

*CONCURRENT SECOND-ORDER SCHEDULES: SOME EFFECTS OF VARIATIONS IN
RESPONSE NUMBER AND DURATION*

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To examine the effects on concurrent performance of independent manipulations of response-unit duration and number, 6 hens were exposed to concurrent second-order schedules of reinforcement. Each first-order operant unit required completion of a fixed-ratio schedule within the time specified by a fixed-interval schedule, with one further response completing the fixed-interval schedule. The fixed-ratio and fixed-interval requirements comprising the first-order operant units were systematically and independently varied under three pairs of concurrent variable-interval schedules to produce differences in the first-order response and duration requirements (response and duration differentials). These manipulations produced consistent changes in response, time, and operant-unit biases. A 1:4 response differential biased the time and operant-unit measures towards the smaller fixed ratio, but to a degree less than the imposed response differential. The response-based biases favored the larger fixed ratio. Duration differentials of 4:1 and 8:1 biased the response and operant-unit measures towards the shorter fixed interval, again less than the imposed duration differential, but the time biases remained close to zero. Both sorts of differentials acted to bias operant-unit completions more systematically than the other measures, but undermatching to the differentials occurred. The undermatching appears to have arisen from a pattern of fix and sample (in which visits to the less preferred alternative involved only a single completed operant unit) under combinations of unequal operant-unit requirements and reinforcer rates. The response and time bias measures appeared to arise as by-products of the changes in operant-unit completions.

Key words: concurrent schedules, second-order schedules, bias, response requirement, fix and sample, key peck, hen

The generalized matching law (GML) relates behavior under concurrent schedules of reinforcement to the obtained reinforcer rates (Baum, 1979). Expressed logarithmically, the GML is:

$$\log B_1/B_2 = a \log (R_1/R_2) + \log c, \quad (1)$$

where B refers to the behavioral measure (responses made or times spent), R denotes the numbers of reinforcers obtained, the subscripts denote the two alternatives, a represents the sensitivity of the measures to changes in the reinforcer-rate ratios, and $\log c$ represents any constant bias for one alternative over another irrespective of the reinforcer rates obtained.

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Most investigations of concurrent-schedule performance have involved single, identical responses at each of two alternatives. Sensitivity (a) values typically have ranged between 0.7 and 1.0 for response measures and have been slightly higher, but rarely much over 1.00, for time measures (Baum, 1979; Myers & Myers, 1977; Wearden & Burgess, 1982). Unless deliberately manipulated, inherent bias values usually have been close to zero, reflecting little tendency to perform one response more than the other.

Attempts to bias performance that have not involved variations in reinforcer rates usually have varied the consequences on the two schedules. For example, arranging different types of reinforcers on two concurrent schedules produced behavior ratios that fitted straight lines according to Equation 1, displaced up or down the y axis on log-log plots (Hollard & Davison, 1971; Matthews & Temple, 1979). Increases in the responses made on a schedule were usually accompanied by increases in the time spent responding to that schedule.

Outside the experimental chamber, organisms often choose between activities that

require different sorts of behavior. Concurrent operants may have different forms, may differ in the amount of work or force required, and may have different durations. Baum (1979) included the possibility that response requirement differences could appear as sources of constant bias, but few studies have varied the required responses.

A simple variation from identical responses on concurrent schedules is the use of different (single) responses such as a lever press and a key peck as the two alternatives. When the responses required were of different forms, but only one response was required on each schedule so they took similar durations to complete, Davison and Ferguson (1978), Hanson and Green (1986), McSweeney (1978), and Sumpter, Foster, and Temple (1995) found that both response and time measures of bias moved in the same direction, although these were not always of the same magnitude.

Differences between the operant responses required on two concurrent schedules have also been arranged using second-order reinforcement schedules (e.g., Beautrais & Davison, 1977; Cohen, 1975; Sumpter *et al.*, 1995; Sumpter, Temple, & Foster, 1998). In such arrangements, the behavior specified by one schedule of reinforcement (e.g., a fixed-ratio [FR] schedule) is defined as the first-order operant, and this first-order operant produces reinforcers according to a second schedule (e.g., concurrent variable-interval [VI] VI schedules; Kelleher, 1966). Such arrangements allow calculation of three bias measures, using Equation 1, based on three behavioral measures: individual responses, completions of the first-order operants, and time allocations. When first-order numerical requirements (e.g., FR) have been varied, the response and operant-completion biases are clearly not independent for any particular pair of schedule values. These manipulations also have entailed variations in the time taken to complete each operant unit and have sometimes led to the operant-completion and time-allocation bias measures moving in different directions (Beautrais & Davison, 1977; Sumpter *et al.*, 1995, 1998).

Beautrais and Davison (1977) observed that increasing the FR requirement defining an operant unit on one of two concurrently available manipulanda increased the bias in

terms of FR completions, or operant units, towards the manipulandum associated with the smaller FR requirement. In terms of time allocation, however, the observed bias was in the opposite direction (i.e., towards the manipulandum associated with the larger FR requirement). Beautrais and Davison suggested that this result could be taken to reflect a preference for the larger FR requirement but that such an interpretation was "quite incompatible with a common sense notion of choice" (p. 68). They suggested further that the counterintuitive result might have arisen from the use of dependent schedules or from the method of measuring time allocation.

Sumpter *et al.* (1995, 1998) varied the first-order numerical (FR) requirements for two topographically different responses also using dependent concurrent second-order schedules and conventional time-allocation measurement. They, too, observed time bias and operant-unit bias moving in different directions. They argued that these measures would differ when responses vary in both response requirement and time taken to complete the requirement (Sumpter *et al.*, 1998). Consider the effects of an FR 1 versus FR 5 concurrent second-order schedule. The first unit will take approximately one fifth as long as the second. If the animal performs an equal number of operant units on the two schedules, then operant-unit bias will be zero, but time and total response number biases will be towards the larger response requirement. If, instead, the animal performs an equal number of responses, as was approximately found by Sumpter *et al.* (1995), then time and response biases will be close to zero and operant-unit bias will be towards the smaller unit. Beautrais and Davison's (1977) findings and those of Sumpter *et al.* (1998) fell between these two extremes, but closer to the second.

So far studies involving alterations in the numbers of responses comprising a first-order operant unit have confounded changes in number with changes in the duration of the unit. To assess the effects of changes in the number of responses required separately from changes in the duration of the operant unit, these two parameters need to be varied independently.

