

Transitive Inference Formation in Pigeons

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Pigeons were trained with 4 pairs of visual stimuli in a 5-term series— $A+ B-$, $B+ C-$, $C+ D-$, and $D+ E-$ (in which plus [+] *denotes reward and minus [-] denotes nonreward)—before the unreinforced test pair B D was presented. All pigeons chose Item B, demonstrating inferential choice. A novel theory (value transfer theory), based on reinforcement mechanisms, is proposed. In Experiment 2, the series was extended to 7 terms. Performance on test pairs was transitive, and performance on training pairs accorded with the theory. The 7-term series was closed in Experiment 3 by training the first and last items together. In accordance with the theory, the Ss could not solve the circular series. The authors suggest that primates, including humans, also solve these problems using the value transfer mechanism, without resorting to the symbolic processes usually assumed.*

Transitive inference denotes the ability to infer relationships between items that have not been trained together. In a transitive-inference task, a subject is given information about some of the relationships between items. This piecemeal information is sufficient to deduce an implied series of the items and thus the relationships between all items. A competent subject performs an operation equivalent to ranking the items, thus allowing direct derivations of relationships between any pair of items selected from the series.

This task has been traditionally presented verbally (Piaget, 1928):

1. Edith is fairer than Suzanne.
2. Edith is darker than Lili.
3. Who is the darkest, Edith, Suzanne, or Lili?

Here the competent subject concludes that Suzanne is the darkest, although no direct information about the relationship between Lili and Suzanne was given. In this purely linguistic

Juan D. Delius and Lorenzo von Fersen were supported by the Deutsche Forschungsgemeinschaft, Bonn; C. D. L. Wynne was supported by the Science and Engineering Research Council, London, and the Alexander von Humboldt-Stiftung, Bonn; and J. E. R. Staddon was supported by the National Science Foundation and the Alexander von Humboldt-Stiftung.

We thank W. Mathäus for initial motivation, F. von Münchow-Pohl for assistance in programming, and A. Lohmann for help in running the experiments. We are grateful to A. Elepfandt, B. McGonigle, J. Pearce, H. Terrace, and T. Trabasso for helpful comments on drafts of this article.

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format, transitive inference is a competence that necessarily pertains only to the human species. Piaget found that only children over about 7 years of age could consistently solve such syllogisms (Piaget, 1928, 1955).

For Piaget (1928, 1955), transitivity is not just successful performance on the task considered here, but covers a range of seriation and coordination tasks that, taken together, demonstrate a subject's competence in handling transitive relations. Here we concentrate on a task derived from Piaget's seriation problems, known as the *n*-term series task.

The five-term series problem was developed by Bryant and Trabasso (1971). In a reanalysis of Piaget's results, they considered the possibility that the failure of small children to infer correctly on syllogistic problems could be due to memory limitations. Bryant and Trabasso trained young children with pairs of rods of varying colors and lengths. In the critical condition, the children were taught to label the rods as *bigger* or *smaller* depending only on how they were paired. The subjects could not see the lengths of the rods. The yellow rod might thus be labeled *bigger* than red on a given trial, red labeled *bigger* than blue on another trial, and so on. Five lengths were used (termed *A*, *B*, *C*, *D*, and *E*) to control for end effects. End effects occur with the first and last items in a series, because they can be uniquely labeled (always *big* or always *small*). Responding on the four pairs was shaped through auditory feedback until subjects were responding at a high level. Finally nonreinforced test trials were introduced with Rods B and D. These rods had never before been presented together and, in training, had been equally often labeled *bigger* and *smaller* than the rods with which they appeared. All subjects, including the youngest (4-year-olds), correctly identified Rod B as longer than Rod D, thus demonstrating their ability to form transitive inferences.

Bryant and Trabasso's (1971) method for small children was adapted by McGonigle and Chalmers (1977) for squirrel monkey subjects. By the use of colored tin containers that

were selectively reinforced in pairs, McGonigle and Chalmers were able to show that these animals can also form transitive inferences. Pairs of different colored containers were reinforced according to the following plan (in which plus [+] identifies reward and minus [-] identifies nonreward): $A+B-$, $B+C-$, $C+D-$, and $D+E-$. The four training pairs were presented in randomized order. Unreinforced tests were then conducted with the stimuli B and D. Choice of the B container on these tests demonstrated that the squirrel monkeys had correctly inferred the series $A-E$. Using a similar procedure, Gillan (1981) has also shown that chimpanzees behave according to transitive inference rules.

Because the value of an object in the natural world is a function of its relation to other concurrently available alternatives, the ability to rank objects on a hedonic scale and make judgments about the desirability of items that have never before been encountered together must often have adaptive value. For example, the ability of a social animal to rank a newcomer relative to itself by observing the newcomer's performance in relation to other individuals may often be advantageous. A clearer understanding of how animals avoid the computational explosions latent in ordering problems could also aid in the programming of artificial reasoning systems.

The aim of this study was to demonstrate that the ability to form transitive inferences is not limited to primates, but is also found in the domestic pigeon. We suggest that these birds solve the task on the basis of a simple learning mechanism and that the behavior of monkeys and children may also be controlled according to this principle. Experiment 1 tests the ability of pigeon subjects to solve a five-term series. Experiments 2 and 3 test a novel theory of transitive performance.

