

MATCHING: ITS ACQUISITION AND GENERALIZATION

MICHAEL A. CROWLEY AND JOHN W. DONAHOE

UNIVERSITY OF MASSACHUSETTS AT AMHERST

Choice typically is studied by exposing organisms to concurrent variable-interval schedules in which not only responses controlled by stimuli on the key are acquired but also switching responses and likely other operants as well. In the present research, discriminated key-pecking responses in pigeons were first acquired using a multiple schedule that minimized the reinforcement of switching operants. Then, choice was assessed during concurrent-probe periods in which pairs of discriminative stimuli were presented concurrently. Upon initial exposure to concurrently presented stimuli, choice approximated exclusive preference for the alternative associated with the higher reinforcement frequency. Concurrent schedules were then implemented that gave increasingly greater opportunities for switching operants to be conditioned. As these operants were acquired, the relation of relative response frequency to relative reinforcement frequency converged toward a matching relation. An account of matching with concurrent schedules is proposed in which responding exclusively to the discriminative stimulus associated with the higher reinforcement frequency declines as the concurrent stimuli become more similar and other operants—notably switching—are acquired and generalize to stimuli from both alternatives. The concerted effect of these processes fosters an approximate matching relation in commonly used concurrent procedures.

Key words: matching, concurrent schedule, changeover response, discrimination, generalization, multiple schedule, key peck, pigeon

This research sought to identify the conditions that promote the development of a matching relation between relative response frequency and relative reinforcement frequency. In initial efforts to measure the relative strengths of operants in Skinner's laboratory (Ferster & Skinner, 1957; Skinner, 1950), concurrent schedules were used in which food was contingent on a pigeon responding to stimuli from either of two keys (A or B) associated with their respective reinforcement schedules. Skinner cautioned

that the relative number of responses on a key should not be regarded as a measure of the relative strength of only two discriminated operants but as a compound measure that reflected the combined strengths of a mixture of operants. These operants included, at a minimum, pecking key A under the control of stimuli from A (S_A-R_1), pecking key B under the control of stimuli from B (S_B-R_2), and two switching operants—pecking key A after pecking key B (S_B-R_1) and pecking key B after pecking key A (S_A-R_2). To regard the relative number of responses on a key as a measure of "choice" overlooked that "we are no longer dealing with just two responses. In order to analyze 'choice' we must consider a single final response, striking [i.e., pecking], without respect to the position or color of the key, and in addition the responses of changing from one key or color to the other" (Skinner, 1950, p. 211). He persisted in this view over the years: "Choice is something to be explained, not to be used in the analysis of basic processes" (Skinner, 1986, p. 232). Thus Skinner held that choice measures conflated responses that were members of different operant classes. In his formulation, the relative number of responses to one alternative, say A, reflected the strengths of at least the following operants:

This paper describes a portion of the research conceived and conducted by the first author in partial fulfillment of the requirements for the PhD in the Biopsychology Division of the Department of Psychology, University of Massachusetts, Amherst. The report was prepared by the second author, who directed the dissertation research. The research was partially supported by a grant from the National Institute of Mental Health, MH 28610 to the second author, and by a Biomedical Research Support grant to the University of Massachusetts. The authors express their appreciation to Vivian P. Dorsel for comments on an earlier version of the manuscript.

Address correspondence to either author: Dr. Michael A. Crowley, Director of Networking for Library, Information, and Technology Services (LITS), Mount Holyoke College, South Hadley, Massachusetts 01075 (e-mail: mcrowley@mtholyoke.edu), or Prof. John W. Donahoe, Department of Psychology, Program in Neuroscience and Behavior, University of Massachusetts, Amherst, Massachusetts 01003 (e-mail: jdonahoe@psych.umass.edu).

$$\begin{aligned}
 & R_1/[R_1 + R_2] \\
 &= [(S_A-R_1) + (S_B-R_1)] \\
 &\quad \div \{[(S_A-R_1) + (S_B-R_1)] \\
 &\quad + [(S_B-R_2) + (S_A-R_2)]\}. \quad (1)
 \end{aligned}$$

Consistent with Skinner's analysis, subsequent research demonstrated that responding on a key was a function not only of the reinforcement contingent on responding on that key but also the delay between responding on the other key and receiving a reinforcer for responding to the first key. The time between responding on the other key and the minimum time of delivery of a reinforcer for a response on the first key defined a changeover delay (COD). The effect of the duration of the COD on the relative frequency of responding was substantial and led a major contemporary contributor to the literature to comment: "One may ask whether changeover responding is a byproduct of response distribution . . . or whether the latter are byproducts of changeover responding. . . . The changeover model more easily employs the language of response and consequence common to behavior analysis, and to that extent, it enjoys an advantage over the response distribution . . . models" (Pliskoff, 1971, p. 255). Moreover, other research confirmed that switching responses were, indeed, operants in that their strengths were sensitive to the specific schedule of reinforcement for switching (Boelens & Kop, 1983; Boelens, Kop, Nagel, & Slangen, 1986, 1987; Brownstein & Pliskoff, 1968; Dreyfus, DePorto, & Pasillo, 1993; Dreyfus, Dorman, Fetterman, & Stubbs, 1982; Machado, 1997; Pliskoff & Green, 1972; Shull & Pliskoff, 1967; Silberberg & Ziriak, 1982; Stubbs & Pliskoff, 1969; Stubbs, Pliskoff, & Reid, 1977).

Given the possible "contamination" of the measurement of the relative strength of an operant; for example, S_A-R_1 , by the strength of switching operants; for example, S_B-R_1 , concurrent-operant procedures were developed that attempted to minimize the reinforcement of switching operants so that choice reflected only the relative strengths of two operants; for example, S_A-R_1 and S_B-R_2 . Two primary procedures were devised to control the strength of switching operants—the COD procedure in which a response to the

switched alternative could produce a reinforcer only after the passage of a specified delay (Catania, 1962, 1966; but see Catania & Cutts, 1963) and the changeover (CO)-key procedure in which switching occurred after pecking a separate CO key caused the stimulus on a second key to change between S_A and S_B . In both procedures, reinforcers were earned only for pecking the second key once the COD had elapsed (Findley, 1958). To the extent that the contribution of switching operants to responding was minimized by these control procedures, the frequency of R_1 relative to total responding to R_1 and R_2 would reflect the strengths of only (S_A-R_1) and (S_B-R_2) , as illustrated in Equation 2:

$$\frac{R_1}{[R_1 + R_2]} = \frac{[(S_A-R_1)]}{[(S_A-R_1) + (S_B-R_2)]}. \quad (2)$$

Using these control procedures, a reliable and robust functional relation was found between the relative frequency of responses to one key and the relative frequency of reinforcers for responding to that key. This relation is known as "matching" in that the relative frequency of responses to one alternative in a concurrent schedule approximates the relative frequency of reinforcers for responding to that alternative. (For quantitative statements of the matching relation, see Baum, 1974, 1979; Herrnstein, 1961, 1970; for reviews see Davison & McCarthy, 1988; de Villiers, 1977; Williams, 1988, 1994). However, as Herrnstein (1970) noted: "If the matching relation were an accident of the duration of the COD, it would hardly be a principle of either response strength or choice" (p. 248; see also Herrnstein & Loveland, 1976, p. 143).

Ideally, a measure of the relative strengths of two discriminated operants would require the two operants to be acquired without simultaneously acquiring other operants, such as switching, which could affect the monitored response. The present experiment sought to meet this requirement by first exposing pigeons to a multiple schedule in which keys of different colors consistently were associated with different variable-interval (VI) reinforcement schedules but in which the location of the illuminated key varied randomly between two locations. By so doing, responding could come under the

control of different key colors and could also be reinforced equally often at either of the two locations. Such a procedure establishes discriminated key-pecking operants of different strengths but without a history of reinforcement for switching. Following this training, two keys were simultaneously illuminated for the first time and the relative frequency of responding was assessed. Thereafter, various concurrent schedules were successively introduced that more closely approximated the conditions customarily used to investigate the relation between relative response frequency and relative reinforcement frequency.

METHOD

Subjects

The experiment used 3 experimentally naive White Carneau pigeons—C51, C52, and C53—derived from stock obtained from the Palmetto Pigeon Plant, Sumter, SC, and bred in a local colony.