Foster, Temple, Mackenzie, DeMello, and Poling (1995) devised a variant of the delayed matching-to-sample procedure that allowed

separate control of the number of responses made to, and the time spent in the presence of, a sample stimulus. They required hens to peck a sample stimulus a specified number of times until a tone sounded, and then to stop pecking for the remaining time the stimulus was on. In an adaptation of their methodology, an operant unit could be defined as the completion of a ratio requirement within the time specified by a fixed-interval (FI) schedule, followed by one further response to complete the FI requirement. In such an arrangement, a single peck to one of two lit keys would start both an FR requirement and an FI schedule and darken the other key. Completion of the FR within the time specified would produce blackout followed by the lighting of the key at the end of the FI schedule. A single further peck (with a limited-hold requirement) would complete the operant unit. Both the total number of responses and the overall duration of such a requirement could be controlled and varied. The concurrent reinforcement under VI schedules of two such first-order operant units would allow assessment of the separate effects on choice of changes in response number without the complication of duration changes, and of changes in duration with ratio requirements held constant. The requirement that, once started, an operant unit had to be completed would mirror normal concurrent scheduling and allow full control.

To the authors' knowledge, no previous studies of concurrent second-order schedule controlled duration and number in this way, yet such control may provide data that bear on the question of how behavior and matching should be thought about and measured under concurrent schedules. The proposed scheduling gives three measures of behavior. Whichever measure gives the most orderly data across manipulations involving independent changes in response number and duration may be the most fundamental. If matching of times spent occurs, then changing one alternative's duration alone would affect the ratio of operant units completed but not the ratio of times spent, and changes in response number alone would not affect the ratio of operant units completed. Conversely, if matching of individual responses occurs, then changing one alternative's FR requirement alone would affect the ratio of operant units completed and

the ratio of times spent, whereas changes in duration alone would affect the ratio of times spent but not the ratio of operant units completed.

Data from the concurrent reinforcement of two different interresponse times (IRTs; e.g., Shimp, 1969, 1970) may bear on the possible effects of variations in operant-unit duration while holding required response number constant. Such a procedure is equivalent to the concurrent reinforcement of two different operants each requiring a total of two responses but having differing durations. Shimp (1969, 1970) showed that IRT emissions matched the reciprocals of their durations and, therefore, that alterations in required duration, but not necessarily number, would affect the operant-unit completion ratios. This supports time-based matching. Hawkes and Shimp's (1974) later data, however, suggest that this may hold over only a limited (intermediate) range of reinforcer rates.

The concurrent second-order schedule procedure proposed here also can be conceptualized as a concurrent chains arrangement with minimal (FR 1) initial links. The first-order operant units would constitute the (intermittently reinforced) terminal links of such an arrangement. Considering first the minimal initial links implied by such an analogy, Davison, Alsop, and Dennison (1988) found virtually no preferences between equal fixed-delay and fixed-interval terminal links and no systematic effects of initial link length (VI 10 s to VI 180 s). In contrast, Fantino (1969) found that shorter initial links exaggerated preferences between differing (VI 30 vs. VI 90) terminal links. Davison et al.'s procedure involved blacking out the key during the fixed-delay terminal links, so presumably no responses occurred and therefore the terminal links differed in response requirement. From their data, one would predict that equal duration operant units should be equally preferred independent of response requirement, a similar prediction to that made above on the basis of Shimp's (1969, 1970) studies. When response requirements are different, however, the lower response requirement may be preferred even with equal durations, although Davison et al.'s results suggest not. If any effect of response number exists, then Fantino's results suggest that the use of

a minimal initial link should maximize this preference and the proposed concurrent second-order procedure should reveal it. Any preference might appear as a constant bias when relative reinforcer rates are manipulated and choice is plotted according to the GML.

Neuringer (1969), using relatively long equal VI 90-s initial links, found only small differences between fixed-interval and fixed-delay terminal links and also concluded that the duration rather than a response requirement was the crucial determiner of preference. Again, this suggests that we may find little effect of changes in ratio requirements and strong effects of changes in duration when one is varied with no confounding variation in the other.

Most concurrent-chain terminal links are single stimulus events, whereas the proposed procedure involves a chain of events and stimulus change at differing points. Leung and Winton (1988) found that, despite there being an interaction between overall duration and segmentation ratio in the terminal links, the segmentation was itself a "potent factor affecting choice" (p. 13). Preference moved in favor of segmentation ratios with a short first portion. This implies that, for the present study, operant units with a small ratio requirement should be preferred over operant units with a large ratio requirement when durations are equal, because the former will be segmented earlier. This prediction contrasts with the above predictions that suggest little or no effect of response number alone.

Overall, some possibly contradictory predictions can be made. Manipulation of operant-unit duration alone may produce matching to the reciprocals of the durations regardless of response number requirement, equivalent to time-based matching. Manipulation of response number, however, seems likely to have some effect. Earlier studies varying response number (e.g., Beauthrais & Davison, 1977; Sumpter *et al.*, 1995, 1998) found effects of response number in the logical direction (i.e., preference for the smaller FR requirement). Although these could have arisen from the duration differences, Leung and Winton's (1988) data also imply preference for the earlier segmented (smaller FR) operant units. Simply considering two different ratio requirements (with equal durations) as differing in the work required could imply preference for

the smaller FR requirement, possibly even matching the ratio of the two requirements.

To examine the effects of independent changes in response duration and number, the present study used concurrent second-order schedules with operant units based on Foster *et al.*'s (1995) method. The first-order operant unit consisted of an FR of which the first peck began an FI. Completion of the FR requirement within the FI was signaled, and one further peck (within 5 s after the end of the interval) completed the operant unit. Both the FR and FI requirements were manipulated independently of one another across three different reinforcer-rate pairings in order to produce three-point matching lines, which have been shown to give satisfactory estimates of bias (Sumpter, 1996).

METHOD

Subjects

Six Shaver Starcross hens, numbered 51 to 56 and approximately 12 months old at the start of the study, served as subjects. They were maintained at $80\% \pm 5\%$ of their free-feeding body weights through daily weighing and the provision of postexperimental feed (commercial laying pellets). Water was freely available in their home cages while vitamins and grit were supplied weekly. All hens had previous experience pecking a single key for food and 1 hen (54) had previous experience on concurrent VI VI schedules of reinforcement.

Apparatus

The particleboard experimental chamber was 570 mm long, 420 mm wide, and 540 mm high. The floor consisted of a metal grid enclosed in an open steel tray, 35 mm high. On the front wall, 360 mm above the floor and 170 mm apart, were two translucent discs (response keys), 30 mm in diameter, which required a minimum force of 0.1 N to operate. A translucent cuelight (10 mm by 20 mm) was located beside each response key. When operative, both the keys and cuelights were illuminated by white 3-mm subminiature bulbs.

Access to the food magazine was provided via a hole (70 mm by 100 mm) centered on the front wall, 85 mm above the grid floor. Mounted at the rear of the magazine was a 1-W white bulb that illuminated the magazine

when a response unit was completed and during reinforcement. The magazine light, keylights, and corresponding cue lights provided the only illumination in the chamber.