Experiment 1: Five-Term Series

The aim of Experiment 1 was to test the ability of pigeons to infer the relationship between two stimuli (B and D) when trained on a series of overlapping arbitrary stimulus pairs as described above.

Method

Subjects. Six experimentally naive pigeons (*Columba livia*) of local stock, maintained at 80% of their free-feeding weights, served as subjects. They were housed in single cages maintained at 18 °C with a 14-hr light/10-hr dark cycle.

Apparatus. The locally constructed operant chamber (internal dimensions 33 × 34 × 33 cm) contained an opening (11 cm [high] × 12 cm [wide]), with an enclosed horizontal work surface (12 × 9 cm) set into its back wall 5 cm above the floor (see Figure 1). This work surface contained two translucent response keys, 2.2 cm in diameter centrally placed and separated 9 cm (center to center) from each other. Food reward (millet grains) was delivered 1 cm from each key through feeders on the roof of the external enclosure. A reward light was positioned in the ceiling of the enclosure, and background illumination was provided by a houselight in the back wall, 5 cm above the top border of the enclosure.

Five different, equally sized (diameter approximately 1 cm on the pecking keys), arbitrarily shaped, white-on-black stimuli (labeled here A , B , C , D , and E) could be projected onto the keys with a modified Kodak Carousel S-AV 2010, 35-mm slide projector and a system of

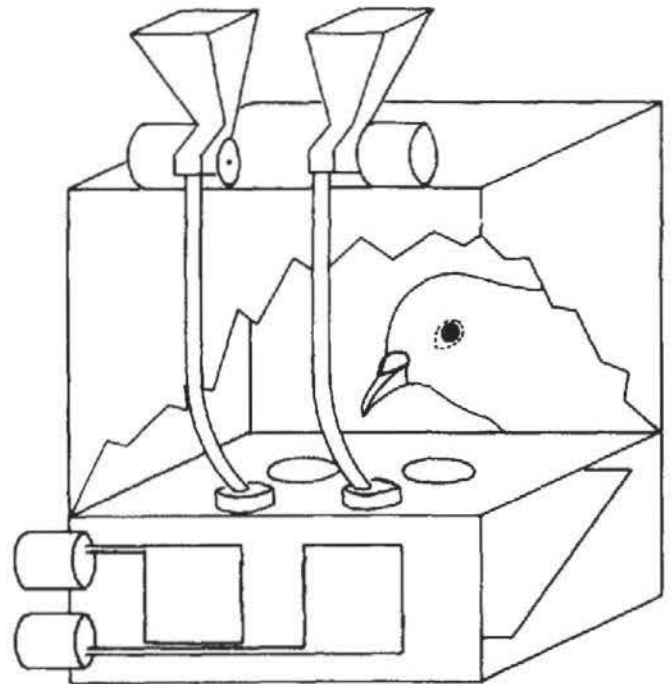


Figure 1. Rear panel attached to the modified Skinner box used in all experiments.

mirrors and shutters. Pairs of stimuli were fixed to modified slide frames containing coding holes, which were read by photocells connected to the experiment-controlling computer (Commodore VIC-20). Stimuli are included in Figure 2.

Procedure. In successive trials, the five stimuli were presented in four pairs. One of the stimuli of each pair was designated positive (rewarded, plus [+]), the other negative (nonrewarded, minus [-]), according to the basic scheme $A+B-$, $B+C-$, $C+D-$, and $D+E-$. This arrangement implies a sequence from $A+$ to $E-$. Correct choices were rewarded with four to six grains of millet and were followed after the 4-s intertrial interval by the next trial. Incorrect choices led

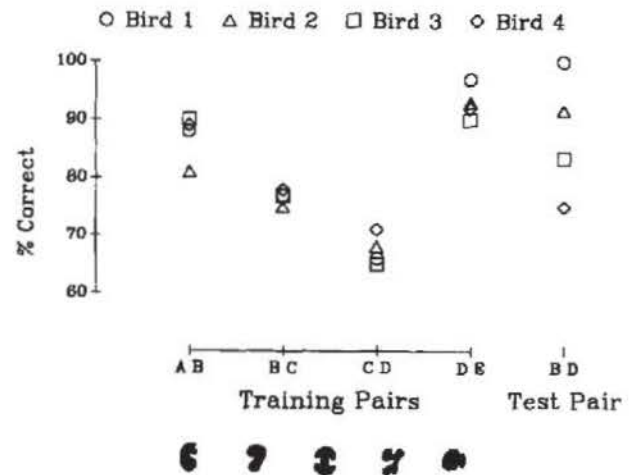


Figure 2. Mean percentage responses during the last 10 sessions of training to the rewarded stimulus of training pairs, as a function of the position of a stimulus pair in the five-item transitivity series. (Also mean percentage correct responses to Inference Test Pair $B D$. Each set of points is 1 pigeon. Inset shows the stimuli used.)

to a 5-s blackout and were followed after the same intertrial interval by a repeat of the same trial (correction trial). Correction trials repeated until a correct choice was made. To control for any spontaneous shape preferences, half the subjects were trained with the series from A+ to E-, and the other half were trained with the reverse series from E+ to A-. These two treatments did not yield significant performance differences at any stage of the experiment, and thus the results were pooled and are all presented here according to the terminology of the series from A+ to E-.

