Markov choice processes in simultaneous matching-to-sample at different levels of discriminability

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Decision and choice processes by pigeons were studied in a simultaneous matching-to-sample task. In order to view the recessed stimuli, the pigeons had to move in front of the pecking keys. They frequently moved back and forth between the comparison stimuli before choosing one of them as the match to the sample stimulus. These looking and choice responses were studied and recorded for five different discriminability levels, from near perfect (92%) to near chance (56%) performance, by changing the wavelength difference of the stimuli to be discriminated. The decision process was shown to be Markovian throughout the discriminability range, and the decision strategy based upon a Markov process is contrasted with other potential decision strategies.

Matching-to-sample (MTS) has been a popular paradigm with which to study pigeon learning, memory, sensory, and attentional processes. In a typical MTS experiment, a sample stimulus is presented, the pigeon responds to it, and then two comparison stimuli are presented. The correct response is a peck (choice) of the comparison that matches the sample. Considerable MTS research with pigeons has been concerned with stimulus control of matching performance (e.g., concepts, prospective vs. retrospective coding, directed forgetting). These endeavors, worthy as they are, do not, however, make contact with how pigeons make their decisions—the topic of this article.

Wright and Sands (1981) showed that for easy discriminations in both delayed matching (sample removed) and simultaneous matching (sample remaining), pigeons made their choices of comparison stimuli via a Markov choice process: the pigeons looked at one comparison stimulus; occasionally they pecked (chose) this first observed stimulus, but at other times they moved back and forth between the stimuli, looking at each several times, before choosing. Analyses of these looking responses revealed that the probability of the stimulus being chosen was the same whether it was the first, second, or third time that it was observed. This stationarity of probabilities is the critical Markov property. In the simultaneous matching setting,

pigeons were tested at performance levels of 95% and 81% correct, and in delayed matching other pigeons were tested at performance levels of 86% and 81% correct.

The purpose of the experiment reported in this article was to determine whether or not the choice/decision process would remain Markovian at considerably less accurate performance levels, for performance in the 80%–50% range, or if at some point subjects would give up and settle for chance performance. The Markov choice processes were tested in a setting somewhat simpler than the Wright and Sands (1981) setting. In the experiment reported in this article, 2 stimuli instead of 88 stimuli were used in each session, and there was only one incorrect comparison stimulus, instead of two, associated with each sample stimulus. Although the analysis of the results has a psychophysical orientation, the thrust of the article bears on issues in learning.

METHOD

Subjects

The subjects were 2 15-year-old White Carneaux pigeons obtained from the Palmetto Pigeon Plant in Sumter, SC. They were maintained on a 14:10-h light-on:light-off cycle with water and grit continuously available in their home-cage environment. Daily experimental sessions were conducted 5 days each week if the pigeons were at 77%–83% of their free-feeding weights. Both pigeons had extensive prior MTS experience of more than 1,700 daily sessions.

Apparatus

A diagram of the experimental apparatus is shown in Figure 1. Three light paths were taken from a xenon arc lamp. The wavelength of each path was controlled by a monochromator, the intensity by a neutral-density wedge pair, and each was projected onto a ground-glass screen located 42.7 mm behind a color-clear glass pecking key. A Hewlett-Packard 2100 minicomputer with a Diablo fixed-disk system positioned the monochromators and density-wedge pairs, controlled the experimental dependencies and contingencies, and collected and analyzed data. (See Wright & Sands, 1981, for additional apparatus details and stimulus calibrations.)

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Figure 1. Diagram of the optical system used to produce three vertical bars of monochromatic light whose wavelength and intensity are separately controlled. LS = xenon arc light source, HG = heat-absorbing glass, L = lens, M = mirror, S = shutter, Mono = monochromator, DW = density wedge, B = baffle, SA = stimulus aperture, PK = pecking key.

The houselight was turned on during intertrial intervals to maintain light adaptation, but the trials themselves were conducted in darkness. An infrared light and camera facilitated recording of the pigeons' responses of looking at the stimuli (pigeons are insensitive to infrared light). A false door to the subjects' portion of the experimental chamber held the infrared light and camera, and during experimental sessions this portion of the chamber was covered with heavy black felt to keep out stray room light.