Procedure

The initial training schedules were dependent concurrent VI VI schedules. The VI schedules were comprised of 15 intervals that were derived from the arithmetic progression $j + kx$, where $x = 0, 1, 2, \dots, 14$, j is equal to one fifteenth of the average VI length, and $k = 2$. During the first two sessions, the VI schedules in effect on both keys were VI 15 s. The VI schedules were then increased over the next five sessions to VI 90 s (two sessions at VI 30 s and three sessions at VI 60 s) where they remained for the following nine sessions.

At this point, the hens were exposed to concurrent second-order schedules of reinforcement. The first-order operant unit was a response-initiated limited-hold FI schedule requiring a minimum of two responses (one initiating and one completing the FI requirement within 5 s of the time elapsing). Under some conditions, a further FR requirement (starting with the first response) had to be completed within the FI schedule. These first-order operant units produced reinforcers according to VI schedules.

Each experimental session began with both keys lit white. Once a peck was made on either key, the other key was darkened and became inoperative, and the specified interval in effect began timing. If the initial FR was FR 1, then the pecked key was also darkened until the end of the specified interval, otherwise it remained on until the required number of pecks specified by the FR had been made. Pecks to darkened keys were counted but had no scheduled effects. To illustrate, consider the schedule specified as concurrent VI 90 s (FR 1, 1 FI 8 s:S) VI 90 s (FR 7, 1 FI 8 s:S). After the initiating peck (FR 1) on the left key, both keys were darkened and the cue light beside the left key was lit. Once the 8-s interval had elapsed, the cue light was turned off, the left key was relit (FR 8 s:S, where S refers to the relighting of the key), and one further response (FR 1, 1) was required within 5 s to complete the operant unit. This resulted in one of two events. If a reinforcer was available, the magazine was lit and the hen was given 3-s access to wheat. If a reinforcer was not avail-

able, the magazine was lit (but not operated) for 0.5 s. Following either of these, both keys were lit. Each effective key peck produced a 25-msec beep with the exception of the final peck of the FR requirement, which produced a 50-msec beep. In the example above, the right key first-order requirement was similar, but seven pecks were required in the first instance (FR 7, 1), and the seventh peck resulted in a 50-msec beep. No changeover delay (COD) was employed.

If a hen did not complete the ratio requirement within the FI in effect, or if the hen failed to peck the effective key within 5 s of the FI elapsing, then the key light was extinguished. The chamber then remained in blackout for 3 s (i.e., the "trial" was aborted). Both keys were then lit again. During blackout, the VI schedules were stopped and time was not counted as occurring on either schedule: Responses that occurred on an unlit key or during blackout were recorded but were ineffective. Sessions ended after 40 min had elapsed (including time spent in blackout) or 30 reinforcers had been delivered, whichever occurred first.

The FR, FI, and VI requirements in effect during each condition of the experiment are shown in Table 1, together with the resulting response and time ratios. During Conditions 1 to 3 of the experiment, completions of the operant units produced reinforcers according to concurrent VI 90-s VI 90-s schedules. During Condition 1, the FR requirements on both keys were FR 1 and both FI durations were 8 s, giving 1:1 time and response ratios. During Condition 2, both FI requirements remained at FI 8 s, and the FR requirement on the right key was increased to FR 7, providing a response-requirement ratio of 1:4. During Condition 3, both FR requirements were FR 1 and the FI requirements were unequal at FI 8 s and FI 2 s, giving a ratio of 4:1. The FR and FI requirements used in Conditions 1, 2, and 3 were then repeated in Conditions 4 to 9 using two pairs of unequal VI schedules (VI 60 s vs. VI 180 s and VI 180 s vs. VI 60 s). During Conditions 10 to 12, the FR requirements remained equal at FR 1 and an 8:1 time ratio (16 s vs. 2 s FI durations) was in effect for the three reinforcer-rate pairings used in the previous conditions.

Each experimental condition remained in effect until the behavior of all hens (i.e., the

Table 1

Sequence of experimental conditions for all subjects. Shown are the FR, FI, and VI schedules used, the resulting first-order response and duration differentials, and the number of sessions during each condition. The asterisks indicate the conditions in which Hens 54 and 55 stopped responding and therefore required retraining on the previous schedules. These hens completed up to 11 extra sessions in order to reach the stability criterion during those conditions.

Condition	FR		FI (s)		Differentials		VI (s)		Number of sessions
	Left	Right	Left	Right	Response	Time	Left	Right	
1	1	1	8	8	1:1	1:1	90	90	39
2	1	7	8	8	1:4	1:1	90	90	19*
3	1	1	8	2	1:1	4:1	90	90	30*
4	1	1	8	8	1:1	1:1	180	60	41
5	1	1	8	8	1:1	1:1	60	180	36
6	1	7	8	8	1:4	1:1	60	180	43
7	1	7	8	8	1:4	1:1	180	60	19
8	1	1	8	2	1:1	4:1	180	60	50
9	1	1	8	2	1:1	4:1	60	180	25
10	1	1	16	2	1:1	8:1	60	180	27
11	1	1	16	2	1:1	8:1	90	90	22
12	1	1	16	2	1:1	8:1	180	60	28

ratios of the times, individual responses, and operant units allocated to each key) was judged to be visually and statistically stable, at which point the experimental conditions were changed for all subjects. The visual criterion was that there be no apparent upward or downward trend in the graphs showing the log response-, operant unit-, and time-ratios plotted against session number, as judged by two or more lab members. The statistical criterion required that the median proportion of left responses over the last five sessions did not differ by more than .05 from the median of the previous set of five sessions. This criterion was to be satisfied five times, not necessarily consecutively. Thus a minimum of 14 sessions was required to reach statistical stability. If, after a change of the FR or FI in effect, a hen stopped responding altogether, this hen was returned to the previous FR or FI for retraining. The hen remained on this FR or FI until 30 reinforcers were obtained in two consecutive sessions. At this point, the FR or FI was adjusted ± 1 (responses or seconds) until it was the same FR or FI as for the other hens. The numbers of sessions required for the behavior of all hens to reach stability are shown in Table 1.

In all conditions, the following measures were taken: the total number of effective and ineffective responses, completed operant units, changeovers, aborted trials, reinforcers obtained, and the amount of time spent responding on each key (timed from the first

response on one key to the first response on the other key, not including time spent in blackout). All measures were recorded daily by a 386 computer running Med PC[®] software and logged in a logbook. The time each effective and ineffective key peck occurred and each reinforcer was delivered (i.e., cumulative data) also were collected.