After standard autoshaping with uniformly colored stimuli, training sessions started in which the negative item was darkened with a gray filter (fading in). During this first phase of training (15 sessions), the response requirement was increased from one to eight pecks per trial. The subjects had to make the eight pecks to the positive stimulus consecutively; eight, not necessarily consecutive, pecks to the negative stimulus led to the 5-s blackout, followed by a correction trial. Each stimulus pair was presented 10 times per session (a total of 40 trials, plus as many correction trials as were necessary). Two sessions were conducted per day.

In the first 85 and the last 20 training sessions, the sequence of stimulus pairs and the right-left positions of positive-negative stimuli on successive trials was quasi-random (Gellerman, 1933). Sessions 86-105 constituted a blocking phase during which the four pairs were presented in each session in blocks of 10 consecutive trials. The order of the blocks within a session was randomized. Trials in which eight responses to a stimulus led directly to the intertrial interval were introduced during the last 15 sessions of training, and their number was gradually raised to 12 out of the 40 trials per session. These extinction trials were interspersed at random among the reinforced training trials, but not in the first or last 5 trials of each session. This phase was to prepare the animals for test trials that ran under the same extinction conditions. Four subjects reached a criterion of 80% or more choices correct after 125 training sessions and proceeded to the test phase.

The test phase consisted of 12 sessions. Alternate sessions included either 12 nonreinforced training pairs or 10 nonreinforced training pairs plus two nonreinforced presentations of the novel stimulus combination B D. There were thus 6 test sessions for each subject, during which the subject saw the test pair a total of 12 times.

As a control for artifacts, four pairs of novel stimuli (similar in size and color to the regular stimuli) were presented as nonreinforced pseudotests, during 10 further sessions for 10 trials per session. These sessions were otherwise identical to the regular training sessions.

Results

Two subjects that did not reach 60% correct after 60 sessions were rejected from the study. Figure 3 presents the learning curves for the remaining 4 subjects. All birds achieved more than 80% correct on training trials over the last 20 sessions (during which stimulus pairs were presented at random), before the start of the test phase.

Figure 2 shows for each pigeon the mean percentage correct performance on Test Pair B D as well as on the training pairs (both reinforced and nonreinforced presentations) presented during the test sessions. On the critical transitivity test, the pigeons achieved an average of 87.5% choices to Stimulus B. Each of the 4 pigeons yielded a test choice score significantly above chance (binomial test, $p < .01$, $n = 48$). An analysis of variance (ANOVA) for repeated measures on the training pair response proportions from the last 10 sessions (transformed according to the square root of the arc sine to homogenize variance; Winer, 1962) was performed with pair and session as factors. This analysis demonstrated a significant effect of

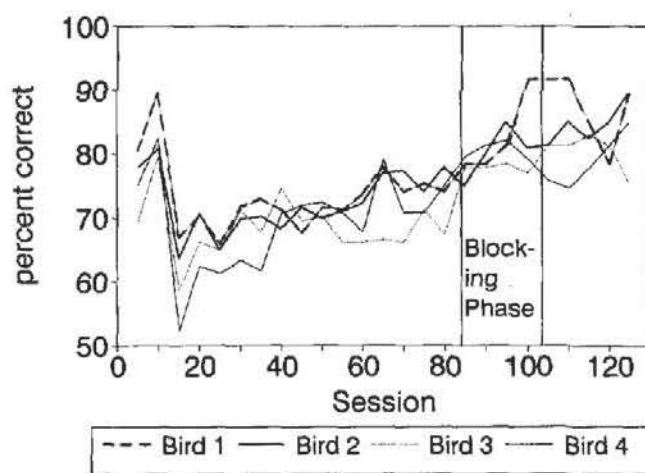


Figure 3. Learning curves of 4 successful subjects in Experiment 1.

pair, $F(3, 16) = 76.10$, $p < .01$, but not of session, $F(9, 18) = 1.56$, *ns*. The interaction of pair and session was also not significant, $F(27, 54) = 1.21$, *ns*. Post hoc comparisons (Scheffé's method; Winer, 1962) showed that the training pairs formed two equivalent groups. Response accuracies to the two end pairs were indistinguishable from each other but were significantly higher ($p < .01$) than those to the two middle pairs, which also did not differ from each other.

During the pseudotests with novel stimuli, stimulus preference was not significantly different from chance ($M = 52.5\%$).

Discussion

The pigeons' consistent choice of Stimulus B on the B D pair is strong evidence of transitive inference formation. Stimuli B and D had been equally often presented and equally often rewarded and nonrewarded during training. An explanation of performance purely in terms of reinforcement seems thus to be excluded. The results of the pseudotests demonstrate that possible artifactual cues were not responsible for performance. This result is in accordance with data from young children (Bryant & Trabasso, 1971), squirrel monkeys (McGonigle & Chalmers, 1977), and chimpanzees (Gillan, 1981) in analogous tests.

Figure 2 shows that performance on the B D test pair was actually better than that on some training pairs. That items farther apart on a transitivity series yield better performance than neighboring items has been previously observed. This is known as the *symbolic distance effect* (Bryant & Trabasso, 1971; McGonigle & Chalmers, 1984; Wocher, Glass, & Hollyoak, 1978). Also, the pigeons' discrimination accuracy on the training pairs displays a U-shaped dependence on the pairs' position in the series. A similar, though weaker, trend is apparent in the squirrel monkey and young children data and has been referred to as the *serial position effect* (Bryant & Trabasso, 1971; Wocher et al., 1978). We shall return to these effects in Experiment 2.