Apparatus

Three experimental chambers (Lehigh Valley Electronics) equipped with two-key intelligence panels were used. The response keys were 2.54 cm in diameter and placed 16.5 cm apart at their centers and 24 cm above the floor. The opening to a food tray was located near the floor and midway between the two response keys. The response keys required between 0.1 and 0.2 N static force to operate their microswitches. Each chamber was constantly illuminated by a white houselight located at the top of the intelligence panel midway between the two response keys, and was ventilated by a fan and shielded from ambient sounds by an 80-dB white noise. An IEE display cell positioned behind each key transilluminated the plastic pecking key with light whose dominant wavelength could be varied. The wavelengths were produced by simultaneously passing light from two bulbs through individual Kodak® Wratten® filters. The dominant wavelengths transmitted by the filters were 538, 555, or 576 nm. Five different stimuli were used during the experiment, three during training and all probe tests (S1, S3, and S5) and two during some probe tests only (S2 and S4). The three training stimuli were produced by the combined effects of two filters transmitting the same dominant wave-

length—S1 (538 nm), S3 (555 nm), or S5 (576 nm). The uniquely probe stimuli, or *generalization* stimuli, were produced by the combined use of filters transmitting different dominant wavelengths—S2 (538 and 555 nm) and S4 (555 and 576 nm). The dominant combined transmissions were intermediate between the two filters; that is, S2 (549 nm) and S4 (559 nm) as determined by Lyons and Klipec (1971). Stimulus presentation was controlled and key pecking was monitored at 50-ms intervals by a ModComp® II minicomputer located in an adjacent room.

Procedure

In overview, the experiment consisted of four phases: multiple-schedule training, equal-concurrent training, full-concurrent training, and a redetermination of multiple-schedule training. During multiple-schedule training, pecking was reinforced on a three-component, multiple schedule consisting of S1 correlated with a VI 30-s schedule, S3 correlated with a VI-90 s schedule, and S5 correlated with a VI 270-s schedule. During equal-concurrent training, concurrent periods were presented in a multiple schedule with three components—S1-S1, S3-S3, and S5-S5. Thus the stimuli on the simultaneously transilluminated keys were always identical. During full-concurrent training, all six possible combinations of the three stimuli in the two key locations were presented, each correlated with its respective VI schedule. Technically, the third phase of the experiment may be described as a multiple schedule with six concurrent-schedule components. During the final phase of the experiment, multiple-schedule training was reinstated to determine if the effects we had obtained with this procedure would recur following the history of reinforcement for switching operants. Throughout the latter portion of each of the four phases of training, probe periods without reinforcement were occasionally introduced between training components. A more complete description of each phase of the experiment follows.

Multiple-schedule training. Using an auto-shaping procedure, key pecking was reinforced whenever S3 appeared on either the left or the right key. Initially, S3 was presented on a key for 8 s with a variable intercomponent interval averaging 45 s during which the

key was darkened. Food was presented at the end of 8 s or immediately following a peck to the lighted key, whichever came first. Once pecking had begun, the stimulus duration was gradually increased to 60 s or until a key peck produced a reinforcer. After a single session of continuous reinforcement, a VI schedule was introduced and gradually increased to VI 90 s. During this period, an equal number of reinforcers were obtained for pecking the right and left keys. The VI 90-s schedule and all other VI schedules were constructed using 18 intervals from an exponential distribution according to the method of Fleshler and Hoffman (1962). The orders of the intervals were balanced such that interreinforcement intervals of different lengths followed one another with approximately equal frequency. The orders were independently changed from session to session and from subject to subject. Reinforcers consisted of 3-s access to grain during continuous reinforcement and were reduced to 2.5 s for the remainder of the experiment. Because all pigeons were eventually exposed to concurrent training with a 2-s COD, a COD of that value was used throughout training including the multiple-schedule phase. Thus the first peck during a stimulus began the COD, and the first reinforced peck occurred after at least 2 s had elapsed without an intervening peck to the other key during the concurrent-schedule procedure. The duration of stimulus periods remained 60 s throughout the experiment.

Once the VI schedule during S3 had reached its final value of VI-90 s, S1 was introduced correlated with a VI 30-s schedule. After 12 sessions of exposure to a multiple schedule consisting of S1 and S3, S5 was introduced correlated with a VI 270-s schedule. When S5 was introduced, the rate of responding systematically declined for Pigeons C51 and C53 over the first four sessions of exposure to that stimulus. Consequently, only S5 was presented for three sessions, whereupon the rate increased. Thereafter, all three components of the multiple schedule were presented for a total of 110 sessions. Throughout the multiple-schedule phase of the experiment, each stimulus was presented equally often and there were 36 VI components per session. Each stimulus appeared equally often on the right and left keys and no stimulus occurred more than two consecutive periods

on the same key. Also, no more than two stimuli of the same wavelength occurred in succession. The intercomponent interval, during which the response keys were darkened, was 30 s to minimize interactions between components.

In the final nine sessions of the multiple schedule, 1-min concurrent-probe tests were inserted after training components 7, 13, 18, and 26. All nine possible combinations of stimuli could not be presented within a single session but, over the course of the nine sessions, each of the nine possible combinations of components for the concurrent-probe tests appeared four times for a total observation time of 4 min per probe. (The nine types of probe periods consisted of three in which the components were the same wavelength—for example, S1-S1—and six in which the components were of different wavelengths with the key locations of the components counter-balanced—for example, S1-S3 and S3-S1.) Because responding during the probe periods was not reinforced, *pseudo-probe periods* consisting of components of the multiple schedule without reinforcement were introduced at the same four points throughout the last 50 sessions of multiple-schedule training. This procedure slightly increased the nominal values of the VI schedules, but enhanced resistance to extinction by increasing the number of components without reinforcement and was intended to retard the discrimination of probe periods from training periods with reinforcement. The practice of introducing pseudo-probe periods at times within the session when true probe periods would ultimately be inserted was implemented for all four phases of the experiment.

Equal-concurrent training. In the second phase of the study, a session consisted of eighteen 60-s periods of concurrent training during which the concurrent stimuli were correlated with the equal VI schedules—S1-S1, S3-S3, or S5-S5. Each of the 57 training sessions contained six instances of the three types of equal-concurrent schedules. Eighteen additional sessions were then run in which concurrent-probe tests were inserted after Training Periods 7 and 13. The number of sessions of probe testing permitted a total observation time of 4 min for each of the nine possible pairs of concurrent-probe stimuli.

Full-concurrent training. In the third phase of training, each session consisted of 24 components during which each of the nine possible pairs of concurrent schedules was presented equally often over a span of three sessions. Following 57 sessions of full-concurrent training, concurrent-probe periods were inserted after Training Periods 7 and 13. The concurrent-probe tests included all combinations of the three training stimuli—S1, S3, and S5—as well as all combinations involving the two generalization stimuli—S2 and S4. Thus there were a total of 25 types of concurrent-probe tests with the locations of the stimuli counterbalanced. Given that there were only two probe periods per session, 25 sessions were required to obtain a total of 2 min of observations for each type of concurrent-probe test. A total of 75 sessions of probe testing (3 cycles of 25 sessions) were given during the final portion of full-concurrent training, yielding a total of 6 min of observations for each pair.

Redetermination of multiple-schedule training. The final phase consisted of 30 sessions of multiple-schedule training identical to the conditions present in the first phase of the experiment followed by nine additional sessions in which concurrent-schedule probe periods were introduced as before. The purpose of repeating multiple-schedule training was to determine if the same distribution of responding would recur during probe periods after the pigeons had a history of reinforcement for CO responses during equal-concurrent and full-concurrent training.

RESULTS AND DISCUSSION

Performance during each of the four phases of the experiment was assessed by the response frequencies during the various combinations of concurrent-probe stimuli and by finer grained analyses that provided a more detailed account of the behavior that contributed to the overall measures.

Effects of Multiple-Schedule Training

Figure 1 shows the effects of changes in relative reinforcement frequency on relative response frequency during the four phases of the experiment. The leftmost column of panels in Figure 1 depicts the frequency of responding on the left key relative to total re-

sponding on both keys following training with the multiple schedule. Responding is shown for each of the 3 subjects during concurrent-probe periods. The findings are reported in terms of relative left-key responses to enable comparisons of performance when a stimulus (e.g., S1) appeared on the left key in a given concurrent-schedule component (e.g., S1-S5) with performance when that same stimulus appeared on the right key (e.g., S5-S1). (See Table 1 for the number of responses on the left and right keys for each stimulus combination during probe periods after multiple-schedule training.) Plotting responses separately to the left and right keys revealed the reliability of preferences during probe periods across the full range of relative reinforcement frequencies. The diagonal lines in Figure 1 illustrate performance if relative response frequency exactly matched relative reinforcement frequency.