RESULTS

The data from the last 5 days of each experimental condition are analyzed here and are shown in the Appendix (summed across the last 5 days of each condition). Regression lines were fitted by the method of least squares to the logarithms (Base 10) of the individual response, operant-unit, and time-allocation ratios, left over right, plotted against the logarithms of the reinforcer-rate ratios. These are shown in Figure 1 for each hen and all conditions. They are shown by circles (solid lines), crosses (dashed lines), and squares (dotted lines), respectively. The slopes (a), intercepts ($\log c$), percentages of the variances in the data accounted for (%VAC) by the regression lines, the standard errors of the estimates (se) and the means of all parameter estimates from each condition are shown in Table 2. Broadly, the effects of the various response-unit manipulations can be seen as displacements of the fitted lines up and down the y axes in Figure 1 (i.e., changes

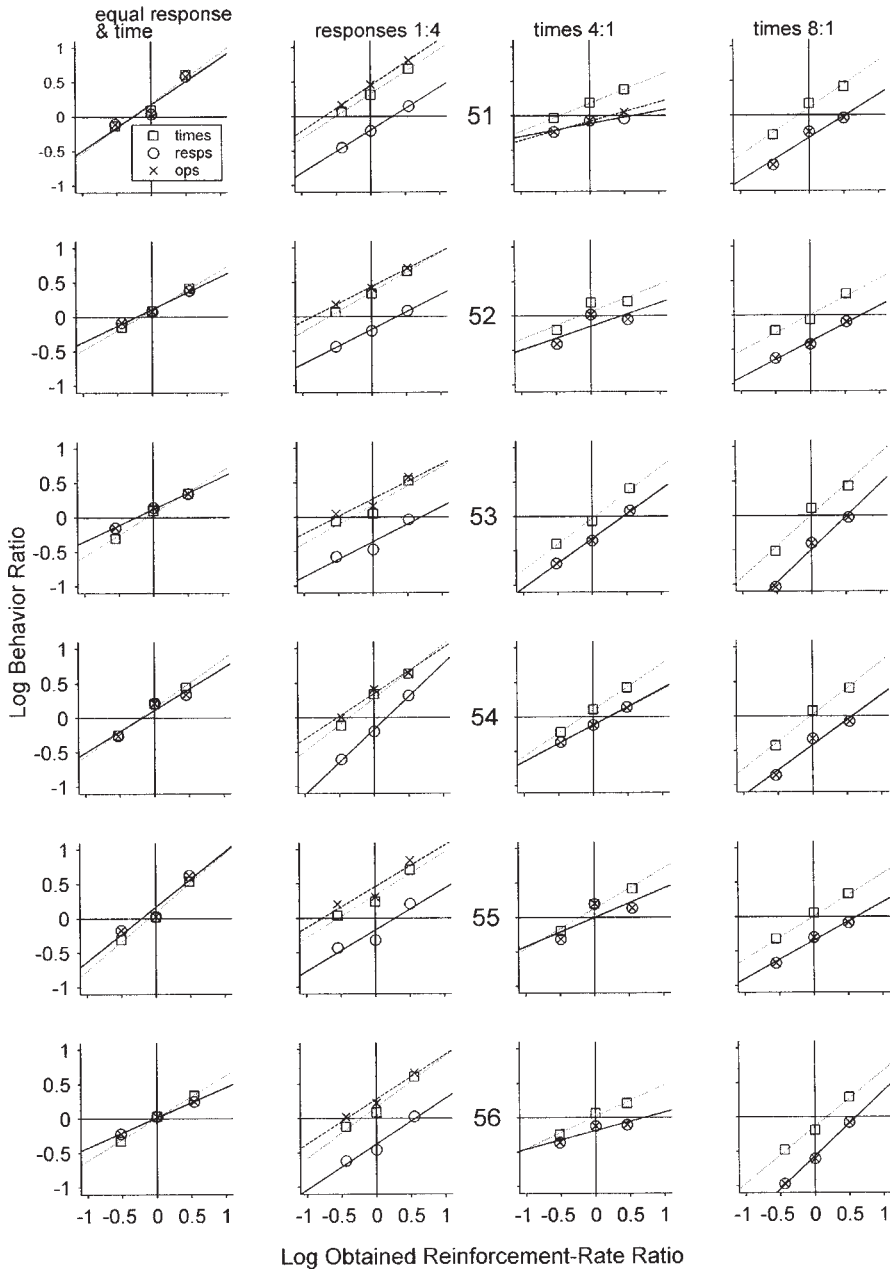


Fig. 1. The log ratios of the time, response, and operant-unit measures plotted as functions of the log obtained reinforcer-rate ratios for all hens and all conditions. The response, operant-unit, and time measures are indicated by circles (solid lines), crosses (dashed lines), and squares (dotted lines), respectively.

in the log c values of the fitted lines). The total numbers of aborted trials were small and close to 1% of all completed operants. Nearly all the aborted trials occurred in Conditions 2 and 7 (both involving FR 7 and FI 8 s on the right key) when the hens failed

to complete the FR requirement within the time specified.

Sensitivity

Figure 1 and Table 2 show that the least-squares regression lines provide satisfactory

Table 2

The slopes (*a*) and the intercepts ($\log c$) of the regression lines fitted to the response, operant-unit, and time-allocation data by the method of least squares are provided. The percentages of the variances accounted for (%VAC) by the regression lines and the standard errors of the estimates (*se*) also are provided.