The results of the B D tests demonstrate that pigeons are as capable as primates of forming transitive inferences. Theories of transitive inference performance in the literature

assuming complex symbolic (McGonigle & Chalmers, 1977, 1984; Trabasso & Riley, 1975), spatial (Riley & Trabasso, 1974; Trabasso & Riley, 1975), or linguistic representations (De Boysson-Bardies & O'Regan, 1973; Trabasso & Riley, 1975) seem unlikely explanations of the behavior of pigeons. A simpler mechanism based on conditioning processes may account for these results.

The account we present here, value transfer theory (VTT), assumes that during pairwise training each of the stimuli acquires a composite value. This effective value V_i of a given stimulus i is determined by the addition of two components: the direct value component R_i and the indirect value component. The direct value component is the value that reinforcement confers directly to stimulus i . The indirect, or transferred, value component is due to a partial generalization of the value of the stimuli presented with a particular stimulus during training. If the indirect value component is predominantly determined by the effective value of the stimulus that is rewarded during training when paired with stimulus i , then the indirect value can be expressed as $a * V_{i+1}$ (where V_{i+1} is the value of the stimulus rewarded when presented with stimulus i and a is a weighting factor having a magnitude between 0 and 0.5). Thus, this version of VTT defines the composite value of stimulus i as follows: $V_i = R_i + a * V_{i+1}$. If, on the other hand, indirect value transfers from the negative stimulus in training (the stimulus that is *not* rewarded when paired with stimulus i), then the indirect value will be $a * V_{i-1}$, and the total value, $V_i = R_i + a * V_{i-1}$. Finally, if indirect value generalizes equally from the positive and negative stimuli presented with a stimulus in training, then indirect value will be $a/2 * (V_{i+1} + V_{i-1})$, and thus the total value is $V_i = R_i + a/2 * (V_{i+1} + V_{i-1})$.

Table 1 shows the predicted values for V_A through V_E from the three versions of VTT. For simplicity's sake, we set R_i equal to 2, 1, or 0, depending on whether the relevant stimulus i is always, half the time, or never rewarded, respectively. The actual values for R_i and a are quantities to be empirically determined. All three versions of the theory produce a ranking of the values of the items that is consistent with transitive inference formation: All versions predict that Item B has a higher value than Item D. This result is independent of the values of the parameters so long as parameter a remains within the limits given ($0 < a < 0.5$) and the values for R_i are ordered according to the frequency of reinforcement. Assuming that choice accuracy is proportional to the difference in value between the two items in a pair enables all versions of the theory to predict a serial position effect. The value differences are also shown in Table 1. These differences in value vary somewhat among the three versions of the theory. For the version in which indirect value generalizes equally from positive and negative stimuli, the serial position effect is symmetrical. For the other two versions of the theory, this effect is asymmetrical in two different directions. The symbolic distance effect is also predicted by all versions of the theory: On average, the further apart two items are in the series, the greater will be the difference in value between them and thus the more effective will be choice on that pairing.

The pigeon data (Figure 2) are most compatible with the theoretical ranking in Table 1, with indirect value generalizing predominately from the positive to the negative stimulus.

Table 1
Stimulus Values, Value Differences, and Ranks for a Five-Item Transitivity Series From Three Versions of Value Transfer Theory

Value	Rank	Value difference	Rank
$V_i = R_i + a * V_{i+1}$			
$V_A = 2$	1	$V_A - V_B = 1 - 2a$	2
$V_B = 1 + 2a$	2	$V_B - V_C = a(1 - 2a)$	3
$V_C = 1 + a + 2a^2$	3	$V_C - V_D = a^2(1 - 2a)$	4
$V_D = 1 + a + a^2 + 2a^3$	4	$V_D - V_E = 1 + a^3(1 - 2a)$	1
$V_E = a + a^2 + a^3 + 2a^4$	5		
$V_i = R_i + a * V_{i-1}$			
$V_A = 2 + a + a^2 + a^3$	1	$V_A - V_B = 1 + a^3$	1
$V_B = 1 + a + a^2$	2	$V_B - V_C = a^2$	4
$V_C = 1 + a$	3	$V_C - V_D = a$	3
$V_D = 1$	4	$V_D - V_E = 1$	2
$V_E = 0$	5		
$V_i = R_i + a/2 * (V_{i+1} + V_{i-1}), a = 0.1$			
$V_A = 2.058$	1	$V_A - V_B = 0.900$	2
$V_B = 1.158$	2	$V_B - V_C = 0.048$	4
$V_C = 1.111$	3	$V_C - V_D = 0.053$	3
$V_D = 1.058$	4	$V_D - V_E = 1.005$	1
$V_E = 0.053$	5		

Note. The third model is based on a simulation with $a = 0.1$. Ranks of values are not dependent on the a value. Value difference ranks can be compared with accuracies obtained empirically (see Figure 2).

Experiment 2: Seven-Term Series

Two versions of VTT predict an asymmetry in the form of the serial position effect. As shown in Table 1, the version of the theory that best fits the results from Experiment 1 predicts that the training pair at the negative end of the series (in Experiment 1, Pair D+ E-) should be the most successfully responded to, whereas the penultimate pair in the series (Pair C+ D-, in Experiment 1) should be the most difficult for the subjects to solve.

