Delayed matching of visual materials by a bottlenosed dolphin aided by auditory symbols

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A bottlenosed dolphin (*Tursiops truncatus*) with good underwater and aerial visual acuity was tested in visual matching-to-sample (MTS) paradigms. Attempts to train visual identity MTS directly, using two simple two-dimensional patterns as sample stimuli and as alternatives (comparison stimuli), met with little success, in keeping with previously observed difficulties of this auditory-specialized species for learning complex tasks utilizing simple visual materials. Pairing of each visual sample with a unique sound, to produce a compound auditory-visual sample, while retaining the two visual alternatives, resulted in the dolphin's learning both auditory-visual symbolic matching and visual-visual identity matching. At 0-sec delay, performance with the auditory element of the sample alone was equivalent (76%) to performance with the visual element alone; performance with the compound was distinctly better (95%-98% correct). Testing with longer delays using the visual element alone resulted in successful matching through to a maximum delay of 34 sec. These results provided the first demonstration of delayed MTS in a dolphin using visual materials, and complemented other data showing the ready capability of this species for delayed auditory MTS. It appeared that the dolphin solved the visual MTS task by forming auditory codes to represent the visual materials, and that these auditory codes were eventually replaced with purely visual codes.

Delayed-matching-to-sample (DMTS) tasks have been used extensively in the analysis of animal memory (Roitblat, 1982). In the typical form of these tasks, a to-be-remembered stimulus (the sample) is presented briefly. The animal then indicates its memory for the sample by choosing a matching stimulus from among subsequently offered alternatives. In identity matching, the correct alternative physically matches the sample. In symbolic matching, the alternatives are learned associates of the samples (e.g., D'Amato & Worsham, 1974; Herman & Thompson, 1982; Roitblat, 1980). For example, a red disk, shown as a sample, may be symbolically represented among the alternatives by an inverted triangle.

With rare exceptions, the stimuli used in matching tests have been limited to the single, dominant sensory modality for the species studied. The reason is straightforward: it has proven extremely difficult to teach any animal a DMTS task when task information is given other than through its presumed major sensory interface with its environment. For the pigeon and nonhuman primate, this has been vision. If both sample and alternatives are visual stimuli (visual-visual, or V-V, matching), DMTS is relatively easy to teach these animals (e.g., D'Amato, 1973;

Roberts & Grant, 1976). If all stimuli are acoustic (auditory-auditory, or A-A, matching), then DMTS can be difficult to teach to monkeys (Stepian & Cordeau, 1960; Thompson, 1980; Worsham & D'Amato, 1973). The source of difficulty would not seem to be a deficiency in auditory peripheral processing, since nonhuman primates have excellent hearing (Fobes & King, 1982). True A-A matching seems not to have been attempted with pigeons (cf. Herman & Forestell, 1986; Kraemer & Roberts, 1984).

Recent work has attempted to describe some of the conditions under which A-A matching can be taught to monkeys (D'Amato & Colombo, 1985; Shyan, Wright, Cook, & Jitsumori, 1987). Not all of the cebus subjects studied by D'Amato and Colombo could carry out the task, but the successful ones were those that had had little or no prior experience with visual tasks. D'Amato and Colombo speculated that prior experience with visual learning retarded the learning of auditory DMTS, presumably because visual training sharply focused attention on visual materials to the exclusion of other modalities. However, this was not the case for the rhesus monkey studied by Shyan et al., as it had had extensive experience with visual materials before encountering an A-A matching task. Shyan et al. used location of a sound and sound intensity as cues to the correct alternative. These cues were gradually eliminated as training progressed. No visual cues were used.

For the bottlenosed dolphin (*Tursiops truncatus*), a species generally considered an auditory specialist, auditory-identity DMTS (Herman, 1975; Herman & Gordon, 1974) and symbolic DMTS (Herman & Thompson, 1982) have

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been trained relatively easily. In these studies, accurate matching was found after delays as long as 2 min and transfer of the matching rule to new problems was shown. Although the dolphin has good vision, both underwater and in air (Herman, Peacock, Yunker, & Madsen, 1975), V-V matching has been difficult to teach. Chun (1978) succeeded in teaching a dolphin simultaneous V-V identity matching using two-dimensional stimuli (the sample and alternative stimuli were exposed at the same time), but extensive, prolonged training was necessary. Also, the dolphin subject failed to demonstrate transfer of the matching rule across successive problems. Chun did not attempt to test for delayed matching.

In a review of cognitive characteristics of dolphins, Herman (1980) briefly summarized the results of a study carried out by the present authors, in which delayed matching of visual materials was shown in a dolphin for the first time. We now report more extensively on the procedures and findings of that study, which addressed a number of current issues in the delayed matching literature, including identity matching, multimodal symbolic matching, delayed matching, coding, and the effects of prior experience with materials from a given sensory modality on later training of DMTS within that modality.

GENERAL METHOD

Subject

The subject was a female bottlenosed dolphin, named Puka, approximately 12 years of age at the time of testing. Puka was the subject in earlier studies of visual acuity (Herman et al., 1975), color discrimination and spectral sensitivity (Madsen, 1976; Madsen & Herman, 1980), and visual discrimination and visual reversal learning (reviewed in Herman, 1980). The visual-acuity study established the ability of this dolphin to resolve visual detail within the general ranges given for many terrestrial carnivores and ungulates. The dolphin, like most nonprimate mammals, is unable to discriminate among different hues (Madsen, 1976).

