocks means there was no opportunity for error.

Delay (sec)	No. of Trials	No. of Errors	Delay (sec)	No. of Trials	No. of Errors	Delay (sec)	No. of Trials	No. of Errors
<i>1-121</i>								
1.5	25 (108)	5 (8)	1.5	2 (8)	1 (1)	1.5	8 (32)	1 (1)
3.0	22 (107)	6 (6)	3.0	2 (8)	0 (2)	4.0	8 (32)	1 (0)
6.0	25 (105)	3 (12)	6.0	2 (8)	0 (0)	9.0	8 (32)	1 (3)
10.0	24 (106)	4 (9)	12.0	2 (8)	1 (0)	15.0	8 (32)	0 (3)
15.0	25 (108)	7 (8)	18.0	2 (8)	0 (2)	24.0	8 (32)	2 (0)
Totals:	121 (524)	25 (43)	10 (40)	2 (5)	40 (160)	5 (7)		
% Correct:		79.3 (91.8)	80.0 (87.5)		87.5 (95.6)			
<i>172-207</i>								
1.5	7 (28)	0 (1)	1.0	2 (8)	0 (0)	1.0	8 (32)	0 (0)
6.0	7 (27)	0 (0)	5.0	2 (8)	0 (0)	5.0	8 (32)	0 (0)
12.0	8 (28)	0 (1)	10.0	2 (8)	0 (0)	15.0	8 (32)	0 (0)
20.0	7 (28)	1 (0)	20.0	2 (8)	0 (0)	35.0	8 (32)	0 (0)
30.0	7 (29)	0 (1)	40.0	2 (8)	0 (0)	60.0	8 (32)	0 (1)
Totals:	36 (140)	1 (3)	10 (40)	0 (0)	40 (160)	0 (1)		
% Correct:		97.2 (97.9)	100.0 (100.0)		100.0 (99.4)			
<i>258-336</i>								
1.0	13 (65)	0 (0)	1.0	0 (4)	— (0)	1.0	0 (6)	— (0)
5.0	13 (65)	0 (0)	6.0	0 (4)	— (0)	10.0	0 (6)	— (0)
10.0	13 (66)	0 (0)	15.0	0 (4)	— (0)	20.0	0 (6)	— (0)
20.0	13 (66)	0 (0)	30.0	0 (4)	— (0)	40.0	0 (6)	— (0)
35.0	13 (66)	0 (1)	60.0	0 (4)	— (0)	70.0	0 (6)	— (1)
60.0	14 (66)	0 (4)	90.0	4 (0)	0 —	120.0	6 (0)	1 —
Totals:	79 (394)	0 (5)	4 (20)	0 (0)	6 (30)	1 (1)		
% Correct:		100.0 (98.7)	100.0 (100.0)		83.3 (96.7)			
<i>341-346</i>								
1.0	0 (6)	— (0)	1.0	0 (6)	— (0)	1.0	0 (6)	— (0)
5.0	0 (6)	— (0)	10.0	0 (6)	— (0)	10.0	0 (6)	— (0)
10.0	0 (6)	— (0)	20.0	0 (6)	— (0)	20.0	0 (6)	— (0)
20.0	0 (6)	— (0)	40.0	0 (6)	— (0)	40.0	0 (6)	— (0)
35.0	0 (6)	— (0)	70.0	0 (6)	— (0)	70.0	0 (6)	— (1)
60.0	0 (6)	— (0)	120.0	6 (0)	1 —	120.0	6 (0)	1 —
Totals:	79 (394)	0 (5)	4 (20)	0 (0)	6 (30)	1 (1)		
% Correct:		100.0 (98.7)	100.0 (100.0)		83.3 (96.7)			

Blocks 7 to 9 (Problems 258 to 346) tested six delay values each, and there were six trials per problem. During Block 7, 6×6 Latin squares were used to balance the six delay values over trials every six problems. For Blocks 8 and 9, the procedure was modified so that the maximum delay in the set (either 90 or 120 sec) always occurred on Trial 1 of a problem. The five remaining shorter delays in the set were then assigned to Trials 2 to 6 using 5×5 Latin squares. The modified procedure was more efficient in that Trial 1 data on maximum delays in the set were accumulated more quickly. The modification was made necessary by an increasing frequency of negative emotional responses during the longer delays.

The overall testing procedures, including use of the chain, were as described during training. The sample duration was always 2.5 sec, as was each of the test sounds (including Trial 1). Noncorrection following errors continued to be used. Occasionally, during the longer delays, the animal surfaced briefly. If this coincided with test sound presentation, the trial was discontinued and then repeated after the normal intertrial interval. Surfacing did not occur on Trial 1 of any problem.