The pigeons' stimulus-looking responses were recorded by an experimenter who had no information about which wavelengths were being presented, or which choice response was correct. The pigeons typically stayed very close to the stimulus panel, and moved horizontally to inspect the stimuli behind the pecking keys. They frequently paused momentarily when inspecting a stimulus and then pecked it or moved on. The pigeons' looking responses were usually very obvious and unambiguous. Periodically, sessions were scored by several different experimenters, and correlations among experimenters averaged 0.99.

Procedure

The procedure was a standard three-key simultaneous MTS procedure. A trial began with the offset of the houselight and display of the sample stimulus behind the center key. Pecks on the center key were ineffective until an observing response requirement (fixed interval) of 4 sec had elapsed. The first peck after this fixed inter-

val opened the shutters to the two comparison stimuli located to either side of the center sample stimulus. A peck on the glass (color-clear) paddle positioned in front of either of the two side comparison stimuli terminated the trial and turned on the houselight for 6 sec (intertrial interval). If the peck (comparison choice) occurred to the comparison stimulus that matched the sample stimulus, the pigeon was occasionally (30% of the time, pseudorandomly determined) reinforced with access to mixed grain (4 sec for Subject 381 and 2.2 sec for Subject 378). If the peck (comparison choice) occurred to the nonmatching comparison stimulus (an error), the pigeon was not reinforced and this response was followed by the 6-sec intertrial interval. No correction procedure was used, and each session contained 176 trials.

The pigeons saw two stimuli in each 176-trial session. The two stimuli appeared equally often as sample stimuli and as right and left comparison stimuli. The sequence of trials varied from session to session according to a random-number generator of the computer and the number seed entered by the experimenter. The wavelengths of the two stimuli were changed every few sessions, and the order in which they were tested is shown in Table 1 (the identification numbers are from Wright, 1978, Table 1). The two wavelengths used in each session were selected so that they would be from separate pigeon hues, one to either side of the sharp pigeon hue boundary at 600 nm (Wright, 1972, 1974; Wright & Cumming, 1971). At the beginning of the experiment, the stimuli were com-

Table 1
Wavelengths, Discriminability Spacing, and Order of Testing of Subjects P378 and P381

Subject	Test		ID Number	Wavelength	ID Number	Wavelength Difference	Discrimination Steps
	Sessions	Wavelength					
P378	1-2	609.8	30	596.7	48	13.1	18
	3-4	608.3	32	598.1	46	10.2	14
	5-8	605.3	36	601	42	4.3	6
	9-10	605.3	36	600.2	43	5.1	7
	11-12	606.1	35	599.5	44	6.6	9
P381	1-2	612	27	594.5	51	17.5	24
	3-4	607.5	33	598.8	45	8.7	12
	5-6	606.8	34	599.5	44	7.3	10
	7-10	606.1	35	600.2	43	5.9	8
	11-12	609.8	30	596.7	48	13.1	18

Note—Wavelengths and wavelength differences are expressed in nanometers. ID numbers are from Table 1 in Wright (1978).

paratively easy to discriminate. As the experiment progressed, they were made more difficult to discriminate, and then they were, once again, made easier to discriminate. Following each change in the discriminability of the stimuli, several adaptation sessions were conducted prior to tests in which the pigeons' looking responses were recorded. Two test sessions were conducted at each of the five wavelength differences tested, except for the smallest wavelength difference, where four test sessions were conducted.

RESULTS

The psychometric functions for each pigeon are shown in Figure 2. Discrimination performance decreased with decreases in wavelength separation between the sample/correct comparison and the incorrect comparison (circles), and then increased with increases in wavelength separation (triangles). Unfilled points indicate test sessions in which the pigeons' looking and choice responses were observed and recorded on each trial. Filled points indicate training sessions prior to recording the looking responses at each wavelength separation tested.

A Model of MTS and Decision Processes

The results from the experiment are presented in the framework of a Markov choice model (Wright & Sands, 1981), a version of which was originally proposed by Bower (1959, Model B). The model was made somewhat simpler than the 1981 model by the use of 2 rather than 88 stimuli in each session, and by having one rather than two possible incorrect stimuli being associated with each sample stimulus.