The relative frequency of reinforcement for a given probe period was based on the number of *programmed* reinforcers. Programmed reinforcers were used instead of obtained reinforcers because reinforcers never occurred during any concurrent-probe period and never occurred in either training or testing when the component included generalization stimuli. An estimate of the relation between obtained and programmed reinforcers during training was provided by observations from the full-concurrent procedure when reinforcers were available during both stimuli in all concurrent components. With this procedure, the number of programmed reinforcers was highly correlated with the number of obtained reinforcers as shown by regression lines whose slopes approximated 1.0 and whose percentages of variation in the number of obtained reinforcers predicted from the number of programmed reinforcers exceeded 98% for all pigeons (See Crowley, 1981). The only systematic departure from the regression line occurred with Pigeons C52 and C53 when the concurrent component involved S1 in combination with S5; that is, the components associated with the most disparate reinforcement schedules (VI 30 and VI 270). In that case, approximately two reinforcers were programmed during the time S5 was presented, but none was obtained by either pigeon. Table 1 shows that no respons-

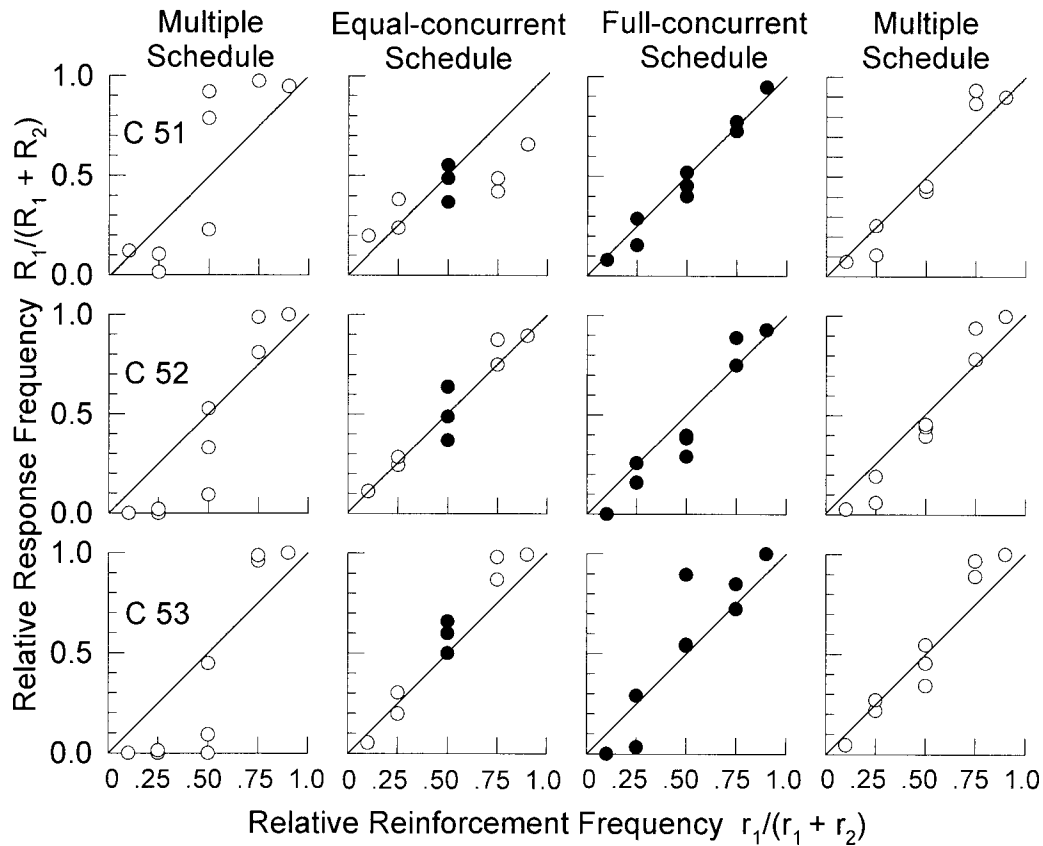


Fig. 1. The relative frequency of responding during concurrent-probe periods without reinforcement as a function of the relative frequency of reinforcement programmed for the alternatives during training. The diagonal lines represent the relation between these variables if exact matching had occurred. Findings are shown for subjects C51, C52, and C53 following multiple-schedule training in which the components were presented separately (first column), following equal-concurrent training in which only stimuli associated with the same reinforcement frequencies were concurrently presented (second column), following full-concurrent training in which all pairs of stimuli were concurrently presented (third column), and following a return to multiple-schedule training in which the components were again presented separately (last column). Open circles designate concurrent probes that were not presented during the immediately preceding training regimen; filled circles designate concurrent pairs that were presented during the immediately preceding training regimen.

es occurred to S5 during concurrent-probe periods for either Pigeon C52 or C53.

As shown in the leftmost column of Figure 1, a matching relation did not emerge after the pigeons had received only multiple-schedule training. Instead, the relation of relative response rate to relative reinforcement rate approximated a step function in which the stimulus associated with the richer VI schedule was always chosen. It is important to note that, in order for near-exclusive preference to occur, *both* of the stimuli had to be accurately discriminated. Thus the establishment of two discriminated operants was not a sufficient condition for relative response frequency to

match relative reinforcement frequency when the stimuli that control those operants were presented in a choice situation prior to the establishment of switching operants.

The absence of matching was not due to the complete absence of switching responses, however. Switching was measured by the number of CO responses, where a CO response was defined as a response on a key that immediately followed a response on the other key without an intervening change in the stimuli on the keys. As shown in Table 1, all pigeons exhibited some CO responding during probe periods. Most CO responses occurred when the concurrently presented

Table 1

The number of key-pecking responses and the number of changeover (CO) responses during concurrent-probe tests for the four phases of the experiment—multiple-schedule training, equal-concurrent training, full-concurrent training, and a redetermination of multiple-schedule training. The numbers of key-pecking responses are shown separately for the left (L) and right (R) keys in all combinations of variable-interval (VI) schedules (in seconds) presented during concurrent-probe periods. Responding is shown for each of the 3 subjects—C51, C52, and C53—for a total of four 1-min probe periods. (Although there were six probe periods during full-concurrent training, only the first four periods are shown to facilitate direct comparisons among the various phases of the experiment.)

Subject	Schedule	Relative reinforcement frequency								
		.50			.25		.75		.10	
	VI (L)	270	90	30	270	90	90	30	270	30
	VI (R)	270	90	30	90	30	270	90	30	270
Multiple-schedule training										
C51	L	26	121	285	1	29	181	293	15	158
	R	85	25	24	184	264	1	0	124	9
	CO	3	22	6	2	5	2	0	10	9
C52	L	29	212	139	9	0	348	379	0	415
	R	290	192	282	508	477	83	7	518	0
	CO	13	87	7	4	0	36	4	0	0
C53	L	46	19	1	0	0	216	308	0	321
	R	59	220	277	224	332	8	8	278	0
	CO	15	6	2	0	0	5	11	0	0
Equal-concurrent training										
C51	L	78	102	168	84	133	96	137	41	143
	R	62	183	177	284	208	103	190	163	74
	CO	11	25	20	25	33	15	25	17	12
C52	L	221	250	250	144	173	375	507	59	524
	R	126	260	451	353	515	123	69	572	68
	CO	18	27	41	22	28	24	15	14	16
C53	L	57	175	222	22	86	255	240	7	297
	R	29	117	225	87	201	8	35	145	3
	CO	11	24	34	9	15	11	23	5	3
Full-concurrent training										
C51	L	73	122	173	51	109	213	261	31	282
	R	67	143	254	272	266	64	96	370	19
	CO	21	23	26	21	24	18	18	12	5
C52	L	127	238	281	82	154	388	418	0	411
	R	315	352	444	434	469	129	52	532	30
	CO	20	27	39	13	20	22	8	0	8
C53	L	64	167	186	5	100	267	232	0	339
	R	7	142	158	132	229	46	88	245	0
	CO	5	27	29	4	20	18	29	0	0
Redetermination of multiple-schedule training										
C51	L	39	103	173	24	91	154	246	22	237
	R	48	136	215	194	278	24	18	262	31
	CO	10	38	13	8	12	16	3	6	5
C52	L	167	249	255	79	39	313	444	17	443
	R	211	386	302	345	545	89	30	575	0
	CO	16	39	36	11	9	15	3	4	0
C53	L	18	177	134	55	69	230	260	8	263
	R	34	143	158	149	239	28	7	216	3
	CO	6	33	11	12	13	10	5	2	2

stimuli were associated with equally rich schedules of reinforcement. When a CO response occurred during a probe period, the time between responding on a key and switching to the other key was typically very brief. Examination of the relative frequency distributions of CO times indicated that the mode was less than 2 s (the duration of the COD). For Pigeons C51, C52, and C53, the percentages of total CO responses that occurred within 2 s was 24%, 37%, and 36%, respectively. (For a comprehensive presentation of other aspects of responding including local frequencies of responding, CO-time distributions, and interresponse-time distributions, see Crowley, 1981; cf. Menlove, 1975.) Taken together, these findings indicate that switching occurred at some baseline level in the absence of an explicit history of reinforcement for CO responses and that both stimuli were discriminated on concurrent-probe periods because the frequency of CO responses varied with the stimulus on the other key. Nevertheless, matching did not occur.

