SENSITIVITY TO REINFORCEMENT IN CONCURRENT ARITHMETIC AND EXPONENTIAL SCHEDULES

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The generalized matching law states that the logarithm of the ratio of responses emitted or time spent responding in concurrent variable-interval schedules is a linear function of the logarithm of the ratio of reinforcements obtained. The slope of this relation, sensitivity to reinforcement, varies about 1.0 but has been shown to be different when obtained in different laboratories. The present paper analyzed the results from 18 experiments on concurrent variable-interval schedule performance and showed that response-allocation sensitivity to reinforcement was significantly smaller when arithmetic, rather than exponential, progressions were used to produce variable-interval schedules. There were no differences in time-allocation sensitivity between the two methods of constructing variable-interval schedules. Since the two laboratories have consistently used different methods for constructing variable-interval schedules, the differences in obtained sensitivities to reinforcement are explained. The reanalysis suggests that animals may be sensitive to differences in the distribution of reinforcements in time.

Key words: variable-interval schedules, concurrent schedules, arithmetic schedules, exponential schedules, generalized matching law, sensitivity to reinforcement

The generalized matching law (Baum, 1974) states that the logarithm of the ratio of responses on concurrent schedules is a linear function of the logarithm of the ratio of obtained reinforcements. The relation is written:

$$\log \left(\frac{P_i}{P_j} \right) = a \log \left(\frac{R_i}{R_j} \right) + \log c, \quad (1)$$

where P and R are the responses emitted and reinforcements obtained from keys i and j . The parameter a is called sensitivity to reinforcement. If it takes a value greater than 1, the performance is called overmatching, and if it takes a value less than 1, the performance is called undermatching. The parameter $\log c$ is called bias. The relation described by Equation 1 is also true when time spent responding at the two alternatives (T_i , T_j) is measured. However, time-allocation sensitivity is often greater than response-allocation sensitivity (Baum, 1979; Lobb & Davison, 1975).

It has generally been accepted that $\log c$ in Equation 1 may take values different from 0

(Baum, 1974; de Villiers, 1977). However, much discussion has centered on whether the parameter a takes a value of 1 or less than 1 in concurrent variable-interval (VI) schedules. Lobb and Davison (1975), Mullins, Agunwamba, and Donohoe (1982), and Myers and Myers (1977) have all suggested that the value was consistently less than 1, but Baum (1979) and de Villiers (1977) have argued that little predictability is lost by assuming a value of 1 (but see Mullins et al.). Baum (1979), however, pointed out that sensitivities to reinforcement measured by response counts were consistently smaller when measured in Davison's laboratory than when measured in Baum's laboratory. Baum suggested that this difference could be caused by unnoticed differences in experimental procedures between the two laboratories. The present paper explores one major and visible difference between the procedures used by Davison and by Baum, the progression used to generate the intervals comprising VI schedules. Davison has consistently used VI intervals drawn from arithmetic progressions, whereas Baum used intervals from exponential progressions (Catania & Reynolds, 1968; Fleshler & Hoffman, 1962).

The analysis carried out here was similar to that done by Baum (1979) and used 18 re-

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Table 1

Least-squares linear regressions for 155 data sets from 18 experimental studies according to Equation 1. *N* is the number of data comprising each set, *VAC* is the variance accounted for by the linear regression, and *IND/DEP* refers to whether the schedules were arranged independently or non-independently. The data have been categorized by type of schedule used and by type of measurement taken. Studies which reported both response and time data are shown twice.