RESULTS

Errors occurred on only six of the 21 training problems (Problems 1, 2, 4, 10, 15, and 18). The total number of errors was 16 and all but two occurred within the first eight trials. The training procedures were thus clearly successful in establishing and maintaining S+ responding (1.7% overall error rate). Also, there were no disruptive effects of introduction of the sample or delay intervals.

Results for the 346 problems given subsequent to training are summarized in Table 1. Trial-1 data are given without parentheses and data for the cumulative trials beyond the first are given within parentheses. The planned number of trials was not completed for seven problems because of equipment failure (after Trial 1), but these problems were retained in the data analysis. The omitted trials and/or an inability to complete the Latin square counterbalancing scheme within the number of problems given contributed to the slight imbalances in the number of trials per delay value within Blocks 1, 4, and 7.

Trial-1 data were of major importance in assessing delayed matching capability and the capacity for formation of a delayed matching learning set. On Trial 1 of each problem, the only cue for a correct response was the sample sound. On trials after the first, a correct response could be additionally controlled by events of preceding trials, *e.g.*, whether or not a response to a given test sound had been reinforced.

The majority of Trial 1 errors, and also errors on remaining trials, occurred within the first block (Problems 1 to 121). The errors in this block were independent of delay, *i.e.*, they were roughly as frequent at shorter delays as at longer ones. Inspection of the data showed that independence of delay and error was also the case for the first 40, second 40, and final 41 problems of the total of 121, suggesting that from the beginning, the animal had no difficulty in remembering a sample sound. That there were only 79.3% correct responses in the first block indicates, however, that learning to respond to the test sound matching the prior sample was still developing.

The acquisition of delayed matching and the development of a delayed matching learning set was shown by the progressive improvement in matching accuracy over the successive blocks of problems, through to the attainment of a consistent capability for immediate learning of new problems. Beginning with the second problem of Block 4 (Problem 173) and continuing through to the first problem of Block 9 (Problem 341), a total of 169 problems, there were no errors in matching on Trial 1. This total included seven correct matches at 30-sec delays, eight at 35 sec, two at 40 sec, 22 at 60 sec, four at 90 sec, and one at 120 sec delays. There were, altogether, five of six correct Trial-1 matches at 120-sec delays.

Figure 1 shows the acquisition of delayed matching within each of the first four blocks of Table 1 (before performance reached the consistent 100% correct level). The per cent correct Trial 1 responses are given for successive testing sessions within blocks. A testing session was a group of problems separated only by the 5- to 10-min interproblem interval required to calibrate the new acoustic stimuli, as contrasted with the 1- to 2-hr interval between sessions (within days). There were generally two daily sessions, with 10 problems per session, unless noted otherwise in the figure.

During the first block, the initial variability in performance during the early sessions progressed to a more consistent and generally higher level of performance during the final four sessions. At each of the three following blocks, there appeared to be an initial small decrease in performance from the final level of the prior block, but with additional sessions (within Blocks 3 and 4) there was rapid re-acquisition. The data clearly showed the development of learning within blocks, as well as across blocks.

Fig. 1. Delayed matching acquisition. The per cent correct responses on Trial 1, independent of delay interval, at successive testing sessions within each of the first four blocks of Table 1. Sessions were 10 problems each, unless noted otherwise (Sessions 1, 2, 8, 9, 11, and 20), with the percentages based on these numbers of problems. Problems within sessions were separated by a 5- to 10-min interval and sessions by 1 to 2 hr or by days. Trial 1 responses on the 17 sessions following the 23 shown produced only a single error.

There was also learning within problems. Table 1 showed that the per cent correct responses on trials beyond the first during the first four blocks was consistently higher than that on Trial 1. As was noted, however, responses after Trial 1 did not necessarily indicate matching capability, so that the degree to which the within-problem learning contributed to the delayed matching learning set cannot be determined unequivocally.

There were indications that the 60-sec and longer delays were aversive. Negative emotional responses—vigorous head shaking, jaw snapping, and shuddering—were observed on occasion during the 60-sec delays, while the animal remained underwater in the listening area. These responses appeared to increase in frequency and severity during the 90- and 120-sec delays, and for this reason further testing with these or even longer delays was not attempted.

After completion of the 120-sec maximum delay problems, a brief test (12 new problems) was made of the control of responses to test sounds by the sample sound. Each problem was four trials long with a constant delay interval of 2.0 sec used throughout. There were four problems with the sample absent entirely, followed by two with the sample at the normal 2.5-sec duration, then two with the duration at 0.1 sec, two with the duration at 0.2 sec, and finally, two again at the 2.5-sec duration. The results indicated chance responding on Trial 1 with the brief or absent sample sounds (four correct of eight Trial 1 responses, with 50% error at each duration value) and no Trial 1 errors following the four 2.5-sec samples. A correct Trial 1 response was thus controlled by a sample sound of adequate duration, a result in keeping with the serially unfolding (temporal) characteristic of sound stimuli.