Hen	Response				Operant unit				Time allocation			
	<i>a</i>	$\log c$	%VAC	<i>se</i>	<i>a</i>	$\log c$	%VAC	<i>se</i>	<i>a</i>	$\log c$	%VAC	<i>se</i>
FR 1,1 FI 8 s:S vs FR 1,1 FI 8 s:S												
51	.67	.17	89.3	.17	.67	.18	89.7	.17	.73	.19	94.9	.12
52	.47	.11	98.5	.04	.48	.11	98.6	.04	.58	.10	99.9	.10
53	.46	.12	99.3	.03	.47	.12	99.3	.03	.62	.05	98.8	.05
54	.61	.11	92.2	.12	.62	.11	92.0	.13	.71	.15	97.9	.07
55	.80	.16	91.9	.17	.80	.17	91.9	.17	.86	.09	98.2	.08
56	.44	.02	99.8	.02	.44	.02	99.8	.02	.62	.01	99.6	.03
Mean	.58	.12	95.2	.09	.58	.12	95.2	.09	.69	.10	98.2	.08
FR 1,1 FI 8 s:S vs FR 7,1 FI 8 s:S												
51	.62	-.20	99.9	.01	.67	.45	99.8	.02	.65	.32	99.9	.01
52	.50	-.19	99.6	.02	.51	.43	99.7	.02	.57	.35	99.7	.02
53	.51	-.36	88.0	.14	.51	.26	90.0	.13	.56	.17	87.7	.16
54	.95	-.17	99.7	.04	.66	.35	97.0	.08	.77	.28	98.0	.08
55	.60	-.17	86.0	.18	.60	.46	85.0	.19	.62	.33	93.8	.12
56	.66	-.37	95.5	.10	.65	.28	97.7	.07	.74	.16	96.9	.09
Mean	.64	-.24	94.8	.08	.60	.37	94.9	.08	.65	.27	96.0	.08
FR 1,1 FI 8 s:S vs FR 1,1 FI 2 s:S												
51	.19	-.12	86.4	.05	.28	-.09	99.5	.05	.40	.18	99.8	.01
52	.34	-.15	59.2	.21	.34	-.15	59.5	.20	.40	.06	76.3	.16
53	.71	-.33	99.7	.03	.72	-.33	99.7	.03	.75	-.03	99.3	.05
54	.53	-.12	100	.00	.52	-.12	100	.01	.67	.10	100	.01
55	.42	-.01	61.2	.25	.42	-.00	60.9	.25	.59	.13	96.2	.09
56	.27	-.19	83.1	.08	.27	-.19	83.1	.08	.46	.02	97.2	.05
Mean	.41	-.15	81.6	.10	.42	-.15	83.8	.11	.55	.08	94.8	.06
FR 1,1 FI 16 s:S vs FR 1,1 FI 2 s:S												
51	.66	-.33	95.2	.11	.66	-.33	95.2	.11	.69	.10	97.6	.08
52	.52	-.38	98.5	.05	.52	-.38	98.6	.05	.52	.01	94.9	.09
53	.95	-.49	97.6	.11	.96	-.49	97.6	.11	.90	.01	96.6	.13
54	.73	-.42	95.9	.11	.73	-.42	95.9	.11	.78	.02	98.6	.07
55	.56	-.35	98.2	.06	.56	-.35	98.2	.06	.62	.00	99.6	.03
56	.72	-.35	93.2	.13	.95	-.57	99.5	.04	.82	-.14	98.8	.06
Mean	.69	-.39	96.4	.10	.73	-.41	97.5	.08	.72	.00	97.7	.08

descriptions of the data. Within the limits of three-point fits there were no systematic deviations from linearity. Percentage variances accounted for are generally high (58 of the 72 were above 90% and only five below 80%) and the standard errors of estimate are generally small (only three greater than 0.2 and most less than 0.1). The slopes (*a*) of the least-squares regression lines were all below 1.00 with all except nine values falling below 0.80 (range, 0.19 to 0.96). Generally, but not exclusively (i.e., in 20 out of 24 fits), the sensitivity for time allocation was greater than the response and operant-unit sensitivities. Although the sensitivity values were lower for all measures during the first (4:1) time-differential

conditions, the sensitivities from the subsequent (8:1) time-differential conditions were similar to those from the equal-unit and response-differential conditions. Hence the main effect of the various operant-unit requirement manipulations is seen in the bias.

Bias

Bias ($\log c$) did not differ greatly or systematically across individual hens for any of the behavioral measures, so the means of bias shown in Table 2 can be taken as representative of overall patterns. During the equal operant-unit conditions, all biases were approximately equal and close to zero. The mean response, operant-unit, and time-bias

measures from these conditions were 0.12, 0.12, and 0.10, respectively, showing only small inherent biases in all behavioral measures.

During the 1:4 response-differential (and equal time) conditions, all of the individual operant-unit and time-allocation biases were similar and, as expected on the basis of Beauthrais and Davison's (1977) and Sumpter et al.'s (1998) results, towards the (left) key associated with the smaller FR requirement. In all cases, the operant-unit bias measures (mean log value of 0.37 or 2.3:1 as a ratio) were larger than the time-allocation bias measures (mean log value 0.27 or 1.9:1 in ratio terms). This small difference must have arisen from more pausing between operant units on the key associated with the larger FR requirement. For all hens, the response biases (mean log -0.24 or 1:1.8 in ratio terms) were in the opposite direction. Thus, when durations were equal but responses differed, there was an average bias in terms of operant units and times spent of approximately 2:1 towards the left key (associated with the smaller FR requirement), whereas for individual responses, a bias of similar magnitude (i.e., approaching 1:2) occurred but towards the right key (associated with the larger response requirement).

Over the two sets of time-differential (but equal response) conditions, alterations from 1:1 through 4:1 and 8:1 did not affect the time-allocation biases, which remained close to zero (mean log values 0.08 and 0.0, respectively) or 1:1 in ratio terms. The response and operant-unit biases did, however, change progressively towards the shorter duration requirement. The mean log bias for both the response and operant-unit measures were -0.15 from the 4:1 conditions and approximately -0.40 (-0.39 and -0.41) from the 8:1 conditions. These correspond to ratios of 1:1.4 for the 4:1 time-differential conditions and approximately 1:2.5 for the 8:1 time-differential conditions. So, whereas the initial increase in time requirement to a 4:1 ratio altered the operant-unit (and response) allocation ratios by only a factor of 1.4:1, the further doubling to 8:1 moved these by nearly a factor of 2 (1.8) to a ratio of 1:2.5.

One way of summarizing both sets of manipulations in the present experiment is to regard them as numerical changes of the operant units from equality in terms of

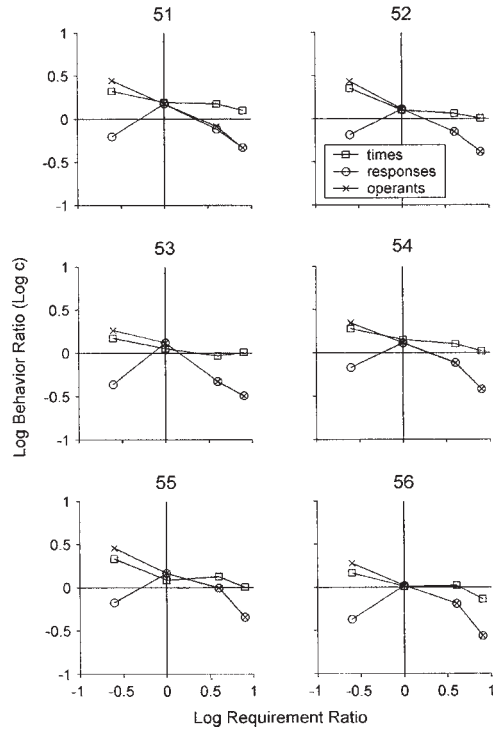


Fig. 2. Bias from the lines fitted to the log behavior ratios plotted as functions of the log operant-unit requirement ratios. The left portions of the figures represent data from the FR variations, and the right portions represent data from the FI manipulations. The unfilled circles show response biases, the unfilled squares show time biases, and the crosses show the operant-unit biases.

either the individual responses or the durations required. Hence one way to present the data is to plot the bias (log c) against these net operant-unit requirement ratios on a common axis representing the ratio differences for both manipulations. To illustrate this, the individual response, operant-unit, and time-allocation biases are shown in Figure 2, for each hen, for all conditions, as functions of the logarithms of the net operant-unit requirement ratios, right over left. Points to the left of the origin (joined with dashed lines) come from the response number alterations in which the left-key operant unit was the smaller ratio requirement. Those to the right (solid lines) come from the duration manipulations in which the left-key operant unit was the longer FI requirement. Although the manipulations to the left and right of the origin are different, the central points (equal operant-unit requirements) are common. The individual response,

operant-unit, and time-allocation biases are shown by circles, crosses, and squares, respectively.