Effects of Equal-Concurrent Training

During equal-concurrent training, subjects were provided with a history of reinforcement for switching but only when stimuli on the concurrently presented keys were the same. Thus, to the extent that CO responses were jointly controlled by the stimuli on both keys, switching during concurrent-probe trials in which the stimuli differed was due to generalized CO responses. As shown in the second column of panels in Figure 1, the near-exclusive preference found after multiple-stimulus training gave way to a more gradual transition in preference that approximated a matching relation. The change resulted primarily from an increase in relative responding to the alternatives associated with a .25 relative reinforcement frequency and a decrease in relative responding to the alternatives associated with a .75 relative reinforcement frequency. Relative responding during probe periods was less affected at the more extreme values (.10 or .90) of relative reinforcement frequency, except for Pigeon C51 whose relative responding changed less across all relative reinforcement frequencies.

The absolute levels of responding that gave rise to the changes in relative response frequency as a function of relative reinforce-

ment frequency are shown in Table 1. Total responding during concurrent-probe periods in equal-concurrent training did not change systematically—increasing for Pigeons C51 and C52 but falling for Pigeon C53 (cf. Killeen, 1972). However, responding during probe periods in which the stimuli were the same on both keys did increase substantially for all pigeons. Thus stimulus combinations that had been present when responses were reinforced showed consistent increases in responding as the result of equal-concurrent training.

Equal-concurrent training substantially increased CO responding for all pigeons, especially when the stimuli on the two keys differed (see Table 1). Thus CO responses generalized from the conditions under which they occurred during equal-concurrent training to the conditions present during probe periods when the stimuli on the keys were different. The increase in CO responses was accompanied by a general decrease in short stay times before switching to the other key. The times between responding on a key and switching to the other key were now seldom as brief as they had been during multiple-schedule training. During probe periods, the relative frequency of CO responses that followed stay times of less than 2 s fell to 3%, 7%, and 12% for Pigeons C51, C52, and C53, respectively. These brief CO times on probe trials occurred most often when switching from pecking S5 (the stimulus associated with the lowest reinforcement frequency) to pecking either S1 or S3.

The relative frequency distributions of CO times during concurrent training trials are shown in Figure 2. These relative frequency distributions were obtained from the same sessions of equal-concurrent training as those in which probe periods were presented. (The corresponding relative frequency distributions of CO times based on probe periods alone were similar, although less stable because they were based on fewer observations; Crowley, 1981.) As shown in the upper row of CO distributions for each pigeon in Figure 2, the modal time before a CO response was typically 6 to 7 s during equal-concurrent training. The modes of the relative-frequency distributions of CO times became less pronounced as reinforcement frequency decreased from S3 to S5, especially for Pigeon

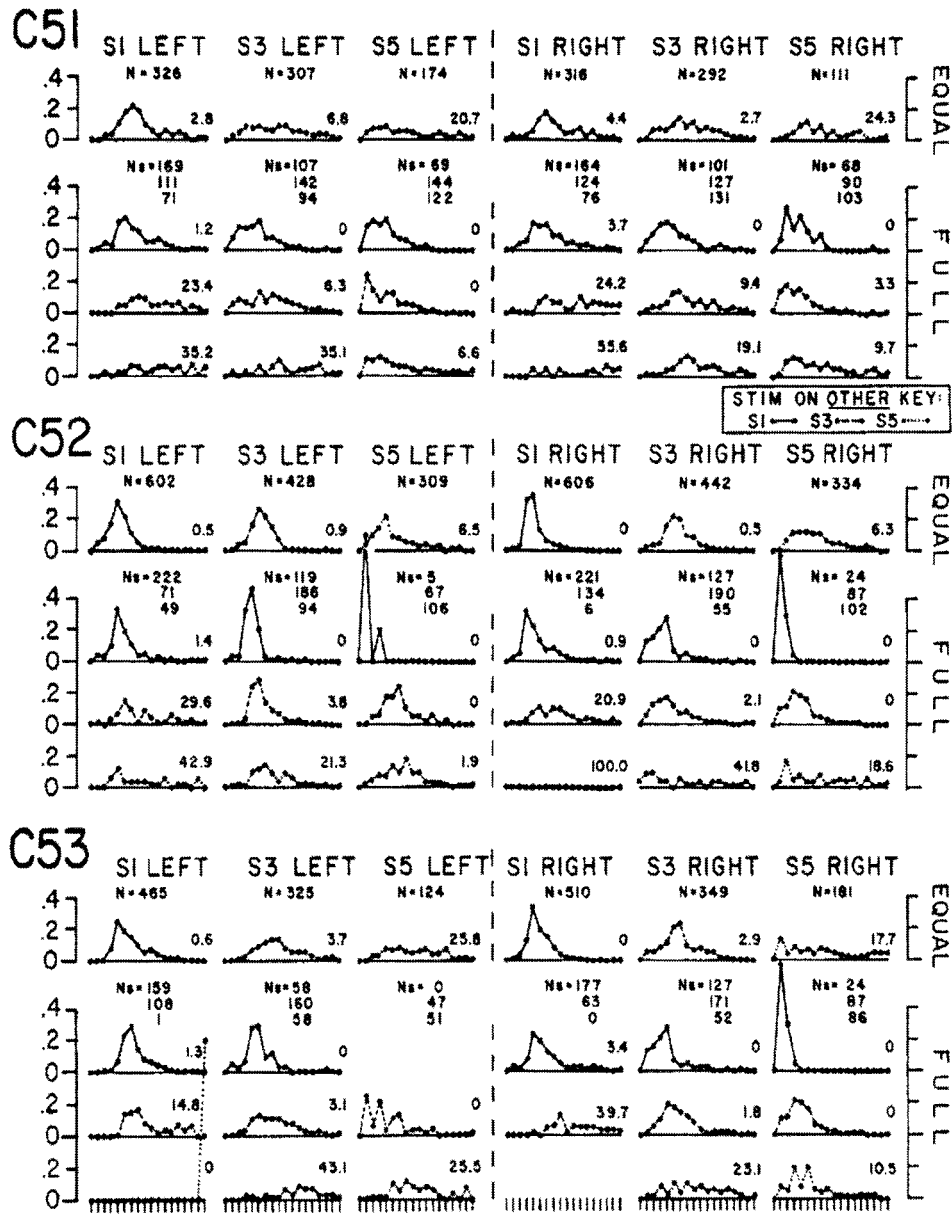


Fig. 2. Relative frequency distributions of the times of changeover (CO) responses during equal-concurrent training (EQUAL) and full-concurrent training (FULL) for subjects C51, C52, and C53. The distributions are shown separately for responding to stimuli (S1, S3, or S5) on the left and the right keys. During equal-concurrent training, CO distributions were obtained only when the stimulus on the other key was the same. During full-concurrent training, CO distributions are separately shown for each of the three stimuli that appeared on the other key—S1, S3, and S5. The number above the right tail of each distribution indicates the percentage of total CO responses whose times were greater than 20 s. The numbers above the equal-concurrent distributions indicate the number (N) of CO responses on which the distribution was based. The numbers (Ns) above the first set of full-concurrent distributions indicate the number of responses for each distribution as the stimulus varied on the other key.

C51 whose total responding was least sensitive to changes in relative reinforcement frequency. For C51, the time before a CO response was more evenly distributed throughout the concurrent period and was less influenced by the stimulus on the other key.