Figure 3 is a schematic diagram showing the model of the decisions confronting the pigeons on red (R) sample trials. (Green sample trials would be similar, but would require an exchange of greens and reds.) The green and red human color names are used for heuristic purposes. On this red-trial example, the pigeon is shown attempting to choose the red comparison, and the process is modeled as follows. Each observation of a comparison stimulus wavelength produces a color sensation that varies slightly from observation to observation. Frequency distributions of these sensations (stimulus effects) are depicted in Figure 3 as normal distributions, but most other distribution forms would serve equally well. The pigeon's decision is accomplished by setting a match criterion. For this red-sample trial, any sensation that is as red (r) or redder than the criterion is followed by a match-acceptance decision by the pigeon. Any sensation greener (g) than the criterion is followed by a match-rejection decision and a switch to the other comparison stimulus. Overlap of the distributions produces situations in which green comparisons are occasionally treated as red ones (Gr), and red comparisons are treated as green ones (Rg). In the former case, the incorrect green comparison will be accepted as a match, and in the latter case, the correct red comparison will be rejected as a match. More will be said later about these two error types.

An example. The lower portion of Figure 3 shows a series of possible outcomes. When the correct comparison

Figure 2. Psychometric functions for the 2 pigeons showing increases and decreases in matching-to-sample performance as wavelengths of the two stimuli were made more different and more similar, respectively. Unfilled points show performance on sessions in which the pigeons were observed as they performed the task and their stimulus-looking responses were recorded.

son is observed first (left), it is chosen (pecked) Rr percent of the time. For example, let us say that in this situation, 80% of the time it qualifies as a match and is chosen. The other 20% of the time the pigeon rejects it (Rg) and switches over to observe the other comparison, the incorrect one in this example. Furthermore, let us say that the incorrect comparison will be accepted as the match 30% of the time (and is correctly rejected 70% of the time). Thus, the chances that the incorrect comparison

Figure 3. Diagram depicting the movements and behavior of the pigeons as they chose between the comparison stimuli. This behavior is modeled by a multiplication of probabilities. These probabilities reflect the pigeons' acceptance rate (Rr) of the correct comparison (the red comparison, because in this case it is a red sample trial), rejection rate (Rg) of the correct comparison, acceptance rate (Gr) of the incorrect comparison, and rejection rate (Gg) of the incorrect comparison. The behavior is divided into two different groups: those in which the correct comparison is observed first, and those in which the incorrect comparison is observed first.

will be chosen after first observing and rejecting the correct comparison is $Rg \times Gr = 0.20 \times 0.30 = 0.06$. If, however, the pigeon correctly rejects the incorrect comparison, then it will switch back to the correct one. The chances of this happening are $Rg \times Gg \times Rr = 0.2 \times 0.7 \times 0.8 = 0.112$. On the other hand, the correct comparison might be rejected upon considering it for the second time, and the incorrect one chosen. The chances of this happening are $Rg \times Gg \times Rg \times Gr = 0.2 \times 0.7 \times 0.2 \times 0.3 = 0.008$. Finally, the case might occur that the pigeon rejects the incorrect comparison (for the second time), returns to the correct one (for the third time), and accepts it. The chances of this happening are $Rg \times Gg \times Rg \times Gg \times Rr = 0.2 \times 0.7 \times 0.2 \times 0.7 \times 0.8 = 0.016$. Similar logic applies to the cases (on red sample trials) in which the incorrect comparison is observed first, shown in the

right-hand portion of Figure 3. For this whole Markov choice process (green as well as red sample trials), there are only two parameters to estimate (since $Rr + Rg = 1.0$ and $Gr + Gg = 1.0$). The acceptance rates when each stimulus (correct and incorrect) was observed first were used as these modeling parameters.

Modeling the Experimental Results

The results for each subject at five levels of discrimination difficulty are displayed along with the Markov model performance in Figure 4. The panels have been arranged in descending order of stimulus spacing and discriminability. Inset into each panel is a pair of distributions and a criterion line, the interpretations of which are identical to those of Figure 3. The distributions of stimulus effects for the correct comparison (the right-hand distributions) have been vertically aligned with one another

Figure 4. Percentages of the different behavioral sequences (unfilled bars) for Subjects P378 and P381 at five levels of discrimination difficulty. Predictions from the Markov model are shown for the 1–4 switch (sw) sequences for instances when the correct comparison was observed first (left-hand panels) and when the incorrect comparison was observed first (right-hand panels), with the zero-switch results serving as the model parameters. The insets of two distributions in each panel show stimulus-effects distributions (correct–right, incorrect–left) and a match-criterion line. The match-acceptance region is to the right of the criterion and the reject region is to the left.

so that changes in spacing of the distributions (discriminability) or criterion (bias) can be readily noticed by displacements.