Puka was housed throughout the earlier and current studies in a 15.2-m-diam open-air tank located at the Kewalo Basin Marine Mammal Laboratory of the University of Hawaii. Light transmissibility through the clear, naturally filtered seawater in the tank averaged 65%, yielding an underwater visibility range for humans of approximately 7 m. Median incident light measurements in the partially shaded testing area were 1,750 lx in air, and 1,500 lx in water (Herman et al., 1975). Thus, underwater and aerial viewing conditions were excellent.

Apparatus and Visual Stimuli

The dolphin was tested in front of a .9-m-wide $\times$.5-m-high underwater viewing window set in the tank wall. All visual stimuli were presented through this window. In front of the window was a stationing area, .75 m wide $\times$ 2 m long, demarcated by a "channel" of three pairs of ropes suspended from two beams extending over the tank wall approximately 1 m above the water surface. When in the stationing area, Puka was located approximately 1 m from the window, a favorable underwater viewing distance for a dolphin (Herman et al., 1975).

Two response paddles, suspended from the projecting beams, reached approximately 30 cm below the surface of the water. The paddles were positioned approximately 1 m apart, one to either side of the underwater window, and 26 cm out from the tank wall. A sideways movement of the paddles activated a circuit to provide acoustic information to the dolphin as to whether or not her response

was correct. A "ready" rod was suspended approximately two-thirds of the way along the stationing area, just above the water surface. A response on the ready rod closed an omnidirectional switch, indicating to the experimenter that the dolphin was prepared for the next trial.

Two visual stimuli, each mounted on 15-cm-high $\times$ 30-cm-wide posterboard, were used as samples and as alternatives. One stimulus was an 8.6-cm-diam white (W) circle centered on black posterboard. The other stimulus was an 8.6-cm-diam black (B) circle centered on white posterboard. Additionally, the white posterboard was bordered at its left and right side by black 7.5-cm-wide trim. Thus, the overall dimensions of the two stimuli were identical, but they could be visually discriminated either on the basis of brightness or form.

The W and B stimuli were presented within a black wooden box affixed to the experimenter's side of the underwater window. The box was divided into an upper and a lower half; the sample stimulus was presented in the middle of the upper half, and the two alternative stimuli, side by side, in the lower half. The stimuli were inserted into Plexiglas holders affixed to tracks that slid in and out of one side of the box. Two independently movable metal shutters, one for each half of the box, prevented the dolphin from viewing the stimuli while they were being changed between trials. The shutters were also used to control the sequence and duration of exposure of the stimuli. A combination of front-lighting by natural light from the open-air tank and artificial lighting in each compartment of the display box illuminated the stimuli when the shutters were raised and provided an excellent underwater view of the stimuli, as judged by human observers. The air interface between the window and the stimuli acted as a barrier to transmission of sound from the tank water, guarding against the use of echolocation cues by the dolphin. Echolocation sounds were not heard from the dolphin during this task.

Control sounds, projected through a University MMPS underwater speaker centrally located above the window, signaled various stages of each trial. These sounds included a "call" tone that initiated each trial, a "release" tone that signaled the dolphin to leave the listening area to make a response on a paddle, and a "reinforcement" tone that sounded after a correct response. Two additional University speakers were located to each side of the central speaker, one adjoining each response paddle. These side speakers projected the sounds that were auditory symbols for the two visual samples. The side speakers could be moved toward the center as desired to reduce their spatial separation. Auditory symbols could also appear at the central speaker, to eliminate spatial cues.

All sounds were produced by computer-controlled programmable waveform generators. In addition to controlling the dedicated waveform generators, the computer determined the temporal and sequential parameters of each trial, according to prearranged schedules, and recorded response data for later analyses.

Procedure

At the beginning of each trial, the call tone (a 280-Hz pure tone) sounded for a maximum of 10 sec. In response, Puka swam into the stationing area and hit the ready rod, turning off the call tone. The experimenter then raised the upper shutter, exposing the sample stimulus. After the predetermined sample display interval, the bottom shutter was lowered to expose the alternative stimuli. Depending upon the particular procedures in effect, the two alternative stimuli could be presented simultaneously with the sample (simultaneous matching) or only after the sample was covered again by its shutter (delayed matching).

After exposure of the alternatives for 4 sec, the release tone (570 Hz pure tone) briefly sounded, signaling Puka to leave the listening area and respond on a paddle. If Puka pressed the paddle adjacent to the alternative that matched the sample for that trial, the reinforcement tone (2.5-kHz pure tone) sounded briefly and the experimenter threw the dolphin a fish reward. If Puka did not

respond to the call tone within 10 sec or if she made an incorrect choice, the channel ropes were raised out of the water, signaling an error, and a 30-sec intertrial interval began. The interval between trials following a correct response was also 30 sec. Trial sequences were designed so that the correct alternative (S+) and the side on which it occurred were determined randomly, with the constraint that the same condition not occur more than three times in succession.