Effects of Full-Concurrent Training

With full-concurrent training, which is the usual procedure under which a matching relation is observed, switching and other operants can occur and be reinforced in the presence of all combinations of stimuli. Unlike equal-concurrent concurrent training, switching between S1, S3, and S5 did not require generalization of CO operants from training to testing. As shown in the third column of panels in Figure 1, relative response frequency even more closely approximated relative reinforcement frequency, especially for Pigeon C51. The absolute frequencies of responding that gave rise to the matching relation are shown in Table 1. The shift from equal-concurrent to full-concurrent training had no systematic effect on the total number of either key-pecking or CO responses (compare within Table 1). The control of switching behavior during full-concurrent training was complex, as shown in Figure 2. CO responses were now clearly affected by both the stimulus on the key that was being pecked and by the stimulus on the other key to which responding was switched. The effects of the stimulus being pecked can be seen by comparing the relative frequency distributions of CO times along the rows of the full-concurrent procedure. In general, the time before the occurrence of a CO response decreased as the reinforcement frequency during the stimulus decreased. That is, when the reinforcement frequency on the key being pecked was lower than for its companion stimulus, switching to the other key occurred sooner. The increase in the times of CO responses was particularly pronounced during S5, the stimulus associated with the VI-270 schedule. The effects of the stimulus on the other key are shown by comparing distributions along the columns of Figure 2. As the reinforcement frequency associated with the other key decreased, the time before a CO response increased and was again most pronounced when S5 was on the other key. That is, when the reinforcement frequency on the

other key was lower, switching to the other key occurred later. In short, CO operants came under the joint control of both stimuli during full-concurrent training.

In addition to assessing the effects of relative reinforcement frequency on responding to stimuli in which reinforcers had occurred, other sessions included concurrent-probe periods in which generalization stimuli (S2 and S4) appeared. The various stimulus combinations were each presented for a total of six probe periods, but stimulus pairs that included generalization stimuli came to be discriminated from pairs in which reinforcers occurred. As a result, responding began to extinguish during probe periods that contained a generalization stimulus, especially when both stimuli of the pair were generalization stimuli. Accordingly, findings are presented for only the first two of the six probe periods (see Crowley, 1981, for further information). The reinforcement frequencies associated with the generalization stimuli were estimated by linear interpolation between the programmed reinforcement frequencies of the two neighboring stimuli.

The concurrent-probe periods may be described by two terms, the first term indicating the stimulus on the left and right keys, respectively, and the second term (shown by a proportion in parentheses) indicating the relative reinforcement frequency. In order of increasing relative reinforcement frequency, the 25 probe periods were: S5-S1 (.10), S5-S2 (.16), S4-S1 (.23), S5-S3 (.25), S3-S1 (.25), S5-S4 (.28), **S4-S2 (.34)**, S2-S1 (.36), S3-S2 (.37), S4-S3 (.47), **S2-S2 (.50)**, S3-S3 (.50), **S4-S4 (.50)**, S1-S1 (.50), S5-S5 (.50), S3-S4 (.53), **S2-S3 (.63)**, S1-S2 (.64), **S2-S4 (.66)**, **S4-S5 (.72)**, S3-S5 (.75), S1-S3 (.75), S1-S4 (.78), **S2-S5 (.84)**, and S1-S5 (.90).

Responding during two types of concurrent-probe periods was of particular interest: (a) probes in which the estimated reinforcement frequency of the generalization stimulus was *greater* than the programmed reinforcement frequency of the stimulus with which it was paired (i.e., S2-S3, S2-S5, and S4-S5), and (b) probes in which both stimuli were generalization stimuli (i.e., S2-S4, S4-S2, S2-S2, and S4-S4). Concurrent-probe periods of the first type are shown in boldface in the prior list: If responding to the generalization stimulus exceeded responding to the rein-

forced stimulus, then generalized key pecking and CO responses likely affected measures of preference not only during these probe periods but also during the others as well. The interpretation of relative responding during concurrent-probe periods in which the estimated reinforcement frequency of the generalized stimulus was *less* than that of the programmed reinforcement frequency of the reinforced stimulus is ambiguous because greater responding to the reinforced stimulus could simply indicate that reinforced responding was stronger than generalized responding. Probe periods of the second type are shown in bold italics in the list: If relative responding during these probe periods approximately matched their estimated relative reinforcement frequencies, then generalized responding could have promoted matching during other probe periods as well.

Figure 3 depicts findings averaged across the first two concurrent-probe periods for all 25 possible pairs of stimuli. Probe periods in which both members of the pair were previously reinforced stimuli are indicated by filled circles. Probe periods in which a generalization stimulus was paired with a directly reinforced stimulus are indicated by triangles—by filled triangles when the estimated reinforcement frequency of the generalization stimulus was greater than the programmed reinforcement frequency of the reinforced stimulus, and by unfilled triangles when the reverse was true. Probe periods in which both stimuli were generalization stimuli (e.g., S2 and S4) are indicated by unfilled circles.

As shown in Figure 3, all pigeons responded more frequently to a generalization stimulus associated with a higher estimated reinforcement frequency than to a directly reinforced stimulus of lesser reinforcement frequency for the S4-S5 and S2-S5 pairs, and Pigeon C51 did so for the S2-S3 pair—the pair with the smallest difference between estimated and programmed reinforcement frequencies. In short, preference for the generalized stimulus over the reinforced stimulus was typically greater than 0.5. When concurrent-probe periods consisted exclusively of generalization stimuli, all pigeons responded more frequently to the stimulus associated with the higher estimated reinforcement frequency, and preference typically approximat-

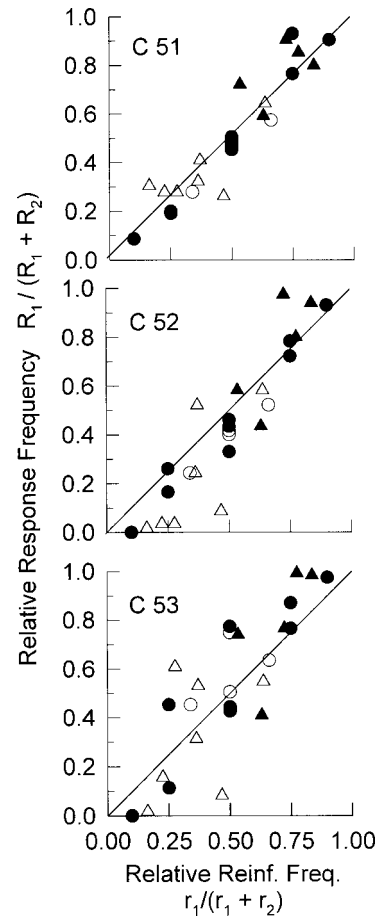


Fig. 3. The relative frequency of responding during concurrent-probe periods as a function of the relative frequency of reinforcement of the components. The diagonal lines represent the relation between these variables if perfect matching had occurred. The findings are shown for subjects C51, C52, and C53 following full-concurrent training in which all combinations of S1, S3, and S5 were presented. Concurrent-probe periods during which both components involved stimuli present during training are shown by filled circles. Concurrent-probe periods during which one of the components was a generalization stimulus (S2 or S4) are shown by triangles—filled triangles when the relative reinforcement frequencies were greater than 0.5 and unfilled when the relative reinforcement frequencies were less than 0.5. Concurrent-probe periods in which both of the components were generalization stimuli are shown by unfilled circles. Each data point is the average of observations from the first two concurrent-probe periods.

ed matching (Figure 3, unfilled circles). Taken together, these findings indicate that both key-pecking and switching operants generalized and that they contributed to convergence toward a matching relation during

equal-concurrent and full-concurrent training.

Effects of Reinstitution of Multiple-Schedule Training

Upon first exposure to multiple-schedule training, choice measures approximated exclusive preference for the alternative associated with the higher reinforcement frequency (see the leftmost column of Figure 1). As shown in the rightmost column of Figure 1, reexposure to multiple-schedule training did not reinstate this performance. Instead, responding during concurrent-probe periods continued to approximate the matching of relative response frequency to relative reinforcement frequency. The response frequencies upon which the relative measures were based are shown in Table 1. The failure to recover near-exclusive preference is consistent with behavioral principles: The conjunctions of stimuli that controlled switching were not present during multiple-schedule training and, hence, switching operants did not have an opportunity to extinguish in their presence. When these stimuli were again available during concurrent-probe periods, switching operants recurred under their persisting control. As also shown in Table 1, the numbers of CO responses following the reinstatement of multiple-schedule training also differed from those found after the initial exposure to multiple-schedule training. CO responses generally remained elevated as they had after equal- and full-concurrent training, especially with relative reinforcement frequencies of .25 and .75. The finding that exclusive preference was not recovered has implications for the use of nonnaive subjects in studies of choice: Once switching operants have been established, they can intrude into subsequent performance to the extent that subsequent conditions contain the stimuli that control them (cf. Todorov, Oliveira Castro, Hanna, Bittencourt de Sa, & Barreto, 1983).