Figure 2 reveals the changes in each bias measure across the different log operant-unit requirement ratios. A negative slope indicates that decreasing the operant-unit requirements on one alternative, by manipulation of either the response (FR) or time (FI) portion of the operant unit, increased the bias measure (operant units, individual responses, or times) toward that alternative.

All hens showed similar patterns. Figure 2 shows that increasing the number of responses required to complete a right-key operant unit (shown in the left half of each graph as negative net operant-unit requirement ratios) moved the time and operant-unit bias measures towards the smaller ratio requirement whereas the response-based measures moved towards the key requiring the larger FR. However, increasing the time (FI) required to complete an operant unit (shown in the right half of each graph as positive net operant-unit requirement ratios) clearly shifted the hens' behavior away from that alternative for two measures of bias (operant units and responses) and only slightly or not at all for the third (time measures). Across the whole of Figure 2, these changes were relatively linear for the operant-unit measures. In the left halves of the graphs in Figure 2 (FR varied), the time measures followed the operant-unit measures. In the right halves of the graphs in Figure 2 (FI varied), the paths of time ratios, although downward-sloping, were relatively flat and separate from the operant-unit data. The response-based ratios all showed inverted U-shaped functions against net operant requirement changes. Therefore, monotonic relations were observed between operant-unit requirements and operant-unit bias measures regardless of the variable manipulated. This was not so for the time and individual response measures.

DISCUSSION

Overall, the lines fitted using Equation 1 provided reasonable descriptions of the data in Figure 1 and allow analysis based on the GML as a summary and description of the main effects. The manipulations controlled the durations and numbers of responses

required, with few failures to complete the units for too few, too many, or too late responses, as indicated by the small number of aborted trials.

Sensitivity

All lines fitted to the behavioral measures from all conditions showed undermatching with sensitivities similar to those previously reported for hens responding on various concurrent schedules (McAdie, Foster & Temple, 1996; Sumpter *et al.*, 1995; Temple, Scown & Foster, 1995). Because there is no logical explanation for the lower sensitivities found during the 4:1, but not 8:1, time-differential conditions, it seems likely that these represent no more than uncontrolled variation. Hence, although sensitivities were low, the manipulations do not appear to have changed them in any systematic way.

One possible complication might arise from considering the effects of differential change-over delays (CODs) between some pairs of schedules. Although there was no COD programmed, the FI schedules employed provided effective CODs of 2, 8, and 16 s in the various conditions. Two sets of conditions had equal FI 8-s schedules and therefore equal COD analogues. The sensitivity values for these were similar to each other and not different from the other two sets of conditions that employed unequal FI schedules. Therefore, any effect of differing COD analogues does not seem to have appeared in the sensitivities. Temple *et al.* (1995) reported that the main effects on sensitivity of changes in (equal) COD lengths occurred at values below 2 s. This value is smaller than any analogue here, and so it appears that the main effect of the response-unit requirement changes has been to change bias, rather than sensitivity.

Bias

Because the fitted lines were reasonable descriptors of the data, the best estimates of bias caused by different operant-unit requirements come from those lines. These estimates can be regarded as independent of the degree of undermatching observed.

Equal operant-unit conditions. Equal operant-unit requirements resulted in all three bias measures being close to zero, indicating that uncontrolled biases were small. Perfor-

mance with relatively small, equal, operant-unit requirements seems similar to that under normal concurrent schedules (cf. Beauthrais & Davison, 1977).

Differential response requirements across alternatives. Quadrupling the response requirement on the right key gave individual response bias measures towards that key of about 1:2 and operant-unit and time biases away from that key of approximately 2:1. The time and operant-unit biases were necessarily similar because the requirements were of equal duration. As Sumpter et al. (1998) argued, the differing (4:1) response requirements predict that the operant-unit and response biases must differ by 4:1 (assuming no aborted trials). The particular numerical values each would take, however, were not predictable.

Simple response matching would have predicted response-unit biases of 1:1 and time and operant-unit biases close to 4:1. Predictions from time matching, together with both Shimp's (1969, 1970) IRT data and Davison et al.'s (1988) concurrent-chain data, would have placed operant-unit or time biases close to 1:1 and response biases near 1:4. The present finding of approximately 2:1 for time and operant-unit biases and 1:2 for response biases lies between these two extremes. Leung and Winton's (1988) findings that terminal links with earlier segmentation were preferred do not provide quantifiable predictions, but do predict some operant-unit bias towards the smaller response requirement, as was found. The 1:2 response bias towards the larger response requirement is clearly counter-intuitive. The operant-unit bias of around 2:1 towards the smaller response requirement is consonant with common notions of preference and may be regarded as similar to undermatching to the ratio of response requirements.

Differential time requirements across alternatives. Because the response requirements were equal, the operant-unit and response biases were trivially similar, and any slight differences arose from the line-fitting process. The time-allocation biases obtained from these conditions were small and may be considered close to zero. With approximately equal times spent and unequal operant-unit durations, the operant-unit bias measures were, necessarily, towards the key associated with the shorter FI requirement.

Because the time-allocation biases approximated zero, and from consideration of concurrent IRT data, one might expect the operant-unit completions in the 4:1 and 8:1 time-differential conditions to be close to 4:1 and 8:1 in favor of the short-duration operant unit, respectively, but 1.6:1 and 2.4:1 were the obtained values. Thus simple matching in terms of any measure also is not apparent in the time-differential data. Here the time biases were closer to equality than either of the other two measures, both of which, in a similar fashion to the response-differential data, moved systematically in the expected direction (i.e., towards the shorter unit). Again, this was to a lesser degree than might have been predicted from the magnitudes of the time differentials, and might be thought of as behavior having undermatched to the operant-unit requirement differences.