The top panels of Figure 4 show the results and Markov model for the easiest of the discriminations. The left-hand portions of these panels show trials in which the correct comparison was observed first. This correct comparison was almost always chosen upon its first observation. In the right-hand portion of these panels, the incorrect comparison was first observed. It was usually rejected. The subject then switched over and observed the alternative comparison stimulus (the correct one), and this observation was usually followed by a choice (peck) of that stimulus. As the discrimination became more difficult (shown in successively lower panels), overall performance declined (from 92% correct to 56% correct). The acceptance rate of the correct comparison when it was observed first, however, declined only slightly. This relative stability of the acceptance rate of the correct comparison is shown in the inset diagrams as a stable criterion (relative to the correct comparison distribution). Furthermore, this stable acceptance rate means that the false negative rate (rejections of the correct comparison stimulus) was also stable, because the two rates must sum to 1.0.

Errors did increase as the discrimination became more difficult, and these were errors of accepting the incorrect comparison as a match to the sample stimulus (false alarms). As the false-alarm rate increased, there were fewer correct rejections of the incorrect comparison (correct negatives), and consequently fewer opportunities to switch over and have an opportunity to accept the correct comparison. The large increase in accepting the incorrect comparison is shown (distribution inset) by a greater proportion of the incorrect comparison distribution falling to the right of the criterion line.

Proportions according to the Markov choice model are shown by the hatched histogram of each pair with the first-observed proportions for the two behavioral sequences providing parameter estimates. In some cases, parameter estimates absorbed a substantial proportion of the overall response frequencies, but in other cases (e.g., top right-hand panels of Figure 4), the proportion absorbed was considerably smaller. The use of only two parameters is minimal when compared with other models today. Following Bower (1959) and others (Bower & Theios, 1964; Brainerd, 1979; Greeno, 1968; Greeno & Scandura, 1966; Humphreys & Greeno, 1970; Izawa, 1971; Kintsch, 1966; Polson, 1972), Kolmogorov-Smirnov goodness-of-fit tests (Siegel, 1956; Sokal & Rohlf, 1969) were conducted and are shown in Tables 2 and 3. The data fit the Markov choice model well at all levels of discrimination difficulty, and it would be difficult to reject the hypothesis that they were generated by a Markov process (in all cases the p s were greater than .99). A slight systematic underestimation, however, did occur for the one-switch performance, and attempts to diminish it (e.g., a three-state model, al-

lowing for forgetting or miscoding the sample) had the opposite effect of exaggerating it.

Should doubts remain regarding the degree to which the Markov model accounts for these results, either due to the proportion of data absorbed by the parameter estimates or the power of the goodness-of-fit tests, a discussion of what would have been produced by alternative strategies is presented in the Discussion section. The results are Markovian in their general form, unlike those generated by other feasible alternative strategies. In the next section, analyses of order and conditional effects also provide support for a Markov choice process.

Additional Analyses

Several different analyses resulted in a lack of performance differences. In some cases, these results support the stationarity of transition probabilities (a result critical for Markov models), and in other cases they support a simpler model than might otherwise be necessary. There were no systematic differences with regard to the different samples, the position of the correct comparison stimulus, or the number of sample reobservations made by the pigeons. (After making a sample reobservation, the pigeons always continued their movement in the direction of the other comparison stimulus.)

There were no significant effects of previous-trial stimuli or responses. Other investigators have shown that pigeons can have a preference to repeat the response on a given trial (n) that was made on the previous trial ($n-1$) independent of whether or not the previous response was rewarded (Edhouse & White, 1988; Hogan, Edwards, & Zentall, 1981; Roberts, 1980; Roitblat & Scopatz, 1983). This preference has evidenced itself as a preference for both the same side and the same stimulus associated with the previous response. Table 4 shows the results of the statistical tests for these sequential response dependencies as a function of which of the two stimuli (Stimulus 1 is the longer wavelength stimulus) was chosen on Trial $n-1$, which of the two side responses was chosen on Trial $n-1$, and whether or not the choice response on Trial $n-1$ was rewarded. These tests were conducted as paired-comparison tests in order to emphasize differences and minimize level changes (each conditional condition was tested against the unconditional condition). Table 4 shows that there is no statistical support for any sequential response dependencies (the p values are all several times larger than those required for statistical significance). It should be added, however, that the mean scores do show slight trends in the direction of the results shown by others, and may represent a vestige of a stronger preference from sometime in the past. Among possible reasons for a lack of order effects here was the vast amount of previous experience (10 years), sometimes involving large numbers (88) of stimuli (Wright & Sands, 1981). Changing the stimuli on a regular basis may thwart the build-up of conditional preferences and stereotyped behavior generally.