GENERAL DISCUSSION

This section offers an interpretation of concurrent responding that draws upon the known effects of three-term contingencies on behavior. Summarizing the present findings, the study demonstrated that—in the absence

of the establishment of switching and perhaps other operants—the relative strength of two concurrently discriminated operants approximated exclusive preference for the more frequently reinforced operant. Once switching operants had been established, the relative frequency of the measured responses changed and thereby obscured exclusive preference. These other operants contributed to the measured response on both alternatives and caused relative responding to become less sensitive to variations in the reinforcement frequencies associated with the alternatives (see Equation 1). The “dilution” of exclusive preference was most apparent for concurrent operants of moderate strength because differences in the strengths of these operants were smaller in comparison to the strengths of switching operants. The conflation of responding controlled by the stimulus on a key and CO responses controlled by stimuli on both keys increased relative responding to the less-preferred stimulus and decreased relative responding to the more-preferred stimulus (cf. Silberberg & Fantino, 1970). The comingling of responses of these two origins had the net effect of producing an approximate matching relation between relative response frequency and relative reinforcement frequency.

The foregoing account is congenial to an interpretation of concurrent-operant performance in terms of well-understood discrimination processes. That is, concurrent procedures implement a discrimination between two stimuli that control operants of different strengths. When other operants are absent, choice depends only on the difference in the strengths of the responses controlled by the discriminated stimuli on the keys. Under such conditions, exclusive preference is approximated to the extent that the stimuli are physically distinguishable. However, as various combinations of stimuli acquire control over other operants—most notably switching—these operants affect measured responding and lessen exclusive preference (Myerson & Miezen, 1980; Shahan & Lattal, 1998; Williams, 1996; Williams & Bell, 1996; cf. McDevitt & Williams, 2003; Williams & Bell, 1999). Consistent with this interpretation, even procedures that permit the formation of switching operants yield relative response frequencies that more closely

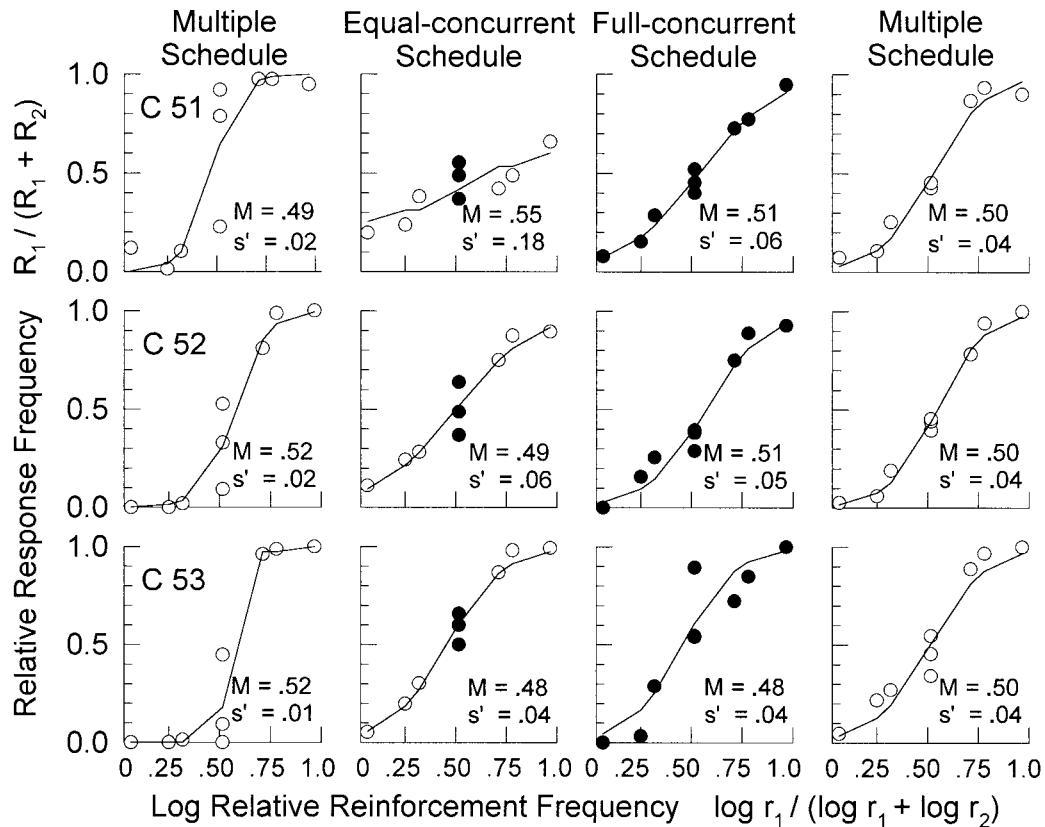


Fig. 4. The effect of relative reinforcement frequency on relative response frequency, where the reinforcement frequencies were logarithmically transformed. Least-squares fits of logistic functions are plotted in each panel. Each panel contains estimates of the parameters of the logistic function—the mean (M) and standard deviation (s'). Filled circles designate concurrent-probe periods that were present during the immediately preceding training regimen; open circles designate concurrent-probes that were not present during the immediately preceding training regimen. Findings are shown for each subject—C51, C52, and C53—during each of the training procedures—multiple schedule, equal-concurrent schedule, full-concurrent schedule, and a return to the multiple schedule.

approximate exclusive preference when the measured responses are confined to the time period before the occurrence of the first switching response (Logue, 1983). Switching and other operants constitute “noise” with respect to the “signal” provided by the concurrently presented stimuli associated with the two reinforcement schedules.

Figure 4 displays the findings from all four phases of the experiment together with psychometric functions arising from a discriminative interpretation of concurrent performance. Because of the well-documented diminishing effect of increases in reinforcement frequency on response frequency, the programmed reinforcement frequencies underwent a logarithmic transformation prior to determining the relative reinforcement

frequencies (cf. Davison & Hunter, 1976; Herrnstein, 1970; Killeen, 1968; Wearden, 1980). These transformed relative reinforcement frequencies were then used in fitting logistic functions to the relative response frequencies. If $R = R_1 / (R_1 + R_2)$ and $r = \log r_1 / (\log r_1 + \log r_2)$, where r is the reinforcement frequency, then the logistic function is given by

$$R = 1 / [1 + e^{-s(r-M)}]. \quad (3)$$

The parameters of the logistic function— M , the mean preference, and s , a term that is inversely proportional to the standard deviation of the noise distribution—were estimated by an iterative procedure that minimized mean-square error. Note particularly that logarithmic transformations of the two

combinations of concurrent stimuli that produced relative untransformed frequencies of .25 and .75 were now distinguished from one another and that their associated relative response frequencies covaried appropriately.

Overall, the logistic function accurately described the functional relation of relative response frequency to relative reinforcement frequency as shown by absolute mean deviations of predicted from obtained relative reinforcement frequencies across all four conditions of less than .06, .06, and .04 for Pigeons C51, C52, and C53 respectively. (It is perhaps worth remarking that the quantitative method used here is essentially that of William Crozier, 1940, Skinner's graduate-school mentor; see Vargas, 2000. For other psychophysical approaches to matching, see Davison & Tustin, 1978; Nevin, Jenkins, Whittaker, & Yarensky, 1982.) The values of M for the various logistic functions are shown in each panel of Figure 4 and were close to 0.5 in all cases. Thus there was relatively little bias toward responding to one key location rather than to the other (i.e., there was little position preference). The values of s' , where $s' = 1/s$, in each panel of Figure 4 reflect the noise level in each procedure, that is the extent to which CO and perhaps other operants contributed to the measured response. As can be seen, responding due to other operants minimally affected the measured response during multiple-schedule training and then increased as switching was conditioned during equal- and full-concurrent training. When training reverted to the multiple-schedule procedure after switching operants had been conditioned, the effects of these other operants continued largely unchanged.