Other theories of transitive inference fall into two classes, which we term *coordination models* and *linear representation models*. According to coordination models of transitive inference (e.g., McGonigle & Chalmers, 1977, 1984; Trabasso & Riley, 1975), training pairs are stored in long-term memory during training. When presented with a test pair (e.g., B D), the subject recalls the relevant training pairs (in this case, B+ C- and C+ D-) and coordinates them to determine which item to choose in the test pair. Coordination models do not seem to offer any explanation of the serial position effect: No explanation is given why particular training pairs should be better stored in, or recalled from, long-term memory than others. Also, coordination models predict an inverted symbolic distance effect. The greater the separation in the series of the two items in a test pair, the larger the number of training pairs that must be recalled from memory and coordinated, and thus the higher the probability of error.

Linear representation models assume that subjects incorporate information about the training pairs into a linear mental representation (e.g., Breslow, 1981; Riley & Trabasso, 1974; Trabasso & Riley, 1975). Such theories can predict a symbolic distance effect, if it is assumed that the discriminability of items increases with increasing separation on the

mental line. With the additional assumption that the mental line is constructed from the ends inward (this is reasonable because the ends of the series can be uniquely labeled), a linear representation model can predict a serial position effect, at least during initial training. The effect thus produced will be symmetrical. In the five-term series, it is difficult to be confident about the shape of the serial position effect independent of the influence of the end pairs. The results of Experiment 1 (Figure 2) show an asymmetry in the serial position effect, which is most compatible with VTT when indirect value generalizes predominantly from the rewarded to the nonrewarded stimulus. The aim of Experiment 2 was to clarify the form of the serial position effect by extending the series to seven items.

The version of VTT most consistent with the results from Experiment 1 predicts that the addition of a new pair at the negative end of the series (E+ F-) will have a dramatic effect on performance on all pairs. This newest pairing should become the most correctly solved pair, and the previous best pair, D+ E-, should become the worst pairing in the series (see Table 2). This prediction is counterintuitive, because it claims that a particular pairing (D+ E-) will increase in difficulty with extended training. The addition of a new pair at the positive end of the series (X+ A-) should have relatively little impact on performance on the other pairings. The symmetrical serial position effect predicted by linear representation models of transitive inference performance would be only slightly and symmetrically re-formed by the extension of the series.

The increased number of possible test pairs that do not contain the end items in the seven-term series makes possible more extensive testing of the symbolic distance effect. The

bottom panel of Table 2 shows the basis for the prediction of a symbolic position effect in VTT. Apparent in this panel is that the value difference between the two items in a test pair is made up of two portions that are multiplied together. The first multiplier depends on the first item in the pair (a for Item A, a^2 for Item B, etc.). The second multiplier depends on the symbolic distance between the items in the pair ($[1 - a - 2a^2]$ for Symbolic Distance 2, $[1 - a - a^2 - 2a^3]$ for Symbolic Distance 3, etc.). The differences in the second multiplier are thus responsible for the symbolic distance effect. These differences are, however, very small quantities. The difference between the second multiplier for Symbolic Distance 2 and for Symbolic Distance 3 is $a^2 - 2a^3$. The difference in this multiplier between Symbolic Distance 3 and Symbolic Distance 4 is $a^3 - 2a^4$. These differences are substantially smaller than differences in performance to be expected on the basis of the first multiplier. This produces an effect of first item in a pairing, which appears to be a unique prediction from VTT.

Method

Subjects and apparatus. Experiment 2 followed directly on Experiment 1 and used the same apparatus and the 4 subjects that had successfully completed Experiment 1. Two new stimuli, similar in size and color to those used in Experiment 1, were used in addition to the stimuli from Experiment 1.

Procedure. The procedure for this experiment was identical to that of Experiment 1, except that two new pairs of stimuli, X+ A- and E+ F-, were added. A trial consisted of the simultaneous presentation of two stimuli: Eight consecutive responses to the positive stimulus led to four to six grains of millet and were followed after the 4-s intertrial interval by the next trial. Eight, not necessarily consecutive, responses to the negative stimulus led to a 5-s blackout and were followed after the same intertrial interval by a repeat of the same trial (correction trial). Correction trials repeated until eight consecutive responses were made to the positive stimulus. Each session consisted as before of 40 trials plus correction trials. The two new stimulus pairs extended the previous five-term series to a seven-term series through the addition of a stimulus at each end. Stimuli X and F were new stimuli similar to those used in Experiment 1. In the course of 170 training sessions, the new stimulus pairs were presented 960 times each, and the pairs familiar from Experiment 1 were presented 660 times each. Initially, each new pair was presented alone and then gradually intermixed with progressively more of the original four training pairs. In the first phase of training (Sessions 163-332, counting from the beginning of Experiment 1), the pairs were always presented in blocks of the same type. In an additional 20 training sessions, the six training pairs were presented in random order (Sessions 333-352). These training sessions were followed directly by an additional 20 sessions (Sessions 353-372), in which the number of nonreinforced trials was progressively increased until they constituted 30% of all trials. In the test phase (Sessions 373-408), test sessions each containing four test pairs alternated with additional training sessions. In test and training sessions, a total of 30% of trials were nonreinforced. All six possible transitivity test pairs (A C, A D, A E, B D, B E, and C E) were presented 12 times each over the course of 18 test sessions.