It appears, then, that both the response- and time-differential manipulations led to orderly, but less extreme, changes in bias when measured in terms of completed operant units. Changes in the other bias measures were considerably less orderly and differed between the two manipulations. A tentative conclusion might be that the Law of Effect has acted in an orderly fashion to produce undermatching of bias to operant-unit requirements, similar to the undermatching of responding found when outcomes are varied. With this interpretation, the changes seen in response and time biases can be thought of as arising from the more fundamental effects on operant-unit completions.

The less-than-expected bias shifts may be understood from the patterns of pausing and the duration of "visits" to each key. The less extreme biases found in the time-differential conditions may have arisen because the operant units themselves could vary in duration by up to 3 s, depending on the timing of the last peck (i.e., from pausing within the operant unit). The extra time taken to complete each operant unit over the last 5 days of these conditions was analyzed to examine this. There was little variation across conditions, with all hens taking less than 1 s to make the final response once the key was lit. Adding 1 s to each of the FI schedules would contribute to a lessening of the difference between the operant units but would not be sufficient to account for the degree of under-

matching of operant-unit biases to imposed requirements that was found. As previously mentioned, it also would not help account for undermatching to response requirements, as adding 1 s to equal duration requirements maintains their equality.

The time between operant units also was free to vary. To produce the data on the left side of Figure 2 (response differential units), extra pausing between (rather than within) operant units must have been equal on each operant unit regardless of which side it was on. To produce the data on the right side of Figure 2 (time-differential conditions), pausing between operant units must have been longer after the shorter operant units than after the longer units. Although this analysis of pausing allows understanding of how the undermatching occurred, it leaves the question of why pausing differed.

The pauses that occurred between operant units were divided into each of the four categories (left–left, left–right, right–left and right–right), and the mean pause durations were calculated for all conditions. There was, as expected from the overall data, more pausing after short units than long units during the time-differential conditions, but no clear pattern (e.g., increased pausing prior to changing to a long unit) was found. Again, this sheds little light on why the pausing occurred. It also offers no understanding of the undermatching of the response requirement manipulations.

Baum, Schwinderman, and Bell (1999), based on a suggestion from Houston and McNamara (1981), proposed that a pattern of behavior known as “fix and sample” may underlie common findings of undermatching on concurrent schedules. In the present study, such a pattern is revealed by an analysis of the number of operant units completed on each visit to a key. Particularly, visits to the less preferred alternative typically would involve only a single completed operant unit. Visits to the more preferred alternative would involve more operant units, but not as many as would be predicted by the requirement differences. Here the less preferred alternative could be defined as the one with the lower reinforcer rate or the larger operant-unit requirement.

Figure 3 presents, for each of the first-order operant-unit manipulations, the number of operant units completed per visit to the left

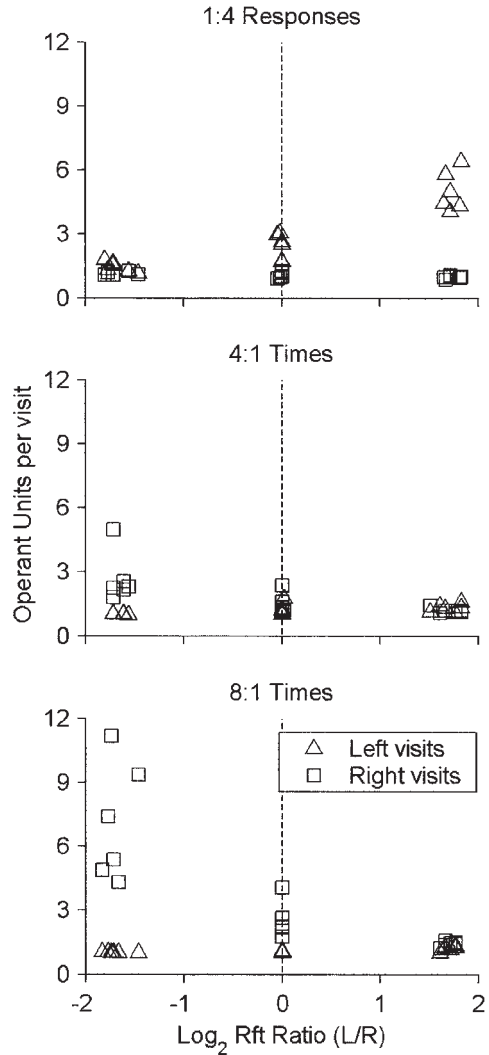


Fig. 3. The average number of operant units per visit to the left and right keys as a function of the log (Base 2) of the reinforcement-rate ratios from the data summed over the last 5 days of each condition.

and right alternatives calculated for each hen from data summed over the last 5 days of each condition plotted against the logarithms (to the base two) of the reinforcer-rate ratios. The top panel presents the 1:4 response-differential data and the second and third panels present the 4:1 and 8:1 time-differential data, respectively. Considering only the conditions with differing reinforcer rates, we see a clear pattern. In the left portion of the top panel (1:4 responses) and the right portions of the lower two panels (time differentials), all data

points fall close to one operant unit per visit. These data points all arise from conditions in which the leaner reinforcer rate was associated with the smaller operant-unit requirement, and the richer reinforcer rate was associated with the larger operant-unit requirement. They show that approximately one operant unit per visit occurred on the smaller operant-unit alternative when it was at the lower reinforcer rate, but also approximately one operant unit per visit occurred on the other (richer) alternative when it had the larger operant-unit requirement.

The right portion of the top panel and the left portion of the two lower panels arise from conditions in which the leaner reinforcer rate was associated with the larger operant-unit requirement, and the richer rate with the smaller operant-unit requirement. These data show that the combination of a large first-order operant requirement and a leaner reinforcement rate produced a pattern of a single operant unit per visit for all hens. By contrast, the combination of a smaller first-order operant requirement and a richer reinforcer rate gave more operant units per visit.

From these results, it does seem that a pattern of fix and sample underlies the undermatching in terms of operant units found. This pattern also casts light on the greater degree of undermatching observed in the 4:1 as opposed to 8:1 time-differential conditions. The fixed periods under the 4:1 conditions by and large involved two operant units per visit (median 2.3), occupying roughly half the duration differential, whereas those under the 8:1 time-requirement differential occupied approximately two thirds of that differential (median 6.4).

Because the degree of undermatching found depends on the degree of fix and sample shown, this can provide an explanation for the less-than-expected shifts in bias, but leaves open the question as to why this particular amount of fix and sample occurred. It does, however, suggest that analysis of the present data in terms of operant units completed is appropriate. Perhaps at this stage, the best conclusion is that independent alterations to operant-unit requirements produced undermatching in behavior measured as those operant units. Operant units, then, rather than responses or times, may be fundamental.