As a possible experimental test of the contribution of switching and other operants to concurrent performance, consider the following: Suppose that a multiple schedule were instituted in which three dissimilar stimuli, A, B, and C, were correlated with VI 90-s, VI 90-s, and VI 270-s schedules, respectively, and in which a darkened key X was correlated with extinction. Following such training, suppose further that pairs of these stimuli were presented during concurrent-schedule periods having components A-A, X-B, B-X, and C-C. With such a procedure, switching operants would have been reinforced during stimulus A and C (as in the equal-concurrent

procedure of the present experiment) but not in the presence of stimulus B (as in the multiple-schedule procedure). If presented for the first time with an A-C probe trial, choice should approximate matching because switching had been reinforced during training with both stimuli. However, if the same subjects were presented for the first time with either A-B or B-C concurrent-probe trials, choice should approximate exclusive preference because switching had never been reinforced in the presence of these combinations of stimuli. Thus choice would approximate matching in the first case but exclusive preference in the second, each case reflecting the particular history of reinforcement with respect to switching (Crowley, 1981, pp. 146–147).

Conceptualizing performance on concurrent schedules as an instance of discrimination formation with multiple sources of stimulus control is fruitful experimentally on other grounds as well. For example, the contribution of switching and other operants to the measured response would be expected to increase as the similarity increased between the stimuli associated with the different reinforcement schedules. Accordingly, one would anticipate that the contribution of switching operants would be substantial in concurrent-operant procedures in which the stimuli on the two keys were the same for all reinforcement schedules and only the locations of the keys differentiated between the two schedules. This is the case in commonly used concurrent-schedule procedures in which matching has been observed. Experimental evidence indicates that stimuli located in proximity to the point on the key contacted by the beak are especially salient for the control of responding (e.g., Jenkins & Sainsbury, 1969; Sainsbury, 1971). Under such circumstances, responses emitted and reinforced in the presence of the stimulus on one key readily generalize to similar stimuli on the other key. These generalized operants promote matching because they affect the measured response on the two keys similarly.

Note that there are two avenues by which generalization promotes matching: First, responses directly conditioned to one stimulus (e.g., S_A-R_1) can generalize to a similar stimulus on the other key (e.g., S_B-R_2). Second, switching and other operants conditioned to

the conjunction of the two stimuli can affect the measured response to both stimuli. Thus concurrent-schedule procedures that employ similar stimuli promote the generalization of responses originally conditioned to the other stimulus to the stimulus on which the response is being measured. In the case of the present experiment, the visual stimuli transilluminating the keys were all from the portion of the visual spectrum that appears in the green region to a human observer. It is likely that relative responding during multiple-schedule training would have more closely approximated exclusive preference if less similar stimuli had been used (Davison, 1996; Hanna, Blackman, & Todorov, 1992; Miller, Saunders, & Bourland, 1980).

Other work is consistent with the proposition that the similarity of stimuli associated with the various reinforcement schedules affects the matching relation. For example, Herrnstein and Loveland (1976) used four dissimilar key colors that were associated with different concurrently presented reinforcement schedules. After training with a subset of the six possible pairs of these stimuli, responding to two previously untrained pairs was assessed. Responding on these untrained concurrent probe tests "deviated systematically from matching in most cases by exaggerating the preference for the alternative that had the higher frequency of reinforcement" (p. 143). These findings were commented upon as follows: "Given the present results, we conclude only that matching requires an ongoing interaction with the conditions of reinforcement and that what is learned about individual alternatives bears an as-yet-unspecified relationship to frequency or probability of reinforcement" (p. 153). The present experiment indicates that switching operants are an important part of what is learned in concurrent procedures and that these operants contribute to matching.

The multiple-schedule procedure used in this experiment minimized the formation of switching operants but probably permitted some generalization of directly conditioned responses between the alternatives. The use of dissimilar stimuli in concurrent schedules does not prevent the conditioning of switching and other operants, but it does limit their generalization and thereby their contribution to the measured response to the other stim-

ulus. When generalization occurs, the measured response to a stimulus is a mixture of responses directly conditioned to that stimulus and responses generalized from other stimuli. Experimental methods exist, such as the differential reinforcement of different response topographies to the two alternatives, that can be used to identify the origins of these responses during concurrent performance (cf. Crowley, 1979).

The acquisition of switching and other operants that affect the measured response can be reduced through means other than decreasing the similarity between stimuli. For example, when transitions between the two stimuli require additional behavior that increases the time between responding to the alternatives (e.g., behavior such as circumventing a physical barrier between the stimuli), relative responding has been found to approximate exclusive preference (e.g., Boelens & Kop, 1983). This additional time is often designated "travel time" in keeping with the terminology of foraging theory. Commenting on the findings of one such study, Baum (1982) noted, "When the travel requirement was small, the relations between choice and relative reinforcement revealed the usual tendencies toward matching and undermatching. When the travel requirement was large, strong overmatching occurred" (p. 35). This finding is consistent with the present interpretation of concurrent performance.

In conclusion, the present experiment argues for the use of a variety of experimental procedures to study the heterogeneous set of behavioral processes that fall under the heading of "choice." Choice—as with other terms of extrascientific origin—encompasses a diverse set of behavioral processes whose understanding requires a variety of experimental methods. Beyond the variables considered in this discussion, many local variables that arise from the successions of responses that occur in free-operant procedures undoubtedly also affect the overall frequency of responding. Methods appropriate to the analysis of such variables are under investigation (e.g., Baum & Davison, 2004; Davison & Baum, 2003; Keen & Machado, 1999; MacDonall, 1999, 2003; Machado & Keen, 1999; Silberberg & Williams, 1974; Williams, 1993). When only a few methods are used, reliability

of findings may be mistaken for validity of principles.

REFERENCES

- Baum, W. M. (1974). On two types of deviations from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior*, 22, 231–242.
- Baum, W. M. (1979). Matching, undermatching, and overmatching in studies of choice. *Journal of the Experimental Analysis of Behavior*, 32, 269–281.
- Baum, W. M. (1982). Choice, changeover, and travel. *Journal of the Experimental Analysis of Behavior*, 38, 35–49.
- Baum, W. M., & Davison, M. (2004). Choice in a variable environment: Visit patterns in the dynamics of choice. *Journal of the Experimental Analysis of Behavior*, 81, 85–127.
- Boelens, H., & Kop, P. F. M. (1983). Concurrent schedules: Spatial separation of response alternatives. *Journal of the Experimental Analysis of Behavior*, 40, 35–45.
- Boelens, H., Kop, P. F., Nagel, A. I., & Slangen, J. I. (1986). Concurrent schedules: Maximization versus reinforcement of changeover behavior. *Quarterly Journal of Experimental Psychology: Comparative and Physiological Psychology*, 38, 267–283.
- Boelens, H., Kop, P. F., Nagel, A. I., & Slangen, J. I. (1987). Concurrent schedules: Effects of reinforcement rate and changeover delay on time allocation in a three-alternative procedure. *Quarterly Journal of Experimental Psychology: Comparative and Physiological Psychology*, 39, 229–244.
- Brownstein, A. J., & Pliskoff, S. S. (1968). Some effects of relative reinforcement rate and changeover delay in response-independent concurrent schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, 11, 683–688.
- Catania, A. C. (1962). Independence of concurrent responding maintained by interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, 5, 175–184.
- Catania, A. C. (1966). Concurrent operants. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application* (pp. 213–270). New York: Appleton-Century-Crofts.
- Catania, A. C., & Cutts, D. (1963). Experimental control of superstitious responding in humans. *Journal of the Experimental Analysis of Behavior*, 6, 203–208.
- Crowley, M. A. (1979). The allocation of time to temporally defined behaviors: Responding during stimulus generalization. *Journal of the Experimental Analysis of Behavior*, 32, 191–197.
- Crowley, M. A. (1981). *The acquisition and generalization of matching*. Unpublished doctoral dissertation, University of Massachusetts, Amherst.
- Crozier, W. J. (1940). The theory of the visual threshold: I. Time and intensity. *Proceedings of the National Academy of Sciences*, 26, 54–60.
- Davison, M. (1996). Stimulus effects on behavior allocation in three-alternative choice. *Journal of the Experimental Analysis of Behavior*, 66, 149–168.
- Davison, M., & Baum, W. M. (2003). Every reinforcer counts: Reinforcer magnitude and local preference. *Journal of the Experimental Analysis of Behavior*, 80, 95–129.
- Davison, M. C., & Hunter, I. W. (1976). Performance on variable-interval schedules arranged singly and concurrently. *Journal of the Experimental Analysis of Behavior*, 25, 335–345.
- Davison, M., & McCarthy, D. (1988). *The matching law: A research review*. Hillsdale, NJ: Erlbaum.
- Davison, M. C., & Tustin, R. D. (1978). The relation between the generalized matching law and signal-detection theory. *Journal of the Experimental Analysis of Behavior*, 29, 331–336.
- de Villiers, P. (1977). Choice in concurrent schedules and a quantitative formulation of the law of effect. In W. K. Honig & J. E. R. Staddon (Eds.), *Handbook of operant behavior* (pp. 233–287). Englewood Cliffs, NJ: Prentice-Hall.
- Dreyfus, L. R., DePorto, C. D., & Pasillo, S. A. (1993). Changeover contingencies and choice on concurrent schedules. *Animal Learning & Behavior*, 21, 203–213.
- Dreyfus, L. R., Dorman, L. G., Fetterman, J. G., & Stubbs, D. A. (1982). An invariant relation between changing over and reinforcement. *Journal of the Experimental Analysis of Behavior*, 38, 327–338.
- Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement*. New York: Appleton-Century-Crofts.
- Findley, J. D. (1958). Preference and switching under concurrent schedules. *Journal of the Experimental Analysis of Behavior*, 1, 123–144.
- Fleshler, M., & Hoffman, H. S. (1962). A progression for generating variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, 5, 529–530.
- Hanna, F. S., Blackman, D. F., & Todorov, J. C. (1992). Stimulus effects on concurrent performance in transition. *Journal of the Experimental Analysis of Behavior*, 58, 335–347.
- Herrnstein, R. J. (1961). Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, 4, 267–272.
- Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior*, 13, 243–266.
- Herrnstein, R. J., & Loveland, D. H. (1976). Matching in a network. *Journal of the Experimental Analysis of Behavior*, 26, 143–153.
- Jenkins, H. M., & Sainsbury, R. S. (1969). The development of stimulus control through differential reinforcement. In N. J. Mackintosh & W. K. Honig (Eds.), *Fundamental issues in associative learning* (pp. 123–161). Halifax, Nova Scotia: Dalhousie University Press.
- Keen, R., & Machado, A. (1999). How pigeons discriminate the relative frequency of events. *Journal of the Experimental Analysis of Behavior*, 72, 151–175.
- Killeen, P. (1968). On the measurement of reinforcement frequency in the study of preference. *Journal of the Experimental Analysis of Behavior*, 11, 263–269.
- Killeen, P. (1972). A yoked-chamber comparison of concurrent and multiple schedules. *Journal of the Experimental Analysis of Behavior*, 18, 13–22.
- Logue, A. (1983). Signal detection and matching: Analyzing choice on concurrent variable-interval schedules. *Journal of the Experimental Analysis of Behavior*, 39, 107–127.
- Lyons, J., & Klipec, W. D. (1971). Color mixing with Kodak Wratten filters. *Journal of the Experimental Analysis of Behavior*, 15, 232.