Preliminary Training for Identity V-V Matching

We first attempted to train Puka directly on simultaneous V-V identity matching using a technique modeled after one used successfully to train another dolphin, named Kea, in auditory matching (Herman & Gordon, 1974). In the training procedure used with Puka, a sample stimulus was introduced after she was responding reliably within a two-choice visual reversal-discrimination task. The latter task used the same W and B visual alternatives described earlier, and presented them simultaneously within the lower half of the underwater display window. One alternative was designated S+ and the other S- (incorrect). A given alternative was maintained as S+ until Puka met the criterion of 9 correct responses within 10 successive trials. The S+ and S- values assigned the alternatives were then reversed, and the performance criterion was reinstated. To assist Puka in learning this reversal task, at the start of each reversal, warm-up trials were given during which the S+ stimulus was larger than the S-. The size difference was then reduced gradually over successive trials, by decreasing the size of S+ and increasing that of S-, until both stimuli were of equal size. Once the size difference was eliminated, testing of uncued trials began and was continued until the criterion of 9 of 10 correct responses was met. With these procedures, Puka was given a total of 99 reversals. Reliable discrimination between the W and B alternatives was attainable with warm-up trials present, but Puka had difficulty in maintaining good performance levels if the warm-up trials were deleted for long periods (see Herman, 1980, Figure 8.12). This instability of performance was seen with other types of visual alternatives as well (and with other dolphins) (Herman, 1980).

To train visual matching, we continued with the reversal-learning procedure described, but substituted a W or B sample stimulus as a reversal cue in place of the size-cued warm-up procedure. Correct use of the sample would be evidenced by successful matching each time the sample was changed from its value on the previous trial.

The sample was displayed centered within the upper half of the underwater display window. The sample was changed at the first trial of each new reversal and was maintained at each succeeding trial of that reversal. The introduction of the sample over the training period was gradual, with the duration of its exposure being increased from 1 to 4 sec across successive training sessions. Approximately 1,200 trials were given over a 1-month period, using these procedures. Puka's performance on trials following a change in the sample never rose above chance. She thus failed to use the sample information to guide her responses to the alternatives. Instead, the outcome of the preceding trial—whether or not the prior choice of alternative was rewarded—determined her response on the succeeding trial. In effect, Puka continued to use the win-stay/lose-shift strategy developed during her prior exposure to the reversal-learning task.

An additional attempt was made to train V-V matching directly, this time by using the spatial position of the sample to guide Puka's response. At first, the sample was positioned either directly above the alternative on the left or above the alternative on the right, so that the visual display consisted of two identical figures, one above the other, versus a single figure. With this procedure, Puka was taught in 202 trials to respond, with 90% accuracy, on the side that had two figures. We then attempted to move the sample toward

the center, gradually deleting the spatial cue. Movement of the sample was in ½-in. steps, toward the center, each time Puka responded correctly. An error resulted in movement away from the center, to the previous ½-in. step. Two successive correct responses were then required to resume movement toward the center. Using these criteria, an additional 520 trials were given over nine testing sessions. Small movements of the sample toward the center often resulted in substantial increases in error. Puka's performance declined to a maximum of 78% correct responses as the sample was moved toward the center to 40% of the distance to the final central location. Performance decreased further to 67% and then to 51% correct responses as the sample was moved to 70% of the distance to the central location. At that point, further testing with this procedure was ended.

On the basis of these failures to teach V-V identity matching directly, we decided to abandon purely visually based procedures in favor of an auditory-based cuing procedure that might make the relationship between the visual sample and the visual alternatives more apparent.

EXPERIMENT 1

The same W and B visual samples employed during preliminary training were used throughout Experiment 1, but were now paired with spatial and nonspatial auditory cues. The nonspatial cues were two different sounds, each mapped onto one visual sample. The spatial cues were the location of the sounds. In Part A, we trained Puka to respond to the location of the sound cue. This spatial cue was then removed, and control of responding was transferred to the auditory-visual compound samples. In Part B, we tested the relative importance of the visual and auditory sample elements by varying the duration of one while holding the other constant. In Part C, we changed the matching task from a simultaneous to a successive procedure, and performance was tested using each of the sample elements alone.

Part A

Procedure

The B visual stimulus was paired with a 4-kHz sine-wave modulated tone, and the W stimulus was paired with a 9-kHz pure tone. The pairing, in effect, produced compound visual-auditory samples. Initially, the 4- or 9-kHz sound was projected through one or the other of the two side speakers adjacent to the underwater window. This served as a spatial cue to direct Puka to the appropriate response paddle. Later, the sound appeared at the center speaker, eliminating the spatial cue while retaining the cue based on sound-quality. The control sounds (call tone, release tone, and reinforcement tone) continued to be played through the center speaker.

Training. Training for use of the spatial cue occurred in four steps. (1) Puka was trained to respond to the paddle adjoining the speaker broadcasting a sound cue. Neither the visual sample nor its alternatives were present. (2) The sound cue was presented together with exposure of the visual sample and its alternatives. The sound cue associated with the particular sample displayed was played through the speaker adjoining the S+ (matching) alternative. A response to the correct paddle resulted in the reinforcement tone; no sound was heard after an incorrect response. The S+ and the side on which it occurred varied from trial to trial according to a preplanned, balanced schedule of trials. (3) After three consecutive sessions with performance above 90% correct, the duration of the auditory cue was reduced in small steps from its previ-

ous value of 4 sec to only 2 sec. (4) The separation between the two speakers was reduced by moving them closer together, symmetrically, toward the center speaker, until they were only 35 cm apart. Throughout Steps 2 to 4, the visual sample and its alternatives continued to be exposed for 4 sec before the release tone sounded. Puka's performance remained nearly errorless throughout these four steps, since she continued to be guided by the spatial cue.