There were no errors on trials beyond the first for the four problems having the normal sample duration. There were errors on 25% of the trials beyond the first for the four problems with the sample absent and on 16.7% of the trials for the four problems with the brief sample durations. Since these error rates were less than that of Trial 1, it appears that whether or not reinforcement followed a response to a given test sound in part controlled subsequent responses to that test sound.

DISCUSSION

No upper limit to delayed matching capability was found. Matching skill, defined as the probability of a correct response on Trial 1 of new problems, continued to develop over approximately the first 150 to 170 problems, during which the maximum delay in a block of problems was extended from 15 sec to 18 and 24 sec. There was then errorless responding at succeeding maximum delays of 30, 40, 60, and 90 sec, and only a single Trial-1 error with the 120-sec delays. This level of delayed matching skill compared favorably with capabilities reported for primates in visual delayed matching tests (D'Amato and O'Neill, 1971; D'Amato and Worsham, 1972) and considerably exceeded capabilities observed for pigeons (Berryman, Cumming, and Nevin, 1963; Smith, 1967).

The maintenance of the matching skill depended on the presence of a sample sound of

adequate duration. If the sample was absent or of brief duration (0.1 or 0.2 sec), as compared with the normal 2.5-sec duration, there was only chance responding on Trial 1, even though the delay used was only 2.0 sec. These results do not necessarily indicate the minimum duration of sound necessary for reliable Trial-1 matching, nor whether the animal could have learned to match reliably using sample sounds briefer than normal.

Since new sounds were used for each problem, the noted improvement in Trial-1 matching over problems (Figure 1 and Table 1) traced the development of a delayed matching learning set, *i.e.*, the ability to form the general concept of matching. The cited studies of delayed matching in pigeons and monkeys used only a limited set of test stimuli (two to five in number) throughout an experiment, and hence the same set of problems was continually repeated. No data on delayed matching learning sets are therefore available from these sources. In nondelayed (simultaneous) matching, however, one-trial learning of new problems has been observed for the chimpanzee and rhesus monkey (see French, 1965, p. 202). The ability of pigeons to acquire the general concept of matching in the nondelayed case has not been demonstrated (Cumming and Berryman, 1965).

The bottlenose dolphin studied here was previously shown capable of forming a discrimination learning set in a two-choice auditory discrimination situation (Herman and Arbeit, 1973). Taken together with the present results, there is convincing evidence for a highly developed general capacity for efficiency in learning and for the transfer of learning. The evidence remains consistent with expectations of learning capacity of the bottlenose dolphin based on the advanced development of its brain (Flanigan, 1972; Jansen and Jansen, 1969).

The present results also demonstrate that auditory short-term memory is very well developed in the bottlenose dolphin. Testing of delays longer than 120 sec was not attempted because of emotional responding during the longer delays. Emotional responding may have developed because of the increasing contrast between the minimum and maximum delays within a set of delays with succeeding blocks of problems, and it might be avoided if a constant delay were used throughout a

block. The latter procedure has been used in some of the cited studies of monkeys, with no report of emotional responding (*e.g.*, D'Amato and O'Neill, 1971; D'Amato and Worsham, 1972).

Comparisons of the present results with those of monkeys and pigeons were made within the context of some procedural differences. However, as was stressed previously by Herman and Arbeit (1973), a major comparative goal is the determination of the maximum skill level attainable by a species on a given learning task. This requires the selection or development of conditions of stimulus control favorable to the species under test. The general procedures used in training and testing of the bottlenose dolphin in delayed matching were shown previously to assist materially in the rapid acquisition of two-choice auditory discriminations (Herman and Arbeit, 1973). These procedures included the initial use of fading methods, the playback of S+ or S- following a response, and the use of a complex chain for the stimulus control of listening behavior. The ceiling level performance reached within the limits of the delays tested attests to the continued efficacy of these methods. Also, the use of auditory rather than visual test stimuli was consistent with the advanced development of the auditory system of the bottlenose dolphin (*e.g.*, Norris, 1969) and the generally accepted sensory dominance of auditory over visual stimuli in this species. It is not likely that performance of the bottlenose dolphin with visual test stimuli would be comparable to levels demonstrated here with auditory stimuli. Correspondingly, the capuchin monkey, which performs so well on visual delayed matching tests (D'Amato and Worsham, 1972), is apparently unable to learn auditory delayed (or undelayed) matching (Worsham and D'Amato, 1973).

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