DISCUSSION

This article extends the results and conclusions of Wright and Sands (1981) by showing that the Markov model accounts for performances from 80% correct down to near chance performance. This article has also shown a good account of individual subjects' performance by the Markov model, and of performance with only one incorrect comparison stimulus associated with each of two sample stimuli. This Markov model does not posit hypothetical learning states, but instead is based upon the objective responses of pigeons looking at individual stimuli. The Markov model identifies a particular decision structure that may represent the actual decision strategy used by the pigeons. When considering the Markov process as the decision strategy used by the pigeons, it may be useful to consider other reasonable alternatives that the pigeons could have used in the MTS setting. Other strategies do not produce the same pattern of results produced by the MTS Markov strategy, and these alternatives are considered in the next section.

Comparison Among Possible MTS Strategies

Giving-up strategy. Settling for chance performance could take the form of always making the choice response to one side, or randomly responding to one or the other side. Such strategies would involve no rejections of comparison stimuli and no switches between the comparison stimuli before the choice response. All responses would occur in the zero-switch categories. The pigeons clearly did not behave in this manner, as shown by some switching and comparing of the choices even for performances near chance (Figure 4, bottom panels).

Exhaustive-comparison strategy. Another possible strategy would be for the subjects to compare both stimuli before making a choice (cf. the two-alternative forced-choice signal-detection strategy discussed below). If this occurred, then the pigeons would never choose the first observed comparison stimulus, and no responses would occur in the zero-switch categories. Clearly, the pigeons did not behave in this manner. The zero-switch categories often contain the largest response proportions, as they should according to the Markov choice rule.

Default strategy. Another possible choice strategy would be to choose the alternative comparison stimulus (by default) following rejection of the first one observed. This choice strategy is based upon the knowledge that one of the two comparison stimuli will always match the sample, and the assumption that if the first observed comparison does not match, then by default the other must match. This type of choice strategy has been hypothesized to account for rats' choices in a two-choice discrimination box (Pullen & Turney, 1977) and in a Lashley jumping-stand apparatus (Hall, 1973), and pigeons' choices in an MTS task (Roberts & Grant, 1978). As Roberts and Grant said, "the alternative key will be pecked automatically if the first is rejected as a match" (p. 80). The default-choice strategy would produce, at most, only one switch between

the comparison stimuli. There should be no instances of two and three switches between the comparison stimuli. The pigeon should never switch back to reconsider the first comparison (which it rejected). But there were switches back to the first rejected comparison, and to the second, the third, and even the fourth. Indeed, there have been (in other experiments) as many as 8–10 switches. The ability to experimentally determine how many times the pigeons actually observe and reject each stimulus before making a choice response depends upon having clearly defined "looking" movements, which in this case was made possible by recessing the stimuli behind the pecking keys.

Multiple-looks strategy. There is some similarity between the pigeons' switching between the comparison stimuli and Tolman's vicarious trial and error (VTE) of rats choosing an arm of a T-maze (e.g., Tolman, 1938). The similarity of the behavior itself is inescapable, but the manner in which it was incorporated into a theory of choice behavior is different. Tolman hypothesized that the more the rat looked back and forth between the stimuli, the more information would be accumulated about the stimuli. As more information accumulated, the rat was more likely to make a choice (see also Luce, 1963, p. 137). This means that the transition probabilities to the absorbing states (R_r and G_r of the example in Figure 3) should increase as VTE increases and as the trial progresses (see Still, 1976). But the transition probabilities do not increase for rats (Siegel, 1969; Still, 1976), nor do they increase for pigeons. If the transition probabilities had increased, then the proportion of responses for increasing numbers of switches would be greater than those shown in Figure 4, and the results would not be adequately modeled by a Markov process.