Testing. To test for control of responding by the nonspatial auditory elements, Puka's performance when the spatial cue was present was compared with her performance when it was absent. Blocks of trials in which the auditory element was played through a side speaker (spatial cue present) were alternated with blocks in which it was played through the center speaker (spatial cue absent). Within each block, W and B occurred as sample in a random, balanced sequence. The duration of the associated auditory cue was increased to 5 sec from the 2-sec value used in training in order to enhance the saliency of sound quality when the spatial cue was absent.

The temporal events for each trial are depicted in the lower portion of Figure 1. The visual sample element and its associated auditory element were presented simultaneously, although the visual element remained exposed for an additional 2 sec after the auditory element had ended (for a total of 7 sec, until the release tone sounded). The visual alternatives first appeared after 3 sec of exposure of the compound visual-auditory sample and remained exposed until Puka pressed one of the response paddles.

Results and Discussion

Testing took place during 11 sessions over a 5-day period. The upper portion of Figure 1 contrasts performance on 289 trials when the spatial cue was present with 337 trials when it was absent. Overall, performance was significantly better in the presence of the spatial cue (91.3% correct responses) than in its absence (81.3% correct) [$F(1,616) = 13.4, p < .05$]. Nevertheless, performance was still well above chance in the absence of the

spatial cue. Although the overall effect across successive days of testing was not significant, there was a significant interaction of days and cue conditions [$F(4,616) = 3.0, p < .05$]. Performance in the absence of the spatial cue improved significantly across days [$F(4,616) = 2.4, p < .05$], but performance on spatially cued trials did not. Clearly, the compound auditory-visual sample was effective in guiding Puka to the correct visual alternative in the absence of a spatial cue. It remained unclear, however, whether Puka was responding principally to the compound sample or to one or the other of the sample elements.

Part B

We tested the relative importance of the auditory and visual elements of the compound sample stimulus by alternately reducing one element in duration while holding the other constant. First, sessions were run in which the duration of the auditory element was reduced while the visual element was held constant. Then the visual element was reduced in duration while the auditory element was held constant. Changes in sample duration have been found to influence matching performance in pigeons (Maki & Leith, 1973; Nelson & Wasserman, 1978; Roitblat, 1980), monkeys (Devine, Jones, Neville, & Sakai, 1977; Herzog, Grant, & Roberts, 1977), and dolphins (Herman & Gordon, 1974).

Procedure

Figure 2A (inset) shows that the auditory element of the sample was reduced from the 5-sec duration used in Part A to 4.5, 4.0, and 3.5 sec, while the visual element was maintained at 7 sec. Figure 2B (inset) shows that the visual element was then reduced from 7 sec to 6.5, 6.0, 5.5, and 5.0 sec, while the auditory ele-

Figure 1. The percentage of correct responses in Experiment 1A over successive days of testing, as a function of the presence of a spatial cue for the auditory element of the sample (open circles) or the absence of a spatial cue (closed circles). The inset shows the onsets and durations of the auditory and visual sample elements and of the visual alternatives. The release tone sounded 7 sec after exposure of the elements began.

ment was held constant at 5 sec. Note that for both Figure 2A and Figure 2B the remaining time parameters were unchanged from the values used in Part A of this experiment.

Durations of sample elements were reduced across sessions or blocks of sessions, depending upon performance. To prevent a high error rate that might interfere with the dolphin's willingness to participate (see Herman & Gordon, 1974), we occasionally increased the duration across sessions before again resuming attempts to reduce duration. Blocks of trials with the spatial cue present continued to be alternated with blocks without a spatial cue, as in Part A.

Results and Discussion

Figure 2A shows that as the duration of the auditory element was reduced, performance tended to decrease.

The data in Figure 2A are based on 507 trials, 299 with the spatial cue present and 208 with it absent, given during 11 sessions over 4 successive days. Overall, performance was very similar across the two cuing conditions: 83.3% correct responses with the spatial cue present and 83.7% with it absent. With the sample elements at the same durations as in the testing phase of Part A (i.e., 5 sec for the auditory element and 7 sec for the visual element), performance was approximately 95% correct for each cuing condition. Performance declined to 75% correct with the spatial cue present and 63% correct with the spatial cue absent when the auditory element was present for only 3.5 sec. The overall decline in performance

Figure 2. The percentage of correct responses in Experiment 1B as a function of the duration of the auditory and visual sample elements. In Figure 2A, the duration of the visual element is held constant while the duration of the auditory element is varied. In Figure 2B, the auditory element is held constant while the visual element is varied. The insets give the time parameters for the stimulus events occurring. The dotted lines for the auditory or visual sample elements indicate the various durations of that element; other parameters are as in Figure 1. Open circles, auditory spatial cue present; closed circles, auditory spatial cue absent.

across all four durations was significant [$F(3,499) = 6.19$, $p < .05$].

The duration of the visual element of the sample was reduced during 402 trials run in 14 sessions over a 6-day period. Figure 2B shows an approximate overall 10% decline in performance level over the first three reductions in duration, followed by improvement and then a marked increase in performance to 100% correct responses at the shortest duration of visual-element exposure. At that point, both the visual and auditory elements were of the same 5-sec duration. Despite the sudden increase in performance, the overall differences in duration of the visual element did not produce significant changes in performance [$F(4,392) = 1.92$, $p > .05$], nor was the effect of cue condition or the interaction significant.