Results

Performance on each training pair during the test sessions (trials both with and without reinforcement) for each bird is

Table 2
Stimulus and Stimulus Difference Ranks for a Seven-Item Transitivity Series According to Value Transfer Theory

Value	Rank
$V_i = R_i + a * V_{i+1}$	
$V_X = 2$	1
$V_A = 1 + 2a$	2
$V_B = 1 + a + 2a^2$	3
$V_C = 1 + a + a^2 + 2a^3$	4
$V_D = 1 + a + a^2 + a^3 + 2a^4$	5
$V_E = 1 + a + a^2 + a^3 + a^4 + 2a^5$	6
$V_F = a + a^2 + a^3 + a^4 + a^5 + 2a^6$	7
Training pair value difference	
$V_X - V_A = 1 - 2a$	2
$V_A - V_B = a(1 - 2a)$	3
$V_B - V_C = a^2(1 - 2a)$	4
$V_C - V_D = a^3(1 - 2a)$	5
$V_D - V_E = a^4(1 - 2a)$	6
$V_E - V_F = 1 + a^5(1 - 2a)$	1
Test pair value difference	
$V_A - V_C = a(1 - a - 2a^2)$	3
$V_B - V_D = a^2(1 - a - 2a^2)$	5
$V_C - V_E = a^3(1 - a - 2a^2)$	6
$V_A - V_D = a(1 - a - a^2 - 2a^3)$	2
$V_B - V_E = a^2(1 - a - a^2 - 2a^3)$	4
$V_A - V_E = a(1 - a - a^2 - a^3 - 2a^4)$	1

Note. Value difference ranks can be compared with accuracies obtained empirically (training pairs in top panel of Figure 4; test pairs in Figure 5).

shown in the top panel of Figure 4. Their ranking matches that predicted in Table 2. In particular, Pair D+ E-, which in Experiment 1 had produced the best performance, now yielded the worst discrimination.

The correct responses for each of the last 10 sessions, transformed as described in Experiment 1, were entered into an ANOVA for repeated measures with the factors pair and session. This analysis demonstrated a significant effect of pair, $F(5, 10) = 39.35, p < .01$, but neither of session, $F(9, 18) = 0.53, ns$, nor of the interaction between session and pair, $F(45, 90) = 0.96, ns$. Post hoc comparisons (Scheffé's method; Winer, 1962) of the mean proportions correct for the different pairs demonstrated that the end pairs (X+ A- and E+ F-) were more successfully solved than three of the four middle pairs (B+ C-, C+ D-, and D+ E-; $p < .01$ in all cases). The two end pairs did not differ from each other, and there were no differences in performance on the three middle pairs. Pair A+ B- was a special case. Performance on this pair was poorer than on the end pairs (against X+ A-, $p < .05$; against E+ F-, $p < .01$), but better than on D+ E- ($p < .05$). The fact that the second pair in the series is more accurately solved

than the fifth pair demonstrates the asymmetry of the serial position effect.

Each of the six possible transitive test pairs yielded, for each subject, results consistent with transitive inference (Figure 5). The 5% probability level (binomial) is 75% correct responses, and the 1% level is 83% or more correct. The top panel of Figure 5 tests for the symbolic distance effect: Pairings of stimuli one, two, and three steps apart on the series yielded increasingly higher average discrimination scores. The bottom panel of Figure 5 tests for the first-item effect: The same data as in the top panel are replotted according to the first item in each test pair. The lines in each panel show the linear tendencies in the data: Both were calculated on the mean data for each class of test pairs. The regression line for the data ordered according to symbolic distance accounts for 75% of the variance in the means, whereas that for the data ordered by first item accounts for 94% of the variance. However, in neither panel is the slope of the regression line statistically significant because of the very small number (3) of classes in each case.

Discussion

Experiment 2 has demonstrated behavior according to transitive inference formation in pigeons trained on a series of seven items. On a seven-term series, six test pairings can be formed that are free from end items. The pigeons responded on most (17 out of 24) of the test pairs at levels significantly above chance. As in Experiment 1, these test pairs all contained stimuli that had appeared equally often, and responses to which had been equally often rewarded and nonrewarded, and thus transitive choice cannot be explained solely in terms of reinforcement.

The prediction that the shape of the serial position curve would re-form when the series is extended at the negative end was confirmed, as can be seen in Figure 4. Pair D+ E-, which on the five-term series was the best pairing, became the pairing with the least successful performance. In the seven-term series, we have also been able to demonstrate, by means of an ANOVA, that the asymmetry of the serial position effect is statistically significant.

Also confirmed was the prediction that response accuracy should increase with increasing separation in the series of the stimuli being compared. This effect has also been found in humans (McGonigle & Chalmers, 1984; Wooner et al., 1978). Such an effect is predicted by VTT and most other theories of transitive inference performance. Unique to VTT is the prediction that response accuracy be dependent on the first item in the test pair. This prediction was confirmed, as was the expectation that this first-item effect be stronger than the symbolic distance effect.