Signal-Detection Strategies and Signal-Detection Theory

The MTS Markov model proposed in this article has some obvious similarities to signal-detection theory (SDT), including a scale of stimulus effects, probability-density distributions for the correct comparison (signal plus noise) and for the incorrect comparison (noise alone), an index of discriminability that is a function of the distance between the modes of the distributions, and a criterion line that divides each of the two distributions into two areas. The correct-comparison distribution is divided into a right-hand area reflecting the proportion of hits (accepting the correct comparison as a match) and a left-hand area reflecting the proportion of false negatives (rejecting the correct comparison as a match). In a like manner, the incorrect-comparison distribution is divided into two areas, the right-hand area reflecting the proportion of false alarms (accepting the incorrect comparison as a match) and the left-hand area reflecting the proportion of correct negatives (rejecting the incorrect comparison as a match).

These similarities to SDT notwithstanding, the predictions from the MTS Markov model are considerably

Figure 5. Performance predictions from the matching-to-sample (MTS-Markov) model, two-alternative forced-choice (2AFC), and yes/no signal-detection theory models as a function of the hit rate [the proportion of the correct-comparison stimulus-effects distribution falling within the match-acceptance region (to the right of the criterion line)]. Also shown are the maximum number of switches that would be expected to occur on a single trial of a 176-trial session. The distributions at the top of the figure depict the decision situation (see Figure 3) at the point indicated by the arrowhead.

different because of a difference in consequences associated with errors of falsely rejecting the correct comparison. In SDT, both false negatives and false alarms end the trial; there are no second chances to make the correct choice. In the two-alternative forced-choice (2AFC) SDT paradigm, the subject observes both stimuli (stimuli-observation intervals) before making a choice (response interval). Errors involve rejection of the correct choice and acceptance of the incorrect choice. In the yes/no SDT paradigm, the stimulus to be detected is presented on half of the trials. The subject responds either "yes" (that the stimulus to be detected was presented) or "no" (that it was not presented). False positives (rejections of the correct comparison) and false negatives (acceptances of the incorrect comparison) terminate the trial and are dealt with accordingly.

By contrast, false rejections of the correct comparison (false negatives) under the MTS Markov choice strategy are redeemable, and the subject receives another chance. These false negatives are not really choice errors; after incorrectly rejecting the correct comparison, the subject may correctly reject the incorrect comparison, switch back and then correctly accept the correct comparison, thus actually being correct on the trial. In this sense, the subject's observations of the stimuli are another level of responses not really defined according to any experimental contingencies. They are observable responses nevertheless, and, as in the experiment of this article, their analysis may identify underlying decision strategies. It is interesting that there is this asymmetry in the consequences of the error types. All stimulus rejections lead to suspen-

sion of decision about the choice response. Because of this error-type asymmetry, overall performance accuracy will not vary in the same way for variations in these two error types. One example is shown in Figure 5.

Figure 5 shows potential performance for one level of discrimination difficulty (separation between the two distributions) for the signal-detection paradigms (2AFC, yes/no) and the MTS Markov strategy. The parameter is the position of the match-criterion line of the two distributions shown along the top of the figure. Toward the left-hand side of the figure, the match criterion is strict, and toward the right-hand side, it is lax. The MTS Markov strategy generates increasingly superior performance relative to the 2AFC or yes/no strategies as the match criterion becomes more strict (toward the left of Figure 5). This advantage occurs because under strict criteria, false positives (errors from the standpoint of the matching paradigm) are minimized. This improved performance by restricting false positives is not possible in signal-detection paradigms. In signal-detection tasks, as false positives decrease, false negatives increase. The price of this improved performance by the MTS Markov strategy is more switching (comparing the stimuli). Rarely, however, do pigeons switch more than several times, and thus it will be a challenge to determine whether or not more switching can be induced and performance improved.

Concluding Remarks

The majority of Markov chain models in psychology have been concerned with transitions to hypothetical learning or memory states (e.g., Atkinson, 1960; Atkinson,

Bower, & Crothers, 1965; Bower, 1959; Estes, 1960; Spence, 1960; Still, 1976). These "state" models have occasionally revealed underlying mechanisms by breaking down complex operations into simple elementary processes (e.g., see Greeno, 1974). In one example, the first stage in paired-associate learning was shown to be storage, not response learning as had been thought (e.g., Underwood & Schulz, 1960), and the second stage was shown to be retrieval learning, not stimulus-response association learning (Humphreys & Greeno, 1970; Polson, Restle, & Polson, 1965). In another example, Markov analysis showed that the first stage in avoidance conditioning was learning to run, not learning to fear the CS as had been thought (e.g., Mowrer, 1947), and the second stage was associating the conditioned stimulus (CS) with unconditioned stimulus (US), not learning to escape from the conditioned (feared) stimulus (Brelsford, 1967; Theios, 1963, 1965; Theios & Brelsford, 1966).