The results indicated that during Part B the spatial cue no longer contributed significantly to accurate performance. The nonspatial elements effectively controlled Puka's responses, but two findings suggested that the auditory element played the more important role. First, decreases in duration of the auditory element significantly decreased performance, even though the visual element continued to be presented together with the visual alternatives through to the end of the trial. Second, the reduction in the duration of the visual element did not result in a significant reduction in performance (Figure 2B). To a large degree, then, Puka must have been carrying out a symbolic A-V matching task, using the auditory element of the sample to select the correct visual alternative.

Part C

The simultaneous matching task was next transformed into a zero-delay successive matching task, by gradually decreasing the temporal overlap between the sample and the alternatives. Performance was then tested when the auditory and visual elements of the sample were presented together and when each element was presented alone. This allowed a comparison of A-V with V-V matching, as well as a comparison of single-element matching with compound-element matching.

Procedure

We continued to use blocks of trials with the spatial cue present and blocks with it absent but greatly reduced the number of spatially cued trials relative to uncued trials. Spatially cued trials were run to a criterion of at least 7 correct responses in a block of 8 trials. After this criterion was reached, 20 uncued trials were given. If 3 errors were made before the 20 trials were complete, the cued condition was reinstated. This procedure, like those described earlier, guarded against excessive errors that might lead to emotional responding and refusal to continue testing.

Continuing with the final temporal parameters of Part B (Figure 2B), we reduced the durations of both the visual and auditory elements of the sample gradually from their initial value of 5 sec to a final value of 3 sec (Figure 3, inset). At the 3-sec value, both elements terminated coincidentally with the onset of exposure of the visual alternatives, creating a zero-delay matching problem. The visual alternatives continued to be displayed for 4 sec before the release tone sounded.

Once zero-delayed matching was attained, testing for matching using the auditory and visual elements alone was begun, using the final temporal-duration values shown in Figure 3. Either the compound sample or one of the individual elements was presented for 3 sec, and then removed just before the visual alternatives were exposed. Within each session, blocks of four compound trials were alternated with either two visual-element or two auditory-element trials. Visual- and auditory-element trials were never presented within the same session, but their occurrence was counterbalanced across sessions.

Results and Discussion

The transition from simultaneous matching to zero-delayed matching took place in 17 sessions over a 5-day period, and consisted of a total of 504 trials. Figure 3 shows that performance was maintained at approximately 90% correct as the duration of the sample elements decreased—and as the overlap between the sample and the exposure of the alternatives was deleted. The slight improvement in performance across the four blocks of sample-duration values was not significant [$F(3,496) = .53$, $p > .05$]. No difference was found between spatially cued and spatially uncued trials, nor was the interaction between cue condition and sample duration significant.

The left-hand portion of Figure 4 contrasts performance with the visual element alone with performance with the compound sample, for sessions restricted to that contrast. The right-hand half of Figure 4 presents a similar contrast for the auditory element. Performance across the four conditions differed significantly [$F(3,283) = 10.99$, $p < .001$]. However, performance with the compound sample was very similar across both contrasts: 98% accuracy during mixed sessions with the visual element and 95% accuracy during mixed sessions with the auditory element. Also, performance with the visual element alone (76.6% correct responses) was almost identical to that with the auditory element alone (76.0% correct). Although the compound sample resulted in superior performance, either sample element alone could now be used effectively by Puka to solve the matching task.

EXPERIMENT 2

To test for memory of the sample, the delay between presentation of the sample and exposure of the alternatives was increased during Experiment 2. This permitted the first assessment of a dolphin's responses on a delayed matching task when the sample information was limited to the visual mode. During Part A, the auditory cue was used at each session during "warm-up" trials and then deleted during subsequent test trials. The warm-up trials were deleted for Part B, and all trials consisted of the visual element of the sample alone.

Part A

Procedure

In general, the procedures of Experiment 1, Part C, were followed, except that a delay of 1 sec or more was inserted between offset of the visual sample and exposure of the alternatives. Ses-

Figure 3. The percentage of correct responses in Experiment 1C as a function of the duration of the auditory and visual sample elements. Both the visual and the auditory elements were reduced in duration, as shown. The inset for the time parameters is as in previous figures, with dotted lines indicating the various durations of the sample elements. Open circles, auditory spatial cue present; closed circles, auditory spatial cue absent.

sions consisted of a warm-up block of spatially cued trials, using the compound auditory-visual sample, followed by a test block using the visual element alone. Within a session, the same delay value was used for warm-up and test blocks, and that delay was maintained throughout the session.

Warm-up trials were run to a criterion of at least 7 correct responses in a block of 8 trials. If the criterion was not met in 16 trials, the test block was not given and the warm-up trials were reinstated at the next session. The test block, when given, consisted of 20 successive trials during which the visual element, alone, was presented for a total of 3 sec and then removed. After the prescribed delay, the visual alternatives were exposed.

There were four sessions each day, with at least 1 h between sessions. Beginning with a 1-sec delay, increases in the delay interval were in 1-sec steps to 10 sec, in 2-sec steps to 18 sec, and in 4-sec steps to 34 sec, the longest delay tested. The delay value was increased at the succeeding session each time Puka met a criterion of at least 17 correct trials during the total of 20 test trials. Testing continued in this manner until Puka failed to meet this criterion for four sessions in a row. At this point, the testing series ended, the delay was reduced to 1 sec, and a replication was begun. With this procedure, an initial test and three replications (four series of tests) were completed, all using warm-up trials followed by test trials.