Experiment 3: Closed Seven-Term Series

According to VTT, successful transitive performance on the n -term series task depends on the series being linear. If the series is closed into a loop by training a new pair (F+ X-) added to the previous repertoire, stimulus values should equalize, making discrimination and transitive inference behavior impossible. Table 3 shows the details of this prediction.

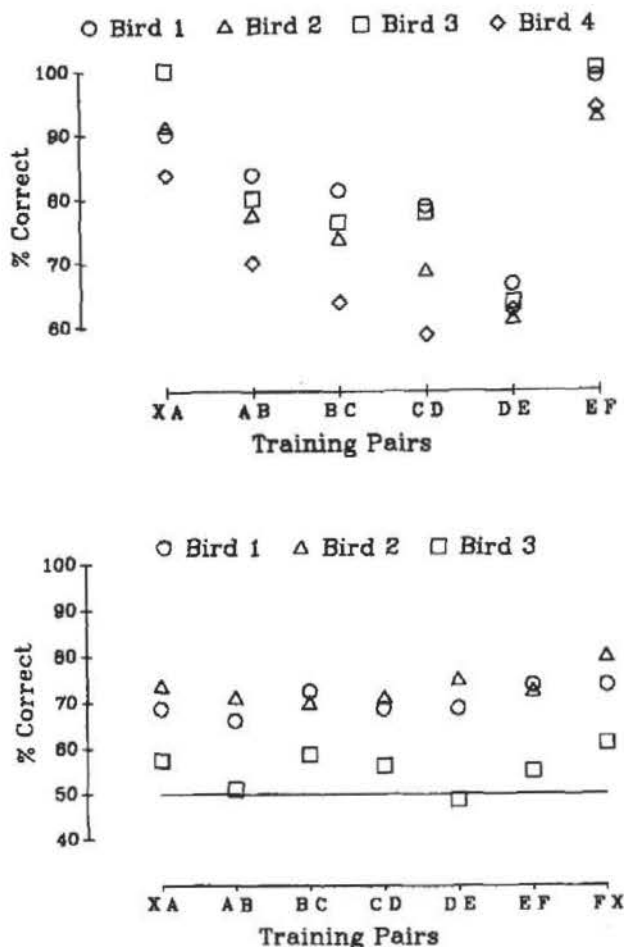


Figure 4. Top: Mean percentage responses to the rewarded stimulus on the training pairs of the seven-item series before closure of the series (4 pigeons). Bottom: Mean percentage correct responses after closure of the series (3 pigeons). (Means from last 10 training sessions in each case.)

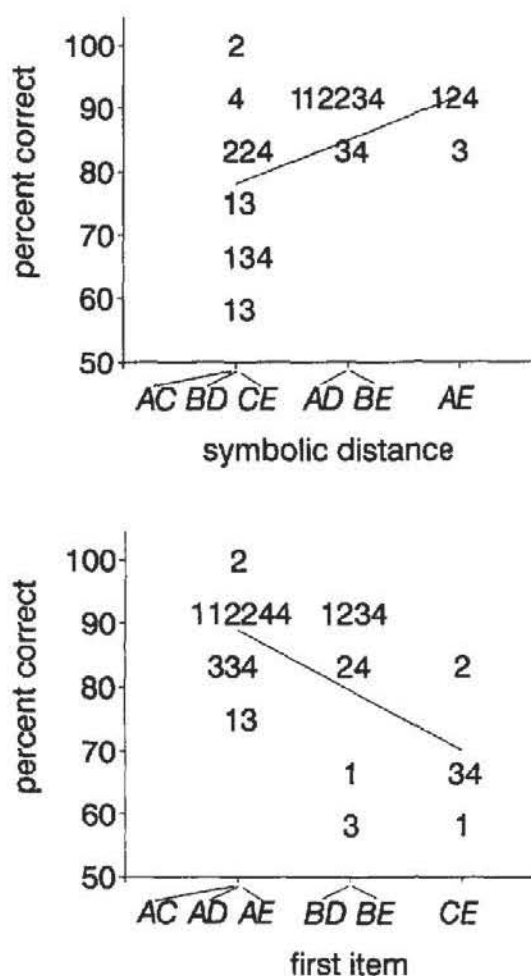


Figure 5. Percentage transitive responses for each pair and pigeon in Experiment 2. (Each digit represents the data for one pair from 1 pigeon [1 for Bird 1, and so on; horizontal separation of data points within a category is for improved readability only]. The 5% level is more than 75% correct; 1% level is more than 83% correct [binomial tests]. Top: Test pairs ordered by symbolic distance. Bottom: Test pairs ordered by first item.)

A coordination theory would appear to be untroubled by the form of the series, so long as the pairs that link stimuli presented in test pairings have been trained. The mental line models of transitive inference performance cannot make pre-

Table 3
Stimulus and Stimulus Difference Ranks for a Seven-Item Transitivity Series Closed Into a Loop by Training Pair F+ X-

Value	Value difference
$V_X = 1 + a + a^2 + a^3 + \dots$	$V_X - V_A = 0$
$V_A = 1 + a + a^2 + a^3 + \dots$	$V_A - V_B = 0$
$V_B = 1 + a + a^2 + a^3 + \dots$	$V_B - V_C = 0$
$V_C = 1 + a + a^2 + a^3 + \dots$	$V_C - V_D = 0$
$V_D = 1 + a + a^2 + a^3 + \dots$	$V_D - V_E = 0$
$V_E = 1 + a + a^2 + a^3 + \dots$	$V_E - V_F = 0$
$V_F = 1 + a + a^2 + a^3 + \dots$	

Note. Compare with bottom panel of Figure 4.

dictions about a nonlinear series of items without additional assumptions (e.g., that a mental representation has to be linear and cannot be circular).