Unfortunately, these states are destined to remain hypothetical. They are established by conjecture and are either supported or refuted by indirect evidence. They are not observable states, and doubts seem to linger about their existence. On the other hand, the transitions shown in the experiment of this article were not among internal psychological states (storage, retrieval, CS-US associations), but between the pigeons' observations of two comparison stimuli. Experimenters do not regularly observe or record such "collateral" observing behavior on the part of their subjects. Instead, we tend to record only the electrical contact closures produced by keypecks, and derive our analyses from these automatically recorded responses. But the keypeck is only the final response in a chain of behavior involving a succession of choices and choice points. The collateral behavior (looking and switching) preceding the keypeck may be at least equally important, providing the basis for determining the actual decision strategy—a Markov decision strategy in this case.

The Markov decision rule is not a theory, in the strict sense of the term. It is a summary of the data (looking responses and keypecks), but through this summary and comparison to other possible decision strategies it might be possible to argue that the model represents the actual strategy used by the subject. At a minimum, the Markov process establishes a sensitive standard against which to judge deviations from this strategy (cf. Bower, 1959; Cane, 1978; Heyman, 1979; Siegel, 1969; Wright & Sands, 1981).

REFERENCES

- ATKINSON, R. C. (1960). The use of models in experimental psychology. *Synthese*, 12, 162-171.
- ATKINSON, R. C., BOWER, G. H., & CROTHERS, E. J. (1965). *An introduction to mathematical learning theory*. New York: Wiley.
- BOWER, G. H. (1959). Choice point behavior. In R. R. Bush & W. K. Estes (Eds.), *Studies in mathematical learning theory* (pp. 109-124). Stanford, CA: Stanford University Press.
- BOWER, G. H., & THEIOS, J. (1964). A learning model for discrete performance levels. In R. C. Atkinson (Ed.), *Studies in mathematical psychology* (pp. 1-31). Stanford, CA: Stanford University Press.
- BRAINERD, C. J. (1979). Markovian interpretations of conservation learning. *Psychological Review*, 86, 181-213.
- BRELSFORD, J. W., JR. (1967). Experimental manipulation of state occupancy in a Markov model for avoidance conditioning. *Journal of Mathematical Psychology*, 4, 21-47.
- CANE, V. R. (1978). On fitting low-order Markov chains to behaviour sequences. *Animal Behaviour*, 26, 332-338.
- EDHOUSE, W. V., & WHITE, K. G. (1988). Sources of proactive interference in animal memory. *Journal of Experimental Psychology: Animal Behavior Processes*, 14, 56-70.
- ESTES, W. K. (1960). A random walk model for choice behavior. In K. J. Arrow, S. Karlin, & P. Suppes (Eds.), *Mathematical methods in the social sciences* (pp. 265-276). Stanford, CA: Stanford University Press.
- GREENO, J. G. (1968). Identifiability and statistical properties of two-stage learning with no successes in the initial stage. *Psychometrika*, 33, 173-215.
- GREENO, J. G. (1974). Representation of learning as discrete transition in a finite state space. In D. H. Krantz, R. C. Atkinson, R. D. Luce, & P. Suppes (Eds.), *Contemporary developments in mathematical psychology: Learning, memory and thinking* (Vol. 1, pp. 1-39). San Francisco: W. H. Freeman.
- GREENO, J. G., & SCANDURA, J. M. (1966). All-or-none transfer based on verbally mediated concepts. *Journal of Mathematical Psychology*, 3, 388-411.
- HALL, G. (1973). Overtraining and reversal learning in the rat: Effects of stimulus salience and response strategies. *Journal of Comparative & Physiological Psychology*, 84, 169-175.
- HEYMAN, G. M. (1979). A Markov model description of changeover probabilities on concurrent variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, 31, 41-51.
- HOGAN, D. E., EDWARDS, C. A., & ZENTALL, T. R. (1981). The role of identity in the learning and memory of a matching-to-sample problem by pigeons. *Bird Behavior*, 3, 27-36.
- HUMPHREYS, M., & GREENO, J. G. (1970). Interpretation of the two-stage analysis of paired-associate memorizing. *Journal of Mathematical Psychology*, 7, 275-292.
- IZAWA, C. (1971). The test trial potentiating model. *Journal of Mathematical Psychology*, 8, 200-224.
- KINTSCH, W. (1966). Recognition learning as a function of the length of the retention interval and changes in the retention interval. *Journal of Mathematical Psychology*, 3, 412-433.
- LUCE, R. D. (1963). Detection and recognition. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of mathematical psychology* (pp. 103-190). New York: Wiley.
- MOWRER, O. H. (1947). On the dual nature of learning: A reinterpretation of "conditioning" and "problem solving." *Harvard Educational Review*, 17, 102-148.
- POLSON, M. C., RESTLE, F., & POLSON, P. G. (1965). Association and discrimination in paired-associates learning. *Journal of Experimental Psychology*, 69, 47-55.
- POLSON, P. G. (1972). A quantitative theory of the concept identification processes in the Hull paradigm. *Journal of Mathematical Psychology*, 9, 141-167.
- PULLEN, M. R., & TURNEY, T. H. (1977). Response modes in simultaneous and successive visual discriminations. *Animal Learning & Behavior*, 5, 73-77.
- ROBERTS, W. A. (1980). Distribution of trials and intertrial retention in delayed matching to sample with pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, 6, 217-237.
- ROBERTS, W. A., & GRANT, D. S. (1978). Interaction of sample and comparison stimuli in delayed matching to sample with the pigeon. *Journal of Experimental Psychology: Animal Behavior Processes*, 4, 68-82.
- ROITBLAT, H. L., & SCOPATZ, R. A. (1983). Sequential effects in pigeon delayed matching-to-sample performance. *Journal of Experimental Psychology: Animal Behavior Processes*, 9, 202-221.
- SIEGEL, S. (1956). *Nonparametric statistics for the behavioral sciences*. New York: McGraw-Hill.
- SIEGEL, S. (1969). Discrimination overtraining and shift behavior. In R. M. Gilbert & N. S. Sutherland (Eds.), *Animal discrimination learning*. London: Academic Press.