Results and Discussion

Figure 5 (open circles) summarizes performance during test trials as a function of delay, for the combined data from the series of tests. Each data point is based on a minimum of 40 trials. Performance remained at nearly 80% correct responses or better through to delays of 26 sec, and then decreased abruptly. During the first test series, at delays of 3 to 5 sec, Puka appeared unwilling to respond following increases in the delay interval. A brief series of retraining sessions were carried out, after which testing resumed. Thereafter, Puka was able to reach criterion on the test

trials at every delay length up to 34 sec. After failing to reach criterion at 34 sec, the delay was reduced to 1 sec, and Replication 1 was begun. Puka failed to meet criterion at 30 sec during this second series, then failed at 16 sec during Replication 2 and at 22 sec during Replication 3.¹ The major limitation on testing the longer delays appeared to be Puka's unwillingness to begin a new trial after experiencing an error at a long delay on the previous trial. Over the four series of tests, Puka's tolerance of these errors tended to decrease, resulting in her aborting the testing relatively earlier at later replications.

Figure 4. The percentage of correct responses in Experiment 1C for single-element trials (visual or auditory) and for compound sample trials (visual and auditory elements both present).

Figure 5. The percentage of correct responses in Experiment 2 as a function of the delay between removal of the visual sample (auditory element not present) and exposure of the two visual alternatives. Open circles: Visual sample trials preceded by "warm-up" trials with auditory spatial cue present (Part A). Closed circles: Visual sample trials given directly without warm-up (Part B).

Part B

Part B immediately followed the completion of Part A. The warm-up trials were deleted entirely. Each session consisted of 20 test trials of the visual sample element alone. Otherwise, all of the remaining conditions of Part A were maintained.

Results and Discussion

Four series of tests were completed during Part B. The first series was carried through to only a 9-sec delay. The remaining three replications were terminated after delays of 22, 14, and 16 sec, respectively.

The overall results are shown in Figure 5 (closed circles), where they may be compared with the results of Part A, in which the warm-up trials were present. Performance remained at 85% correct or better through to the 8-sec delay and then generally paralleled the decline seen with warm-up trials present, but with a loss of roughly 10 percentage points. There was a "blip" in performance at the 18-sec delay, similar to the blip noted at 26-sec delay with the warm-up trials present. Overall, Puka gave 85.2% correct responses (of a total of 1,374 trials) in Part B and 86.3% correct responses during Part A (1,911 total trials). As in Part A, Puka at times refused to continue responding after making an error at a long delay.

GENERAL DISCUSSION

The initial results showed that when the stimuli were limited to simple two-dimensional visual materials, the dolphin was unable to solve the matching problem, at least within the limits of the procedures applied. This constraint was in keeping with findings from a variety of studies in

which dolphins have shown difficulty in using these kinds of visual stimuli as input in a variety of complex learning tasks (Beach & Pepper, 1973; Chun, 1978; Herman, 1980; Herman, Beach, Pepper, & Stalling, 1969; Mobley, 1984; Spong & White, 1971). Herman et al.'s (1975) findings, which evidenced Puka's good visual resolution capabilities, indicate that the limitations with these types of materials are not traceable to an inability to resolve fine visual detail. The matching problem itself is not the likely bottleneck, since a variety of types of auditory matching problems, including matching from among multiple samples provided in list form, are relatively easily mastered by the dolphin (Herman & Gordon, 1974; Herman, 1975, 1980; Herman & Thompson, 1982; Thompson & Herman, 1977).

Experiment 1 demonstrated a procedure for releasing the observed constraint on visual matching through the use of auditory associates for the visual materials. Each of the two visual samples was paired with a unique sound, which first led to A-V symbolic matching and, after deletion of the sound cues, to apparent V-V identity matching. While evidence of simultaneous V-V matching in a dolphin was also reported by Chun (1978), Experiment 2 established, for the first time, the dolphin's ability for delayed V-V matching, over retention intervals as long as 34 sec. The limits in Puka's delayed-matching performance were often emotionally based, in that she at times refused to respond further after experiencing an error at a long delay. This was the same behavioral characteristic noted in studies of auditory delayed matching with the dolphin Kea (e.g., Herman & Gordon, 1974). Chun's dolphin solved the visual matching problem only after extensive training and was not able to transfer the matching rule to new visual materials. The loss of Puka shortly af-

ter the conclusion of Experiment 2 precluded our testing for transfer of the matching rule to new visual materials.

The results of Experiment 1 indicated that Puka's matching performance developed from the learned association between each sound sample and its corresponding visual alternative. Reducing the duration of the auditory sample element while maintaining the visual element at a constant duration resulted in decreased levels of performance. This suggests that the visual element was largely ignored in favor of the auditory element. Experiments with pigeons (Grant, 1976) and monkeys (Herzog et al., 1977) have shown that decreased presentation time of the (visual) sample results in decreased levels of performance. When monkeys (but not pigeons) are given extensive experience with short sample durations, the deleterious effect of decreasing durations can be eventually overcome. The latter was also true for the dolphin Kea, who, after some experience with increasingly shorter auditory sample durations, was able to perform highly accurate A-A matching with sample durations of only 3 msec (Herman, 1980, Figure 8.5). Puka, in contrast, had no long-term experience with decreasing sample durations. That her performance did suffer from the decreased duration of the auditory element but not from a reduction in the duration of the visual element is evidence of her initial reliance on auditory codes for performing the matching task.