The purpose of Experiment 3 was to extend and close the seven-term series from Experiment 2 by training Pair F+ X- and to test whether stimulus discrimination and transitive choice is still possible.

Method

Subjects and apparatus. Experiment 3 followed directly on Experiment 2 with the same subjects and apparatus.

Procedure. The subjects in this experiment were further trained under the conditions described in Experiments 1 and 2. After 10 additional training sessions with the stimulus pairs from Experiment 2, the new pair F+ X- was introduced alone for 20 twenty-trial sessions. Thereafter, there followed a phase of 95 sessions containing all seven stimulus pairs. Test sessions were conducted according to the method described in Experiment 1 with four test pairs per session for 21 sessions. From the many possible test pairs, the following seven were selected: X B, X C, X D, X E, B D, B E, and B F.

Results

One subject ceased to respond under this training schedule after 15 sessions. The bottom panel of Figure 4 presents the serial position curve for the remaining 3 subjects. A serial position effect is no longer apparent. Of these 3 subjects, only 2 actually discriminated above chance level. An ANOVA, as described for Experiments 1 and 2, was performed on the transformed percentage correct scores of the training pairs, for the 3 subjects that had relearned them: No significant effect of pair (or any other factor) was found, $F(6, 54) = 2.29, p > .10$. Only the 2 subjects that achieved above chance scores on the training pairs were presented the test pairs, and neither of them yielded stimulus preferences above chance level on any pair. Mean performance on the test pairs was X B, 54.2%; X C, 37.5%; X D, 54.2%; X E, 54.2%; B D, 50.0%; B E, 50.0%; and B F, 50.0% (binomial tests, each pair $p > .05$).

Discussion

The failure of 2 pigeons to learn to discriminate the training pairs of the closed series, the leveling off of the mean serial position function of 3 pigeons, and the chance-level performance on transitivity tests of the 2 pigeons that somehow learned to discriminate the training pairs, all support VTT predictions. Gillan's (1981) chimpanzee also managed to discriminate the training pairs of a closed series but similarly could not then differentiate the transitivity test pairs.

According to VTT, it should not have been possible for the training pairs to be relearned: Thus, the 2 pigeons that succeeded in learning the training pairs must have used a different strategy to do so. This supposition is supported by the fact that no serial position effect was observed and that the transitivity tests could not be solved. Such an alternative strategy would presumably involve rote learning of each stimulus pair. Because the subjects had by this stage received more than 600 sessions, this supposition does not seem unreasonable.

General Discussion

The results presented here show that pigeons are capable of behaving according to transitive inference rules on linear series of five and of seven items, but not on a circular series. Their successes and failures can be explained by a simple model based on reinforcement principles acting on series items presented together during training. The VTT correctly predicts inferential performance so long as an item series implies a linear, but not a circular, ordering. It also provides explanations for the serial position and symbolic distance effects and predicts an effect of first item in test pairings that exclude the end items. In particular, the version of VTT that most effectively described the results from Experiment 1 predicts an asymmetrical serial position effect in which the penultimate pair in the series is the least efficiently solved. This prediction implies that when the series is extended by the addition of a new stimulus in a new pairing at the unrewarded end of the series, the previously most efficiently solved pair should become the worst pair. This prediction was strikingly supported by the results of Experiment 2.

Other theories of performance on the n -term series either fail to predict a serial position effect (McGonigle & Chalmers, 1977, 1984; Trabasso & Riley, 1975) or predict a symmetrical position effect (Breslow, 1981; Riley & Trabasso, 1974). The asymmetry of the serial position effect can be observed in Figures 3 and 4 and was statistically significant in Experiment 2. In addition, the re-formation of the serial position effect in Experiment 2, so that the previous end pair D+ E- became the least successfully solved pair, would not be expected from any other published account of transitive behavior.

The symbolic distance effect observed in Experiment 2 is compatible with a number of theories of transitive-inference performance and thus, although consistent with VTT, is no special support for our theory. However, the first item effect found in that experiment is strong support for the theory.

Available data from other species (humans, squirrel monkeys, and chimpanzees) are very similar to our results from pigeons. First, all subjects that have been tested on the n -term series have chosen B on the B D test trial. Second, the symbolic distance effect has always been observed. This effect has been repeatedly found in humans (McGonigle & Chalmers, 1984; Trabasso & Riley, 1975; Wocher et al., 1978) and is also observed in squirrel monkeys (McGonigle & Chalmers, 1985). Third, all species tested also show a serial position effect.

In general, it seems that, because available primate data on transitive inference (human as well as nonhuman) are similar to those described here for pigeons, it can be assumed that the value transfer mechanism also underlies the transitivity

performance of these species. That VTT is based on reinforcement mechanisms whose utility in other contexts is not in doubt strengthens its plausibility as the mechanism underlying behavior in the transitive inference context. It remains possible, however, that more advanced species, such as humans, have available additional information processing strategies to solve particular types of transitive inference problems, but this has not yet been demonstrated.

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