- SOKAL, R. R., & ROHLF, F. J. (1969). *Biometry*. San Francisco: W. H. Freeman.
- SPENCE, K. W. (1960). Conceptual models of spatial and non-spatial discrimination learning. In K. W. Spence (Ed.), *Behavior theory and learning* (pp. 366-393). Englewood Cliffs, NJ: Prentice-Hall.
- STILL, A. W. (1976). An evaluation of the use of Markov models to describe the behavior of rats at a choice point. *Animal Behaviour*, **24**, 498-506.
- THEIOS, J. (1963). Simple conditioning as two-stage all-or-none learning. *Psychological Review*, **70**, 403-417.
- THEIOS, J. (1965). The mathematical structure of reversal learning in a shock-escape T-maze; Overtraining and successive reversals. *Journal of Mathematical Psychology*, **2**, 26-52.
- THEIOS, J., & BRELSFORD, J. W., JR. (1966). Theoretical interpretations of a Markov model for avoidance conditioning. *Journal of Mathematical Psychology*, **3**, 140-162.
- TOLMAN, E. C. (1938). The determiners of behaviors at a choice point. *Psychological Review*, **45**, 1-41.
- UNDERWOOD, B. J., & SCHULZ, R. W. (1960). *Meaningfulness and verbal learning*. New York: Lippincott.
- WRIGHT, A. A. (1972). Psychometric and psychophysical hue discrimination functions for the pigeon. *Vision Research*, **12**, 1447-1464.
- WRIGHT, A. A. (1974). Psychometric and psychophysical theory within a framework of response bias. *Psychological Review*, **81**, 332-347.
- WRIGHT, A. A. (1978). Construction of equal-hue discriminability scales for the pigeon. *Journal of the Experimental Analysis of Behavior*, **29**, 261-266.
- WRIGHT, A. A., & CUMMING, W. W. (1971). Color-naming functions for the pigeon. *Journal of the Experimental Analysis of Behavior*, **15**, 7-17.
- WRIGHT, A. A., & SANDS, S. F. (1981). A model of detection and decision processes during matching to sample by pigeons: Performance with 88 different wavelengths in delayed and simultaneous matching tasks. *Journal of Experimental Psychology: Animal Behavior Processes*, **7**, 191-216.

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