Puka's performance on single-element trials indicates that eventually the visual sample element as well as the auditory element became effective in controlling responses. That performance decreased equivalently when either element was tested alone, as compared with performance with the compound, showed that both elements contributed approximately equivalently to performance. This had not been apparent earlier, when simultaneous procedures were in effect. At that stage of testing, the auditory element was prepotent.

The finding that performance with a compound was superior to performance with an element is in keeping with findings of Grant and MacDonald (1986) in a study of matching to element and compound samples in pigeons. These authors concluded that the decrement in performance resulting from the use of single-element samples following training on compound samples was due to the failure of either element of the compound to activate the code associated with the compound itself. Our results do not bear directly on Grant and MacDonald's theoretical position, but do suggest that unless the elements of the compound begin and end together, the elements may not be compounded. Instead, one or the other may gain primary control of responding, as did the auditory element in our case. Control by an element may be shifted to control by a compound, under procedures such as those used by us; later, both elements, as well as the compound, can come to control responding.

A related, coding issue is whether the representation of the sample element necessarily reflects the sensory modality through which the element arrives. Some investi-

gators have suggested or implied that isomorphism of modality and code may be involved (D'Amato & Colombo, 1985; Kraemer & Roberts, 1984; Roberts & Grant, 1976). However, a code may be an amodal representation, such as a response instruction in prospectively encoded tasks (Honig & Thompson, 1982; Roitblat, 1984), or some stimulus-based transformation that does not preserve modality information in retrospectively encoded tasks (Herman & Forestell, 1986). While it is clear that the auditory cuing of the visual stimuli was responsible for overcoming Puka's apparent inability to readily learn matching using two-dimensional visual stimuli, the exact nature of the facilitative effect remains unclear. D'Amato and Colombo (1985) have suggested that, in monkeys, prior experience with visual stimuli interferes with learning auditory matching, but this was not confirmed by Shyan et al. (1987). Also, in the present study, extensive prior visual experience coupled with little prior experience with auditory materials did not facilitate visual matching in the dolphin (also see Chun, 1978; Mobley, 1984). It appears that Puka's initial matching difficulty was overcome through representation of the visual materials by auditory codes as a result of the temporal association of the visual materials with distinctive auditory stimuli. In effect, this would have allowed for processing of the recoded visual stimuli through the highly developed auditory system. Puka's later ability to perform delayed matching in the absence of the auditory element, using the visual element alone, suggests that a visual code may have eventually developed. We cannot be sure that such development took place, and if so, that it was generalizable, since this would have required further testing of new visual materials without the use of auditory "crutches." In general, our results underscore the idea that although animals may exhibit predispositions to gather information from the environment through "primary" sensory modalities, the nonisomorphic nature of representations (Herman & Forestell, 1986; Roitblat, 1984) can eventually permit a wider utilization of available information-processing systems than might normally occur.

During delayed matching, the interval over which Puka was able to remember the visual element alone, or the auditory element alone, was shorter than that observed in the dolphin Kea, who was given purely auditory (A-A) DMTS tasks (e.g., Herman & Thompson, 1982). A similar asymmetry in A-A versus V-V matching, but in the reverse direction (V-V superior), has been reported for monkeys (Colombo & D'Amato, 1986). At the same time, however, achieving delayed visual matching at any interval with a dolphin was a notable accomplishment, given the original intractability of the problem both in prior studies and in the present work.

REFERENCES

- BEACH, F. A., III, & PEPPER, R. L. (1973). *Conditioned differential vocalization in a position and shape discrimination task with the dolphin* (Report NUC TN996, March). San Diego: Naval Undersea Center.