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APPENDIX

The raw data, summed across the last 5 days of each condition, are presented for each hen. Shown are the hen number, condition number, the FR schedules in effect on the left (L) and right (R) alternatives, the FI schedules in effect on the left and right alternatives, the VI schedules in effect on the left and right alternatives, the total number of individual responses made on the left and right alternatives, the total time spent responding on the left and right alternatives, the total number of reinforcers obtained on the left and right alternatives, the total number of operant units completed on the left and right alternatives, the total number of aborted trials due to an incomplete FR on the left and right alternatives, the total number of aborted trials due to an incomplete FI on the left and right alternatives, the total number of ineffective responses made on the left and right alternatives, the number of changeover responses from the left and right alternatives, and the total session time.

Hen	Condition	Schedules												Change-over responses	Total session time (s)											
		FR		FI		VI		Number of Responses		Time (s)		Number of reinforcers				Operant units		FR aborted		FI aborted		Ineffective responses				
		L	R	L	R	L	R	L	R	L	R	L	R			L	R	L	R	L	R	L	R	L	R	
51	1	1	1	8	8	8	8	90	90	658	601	5,232	4,212	75	75	329	300	0	0	0	0	1	192	47	555	9,573
51	4	1	1	8	8	180	60	580	60	734	4,031	5,517	35	115	288	367	0	0	4	0	0	27	77	553	9,626	
51	5	1	1	8	8	60	180	1,017	1,017	274	7,564	1,874	114	36	507	137	0	0	3	0	69	99	270	9,550		
51	2	1	7	8	8	8	90	90	1,091	1,563	7,464	3,282	74	75	543	170	0	38	5	1	109	49	354	10,902		
51	7	1	7	8	8	180	60	738	60	2,118	5,169	4,493	35	115	369	258	0	10	0	0	16	12	482	9,760		
51	6	1	7	8	8	60	180	1,156	60	824	8,199	1,700	117	33	577	90	0	23	2	0	26	6	180	10,011		
51	3	1	1	8	2	90	90	783	90	930	5,093	3,324	75	75	391	465	0	0	1	0	33	27	762	8,492		
51	8	1	1	8	2	180	60	664	60	1,148	4,124	4,520	35	115	332	574	0	0	0	0	25	23	637	8,703		
51	9	1	1	8	2	60	180	864	60	890	6,267	2,656	114	36	432	390	0	0	0	0	32	6	660	8,983		
51	11	1	1	16	2	90	90	510	90	897	5,639	3,867	75	75	255	448	0	0	0	1	9	2	504	9,563		
51	12	1	1	16	2	180	60	290	60	1,516	3,103	6,027	35	115	145	758	0	0	0	0	3	7	283	9,170		
51	10	1	1	16	2	60	180	568	60	633	7,150	2,772	114	36	284	316	0	0	0	1	11	3	455	9,971		
52	1	1	1	8	8	90	90	719	90	601	5,495	4,508	75	75	359	300	0	0	1	1	1	1	296	437	10,057	
52	4	1	1	8	8	180	60	578	60	692	3,630	5,115	40	110	288	346	0	0	2	0	1	1	501	8,816		
52	5	1	1	8	8	60	180	926	60	383	6,606	2,533	116	34	462	191	0	0	2	1	3	2	373	9,193		
52	2	1	7	8	8	8	90	90	1,043	1,438	7,415	3,004	64	66	520	161	0	39	3	0	6	16	350	10,573		
52	7	1	7	8	8	180	60	811	60	2,211	5,428	4,672	35	115	405	267	0	16	1	0	0	0	0	491	10,211	
52	6	1	7	8	8	60	180	1,191	60	982	8,256	1,810	115	35	595	119	0	6	1	0	0	0	238	10,137		
52	3	1	1	8	2	90	90	869	60	838	5,195	3,359	75	75	434	419	0	0	1	0	0	0	734	8,630		
52	8	1	1	8	2	180	60	570	60	1,436	3,244	5,123	37	113	285	716	0	0	0	0	4	0	1	559	8,455	
52	9	1	1	8	2	60	180	847	60	952	5,505	3,424	116	34	423	475	0	0	1	2	0	31	792	9,024		
52	11	1	1	16	2	90	90	413	90	1,059	4,420	5,129	75	75	206	527	0	0	1	5	2	9	397	9,625		
52	12	1	1	16	2	180	60	344	60	1,452	3,383	5,663	36	114	172	726	0	0	0	0	1	0	338	9,093		
52	10	1	1	16	2	60	180	584	60	744	6,642	3,350	115	35	292	372	0	0	0	0	2	7	505	10,058		
53	1	1	1	8	8	90	90	756	90	542	5,308	4,278	75	75	378	271	0	0	0	0	0	656	425	470	9,634	
53	4	1	1	8	8	180	60	576	60	802	3,163	6,472	31	110	288	401	0	0	0	0	0	605	791	562	9,688	
53	5	1	1	8	8	60	180	1,007	60	460	6,182	2,817	114	36	503	230	0	0	1	0	1,195	175	442	9,051		
53	2	1	7	8	8	8	90	90	711	2,120	5,350	4,905	74	74	355	246	0	35	0	0	525	417	411	10,450		
53	7	1	7	8	8	180	60	676	60	2,523	4,533	5,248	34	116	337	303	0	24	2	1	578	466	510	9,930		
53	6	1	7	8	8	60	180	1,118	60	1,221	7,118	2,142	115	35	558	148	0	7	2	0	1,370	178	275	9,342		

APPENDIX
(Continued)

Hen Condition	Schedules												Total session time (s)										
	FR		FI		VI		Number of Responses		Time (s)		Number of reinforcers			Operant units		FR aborted		FI aborted		Ineffective responses		Change-over responses	
	L	R	L	R	L	R	L	R	L	R	L	R		L	R	L	R	L	R	L	R		L
56	1	7	8	8	8	60	180	1,027	968	8,275	2,073	116	33	513	113	0	16	0	2	28	27	237	10,454
56	3	1	1	8	2	90	90	822	1,090	4,581	3,962	75	75	411	545	0	0	0	0	18	4	808	8,613
56	8	1	1	8	2	180	60	545	1,216	3,223	5,559	35	115	272	608	0	0	1	1	1	22	543	8,836
56	9	1	1	8	2	60	180	740	938	5,300	3,293	111	39	370	469	0	0	0	0	26	49	656	8,661
56	11	1	1	16	2	90	90	362	1,446	3,970	6,156	75	75	181	723	0	0	0	0	12	14	357	10,162
56	12	1	1	16	2	180	60	232	2,158	2,359	7,097	40	110	116	1,079	0	0	0	0	8	45	231	9,485
56	10	1	1	16	2	60	180	534	641	6,223	3,210	113	37	267	320	0	0	0	1	8	2	524	9,536