- MacDonall, J. S. (1999). A local model of concurrent performance. *Journal of the Experimental Analysis of Behavior*, *71*, 57–74.
- MacDonall, J. S. (2003). Reinforcing staying and switching while using a changeover delay. *Journal of the Experimental Analysis of Behavior*, *79*, 219–232.
- Machado, A. (1997). Increasing the variability of response sequences in pigeons by adjusting the frequency of switching between two keys. *Journal of the Experimental Analysis of Behavior*, *68*, 1–25.
- Machado, A., & Keen, R. (1999). The learning of response patterns in choice situations. *Animal Learning & Behavior*, *27*, 251–271.
- McDevitt, M. A., & Williams, B. A. (2003). Arousal, changeover responses, and preference in concurrent schedules. *Journal of the Experimental Analysis of Behavior*, *80*, 261–272.
- Menlove, R. L. (1975). Local patterns of responding maintained by concurrent and multiple schedules. *Journal of the Experimental Analysis of Behavior*, *23*, 309–337.
- Miller, J. T., Saunders, S. S., & Bourland, G. (1980). The role of stimulus disparity in concurrently available reinforcement schedules. *Journal of the Experimental Analysis of Behavior*, *8*, 635–641.
- Myerson, J., & Miezian, F. M. (1980). The kinetics of choice: An operant systems analysis. *Psychological Review*, *87*, 160–174.
- Nevin, J. A., Jenkins, P., Whittaker, S., & Yarensky, P. (1982). Reinforcement contingencies and signal detection. *Journal of the Experimental Analysis of Behavior*, *37*, 65–79.
- Pliskoff, S. S. (1971). Effects of symmetrical and asymmetrical changeover delays on concurrent performances. *Journal of the Experimental Analysis of Behavior*, *16*, 249–256.
- Pliskoff, S. S., & Green, D. (1972). Effects on concurrent performances of a stimulus correlated with reinforcer availability. *Journal of the Experimental Analysis of Behavior*, *17*, 221–227.
- Sainsbury, R. S. (1971). Effect of proximity of elements on the feature-positive effect. *Journal of the Experimental Analysis of Behavior*, *16*, 315–325.
- Shanan, T. A., & Lattal, K. A. (1998). On the functions of the changeover delay. *Journal of the Experimental Analysis of Behavior*, *69*, 141–160.
- Shull, R. L., & Pliskoff, S. S. (1967). Changeover delay and concurrent schedules: Some effects on relative performance measures. *Journal of the Experimental Analysis of Behavior*, *10*, 517–527.
- Silberberg, A., & Fantino, E. (1970). Choice, rate of reinforcement, and the changeover delay. *Journal of the Experimental Analysis of Behavior*, *13*, 187–198.
- Silberberg, A., & Williams, D. (1974). Choice behavior in discrete trials: A demonstration of the occurrence of a response strategy. *Journal of the Experimental Analysis of Behavior*, *21*, 315–322.
- Silberberg, A., & Ziriax, J. M. (1982). The interchange-over time as a molecular dependent variable in concurrent schedules. In M. L. Commons, R. J. Herrnstein, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 3. Matching and maximizing accounts of behavior* (pp. 111–130). Cambridge, MA: Ballinger.
- Skinner, B. F. (1950). Are theories of learning necessary? *Psychological Review*, *57*, 193–216.
- Skinner, B. F. (1986). Some thoughts about the future. *Journal of the Experimental Analysis of Behavior*, *45*, 229–235.
- Stubbs, D. A., & Pliskoff, S. S. (1969). Concurrent responding with fixed relative rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, *12*, 887–895.
- Stubbs, D. A., Pliskoff, S. S., & Reid, H. M. (1977). Concurrent schedules: A quantitative relation between changeover behavior and its consequences. *Journal of the Experimental Analysis of Behavior*, *27*, 85–96.
- Todorov, J. C., Oliveira Castro, J. M., Hanna, E. S., Bittencourt de Sa, M. C. N., & Barreto, M. Q. (1983). Choice, experience, and the generalized matching law. *Journal of the Experimental Analysis of Behavior*, *40*, 99–111.
- Vargas, J. (2000). *Brief biography of B.F. Skinner*. B. F. Skinner Foundation, <http://www.bfskinner.org/bio.asp>
- Wearden, J. H. (1980). Undermatching on concurrent variable-interval schedules and the power law. *Journal of the Experimental Analysis of Behavior*, *33*, 49–152.
- Williams, B. A. (1988). Reinforcement, choice, and response strength. In R. C. Atkinson, R. J. Herrnstein, G. Lindzey, & R. D. Luce (Eds.), *Stevens' handbook of experimental psychology* (2nd ed., pp. 167–244). New York: Wiley.
- Williams, B. A. (1993). Molar versus local reinforcement probability as determinants of stimulus value. *Journal of the Experimental Analysis of Behavior*, *59*, 163–172.
- Williams, B. A. (1994). Reinforcement and choice. In N. J. Mackintosh (Ed.), *Animal learning and cognition* (pp. 81–108). San Diego, CA: Academic Press.
- Williams, B. A. (1996). Changeover behavior and preference in concurrent schedules. *Journal of the Experimental Analysis of Behavior*, *65*, 513–526.
- Williams, B. A., & Bell, M. C. (1996). Changeover behavior and preference in concurrent schedules. *Journal of the Experimental Analysis of Behavior*, *65*, 513–526.
- Williams, B. A., & Bell, M. C. (1999). Preference after training with differential changeover delays. *Journal of the Experimental Analysis of Behavior*, *71*, 45–55.

Received November 11, 1994
Final acceptance July 12, 2004