- CHUN, N. K. W. (1978). *Aerial visual shape discrimination and matching-to-sample problem solving ability of an Atlantic bottlenosed dolphin* (Report NOSC TR236, May). San Diego: Naval Ocean Systems Center.
- COLOMBO, M., & D'AMATO, M. R. (1986). A comparison of visual and auditory short-term memory in monkeys (*Cebus apella*). *Quarterly Journal of Experimental Psychology*, **38B**, 425-448.
- D'AMATO, M. R. (1973). Delayed matching and short-term memory in monkeys. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 7, pp. 227-269). New York: Academic Press.
- D'AMATO, M. R., & COLOMBO, M. (1985). Auditory matching-to-sample in monkeys (*Cebus apella*). *Animal Learning & Behavior*, **13**, 375-382.
- D'AMATO, M. R., & WORSHAM, R. W. (1974). Retrieval cues and short-term memory in capuchin monkeys. *Journal of Comparative & Physiological Psychology*, **86**, 274-282.
- DEVINE, J. V., JONES, L. C., NEVILLE, J. W., & SAKAI, D. J. (1977). Sample duration and type of stimuli in delayed matching-to-sample in rhesus monkeys. *Animal Learning & Behavior*, **5**, 57-62.
- FOBES, J. L., & KING, J. E. (1982). Auditory and chemoreceptive sensitivity in primates. In J. L. Fobes & S. E. King (Eds.), *Primate behavior* (pp. 245-270). New York: Academic Press.
- GRANT, D. S. (1976). Effect of sample presentation time on long-delay matching in the pigeon. *Learning & Motivation*, **7**, 580-590.
- GRANT, D. S., & MACDONALD, S. E. (1986). Matching to element and compound samples in pigeons: The role of sample coding. *Journal of Experimental Psychology*, **12**, 160-171.
- HERMAN, L. M. (1975). Interference and auditory short-term memory in the bottlenosed dolphin. *Animal Learning & Behavior*, **3**, 43-48.
- HERMAN, L. M. (1980). Cognitive characteristics of dolphins. In L. M. Herman (Ed.), *Cetacean behavior: Mechanisms and functions* (pp. 363-429). New York: Wiley.
- HERMAN, L. M., BEACH, F. A., III, PEPPER, R. L., & STALLING, R. B. (1969). Learning-set formation in the bottlenose dolphin. *Psychonomic Science*, **14**, 98-99.
- HERMAN, L. M., & FORESTELL, P. H. (1986). Short-term memory in pigeons: Modality-specific or code-specific effects? *Animal Learning & Behavior*, **13**, 463-465.
- HERMAN, L. M., & GORDON, J. A. (1974). Auditory delayed matching in the bottlenosed dolphin. *Journal of the Experimental Analysis of Behavior*, **21**, 19-26.
- HERMAN, L. M., PEACOCK, M. F., YUNKER, M. P., & MADSEN, C. (1975). Bottlenosed dolphin: Double-slit pupil yields equivalent aerial and underwater acuity. *Science*, **139**, 650-652.
- HERMAN, L. M., & THOMPSON, R. K. R. (1982). Symbolic, identity, and probe delayed matching of sounds in the bottlenosed dolphin. *Animal Learning & Behavior*, **10**, 22-34.
- HERZOG, H. L., GRANT, D. S., & ROBERTS, W. A. (1977). Effects of sample duration and spaced repetition upon delayed matching-to-sample in monkeys (*Macaca arctoides* and *Saimiri sciureus*). *Animal Learning & Behavior*, **5**, 347-354.
- HONIG, W. K., & THOMPSON, R. K. R. (1982). Retrospective and prospective processing in animal working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 16, pp. 1-69). New York: Academic Press.
- KRAEMER, P. J., & ROBERTS, W. A. (1984). Short-term memory for visual and auditory stimuli in pigeons. *Animal Learning & Behavior*, **12**, 275-284.
- MADSEN, C. J. (1976). *Tests for color discrimination and spectral sensitivity in the bottlenosed dolphin*, *Tursiops truncatus*. Unpublished doctoral dissertation, University of Hawaii.
- MADSEN, C. J., & HERMAN, L. M. (1980). Social and ecological correlates of cetacean vision and visual appearance. In L. M. Herman (Ed.), *Cetacean behavior: Mechanisms and functions* (pp. 101-147). New York: Wiley.
- MAKI, W. S., JR., & LEITH, C. R. (1973). Shared attention in pigeons. *Journal of the Experimental Analysis of Behavior*, **19**, 345-349.
- MOBLEY, J. R., JR. (1984). *Visual discrimination of relative distance by a bottlenosed dolphin (Tursiops truncatus): Evidence for relational learning*. Unpublished doctoral dissertation, University of Hawaii.
- NELSON, K. R., & WASSERMAN, E. A. (1978). Temporal factors influencing the pigeon's successive matching-to-sample performance: Sample duration, intertrial interval, and retention interval. *Journal of the Experimental Analysis of Behavior*, **30**, 153-162.
- ROBERTS, W. A., & GRANT, D. S. (1976). Studies of short-term memory in the pigeon using the delayed match to sample procedure. In D. L. Medin, W. A. Roberts, & R. T. Davis (Eds.), *Processes of animal memory* (pp. 79-112). Hillsdale, NJ: Erlbaum.
- ROITBLAT, H. L. (1980). Codes and coding processes in pigeon short-term memory. *Animal Learning & Behavior*, **8**, 341-351.
- ROITBLAT, H. L. (1982). The meaning of representation in animal memory. *Behavioral & Brain Sciences*, **5**, 353-406.
- ROITBLAT, H. L. (1984). Representations in pigeon working memory. In H. L. Roitblat, T. G. Bever, & H. S. Terrace (Eds.), *Animal cognition* (pp. 79-97). Hillsdale, NJ: Erlbaum.
- SHYAN, M. R., WRIGHT, A. A., COOK, R. G., & JITSUMORI, M. (1987). Acquisition of the auditory same-different task in a rhesus monkey. *Bulletin of the Psychonomic Society*, **25**, 1-4.
- SPONG, P., & WHITE, D. (1971). Visual acuity and discrimination learning in the dolphin (*Lagenorhynchus obliquidens*). *Experimental Neurology*, **31**, 431-436.
- STEPHAN, L. S., & CORDEAU, J. P. (1960). Memory in monkeys for compound stimuli. *American Journal of Psychology*, **73**, 388-395.
- THOMPSON, R. K. R. (1980, July). *Auditory cued reversal and matching-to-sample learning by rhesus monkeys*. Paper presented at the Eighth International Congress of Primatology, Florence, Italy.
- THOMPSON, R. K. R., & HERMAN, L. M. (1977). Memory for lists of sounds by the bottlenosed dolphin: Convergence of memory processes with humans? *Science*, **195**, 501-503.
- WORSHAM, R. W., & D'AMATO, M. R. (1973). Ambient light, white noise, and monkey vocalization as sources of interference in visual short-term memory in monkeys. *Journal of Experimental Psychology*, **99**, 99-105.

NOTE

1. Replication 2 was inadvertently omitted from the data published previously in Figure 8.9 of Herman (1980).

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