Reference	Subject No.	Regression	VAC	IND/DEP	N
<i>1. Exponential Schedules: Response Allocation.</i>					
Stubbs & Pliskoff (1969)	P103	$Y = .86X + .08$	.96	DEP	4
	P104	$Y = 1.24X - .01$	.93	DEP	4
	P108	$Y = .94X + .02$	.94	DEP	4
McSweeney (1975)	8422	$Y = .74X + .03$	.94	IND	4
	8772	$Y = .89X - .01$	.87	IND	4
	8845	$Y = 1.01X - .03$	.95	IND	4
	8895	$Y = .79X - .02$	.84	IND	4
Baum (1976)	1	$Y = .79X + .00$	.94	IND	12
	2	$Y = 1.01X - .12$	.96	IND	12
	3	$Y = .88X - .07$	.96	IND	12
	4	$Y = .82X + .02$	.94	IND	10
	6	$Y = .96X - .19$	.92	IND	11
Bradshaw, Szabadi, & Bevan (1976)	S.M.	$Y = .89X + .03$	.98	*	5
	A.M.	$Y = 1.00X - .05$	.98	*	5
Miller (1976)	254(1)	$Y = .61X + .08$	.96	IND	5
	(2)	$Y = .70X + .18$	.96	IND	5
	(3)	$Y = .87X + .09$	.99	IND	5
	255(1)	$Y = .94X + .35$	.98	IND	5
	(2)	$Y = 1.11X + .10$	.99	IND	5
	(3)	$Y = 1.14X - .32$	.97	IND	5
	452(1)	$Y = 1.06X - .30$	.99	IND	5
	(2)	$Y = 1.08X + .18$	.99	IND	5
	(3)	$Y = 1.16X - .14$	.98	IND	5
	43(1)	$Y = 1.35X + .09$	.98	IND	5
	(2)	$Y = 1.09X + .12$	.95	IND	5
	(3)	$Y = 1.05X - .21$	.97	IND	5
Norman & McSweeney (1978)	1	$Y = .92X + .09$	.91	IND	5
	2	$Y = 1.17X - .04$	.95	IND	5
	3	$Y = .78X - .18$	.87	IND	5
	4	$Y = .90X + .00$	.99	IND	5
	5	$Y = .98X + .06$	.98	IND	5
Heyman (1979)	165	$Y = 1.16X - .08$	1.00	DEP	3
	209	$Y = .83X - .02$	1.00	DEP	3
	241	$Y = 1.04X - .03$	1.00	DEP	3
	205	$Y = 1.02X - .10$	.95	DEP	3
<i>2. Exponential Schedules: Time Allocation.</i>					
Baum & Rachlin (1969)	488	$Y = 1.10X - .32$	.87	IND	19
	489	$Y = 1.09X - .61$	.85	IND	19
	490	$Y = 1.35X - .01$	.90	IND	19
	496	$Y = .97X - .28$	.96	IND	19
	334	$Y = .84X - .21$	.96	IND	19
	360	$Y = .61X - .12$	.96	IND	19
Stubbs & Pliskoff (1969)	P103	$Y = 1.03X + .11$	.98	DEP	4
	P104	$Y = 1.24X + .00$	.93	DEP	4
	P108	$Y = 1.07X + .01$	.99	DEP	4
Baum (1975)	Doug	$Y = 1.16X - .08$	.91	DEP	14
	Noa	$Y = .98X + .03$	.93	DEP	10
	John	$Y = .94X + .15$	.94	DEP	11
Miller (1976)	254(1)	$Y = .66X + .12$	.93	IND	5
	(2)	$Y = .86X + .18$	.97	IND	5
	(3)	$Y = .93X - .01$	1.00	IND	5
	255(1)	$Y = .90X + .17$	.98	IND	5
	(2)	$Y = .94X + .05$	.98	IND	5
	(3)	$Y = 1.02X - .20$	.98	IND	5

Table 1 (continued)

Reference	Subject No.	Regression	VAC	IND/DEP	N
Norman & McSweeney (1978)	452(1)	$Y=1.04X-.22$	.97	IND	5
	(2)	$Y=1.02X+.21$	.99	IND	5
	(3)	$Y=1.17X+.01$	1.00	IND	5
	43(1)	$Y=1.29X+.05$	1.00	IND	5
	(2)	$Y=.88X+.07$	.89	IND	5
	(3)	$Y=.93X-.17$	.96	IND	5
	1	$Y=.96X-.09$	.96	IND	5
	2	$Y=1.08X+.10$	.99	IND	5
	3	$Y=.72X-.13$	.86	IND	5
	4	$Y=1.01X+.01$	.99	IND	5
Heyman (1979)	5	$Y=1.01X+.16$	.99	IND	5
	165	$Y=.78X-.03$	1.00	DEP	3
	209	$Y=.75X+.04$	1.00	DEP	3
	241	$Y=.71X-.06$	1.00	DEP	3
	205	$Y=.69X-.07$	.94	DEP	3
<i>3. Arithmetic Schedules: Response Allocation.</i>					
Herrnstein (1961)	P231	$Y=1.36X-.04$	.99	IND	5
	P055	$Y=.80X-.01$	.98	IND	5
Catania (1963)	117	$Y=.83X-.01$	.91	IND	8
	243	$Y=.77X+.01$	.93	IND	8
	294	$Y=.80X+.03$	.98	IND	8
Silberberg & Fantino (1970)	A	$Y=.74X-.05$	1.00	IND	3
	E	$Y=.77X-.06$	1.00	IND	3
	C	$Y=.94X+.07$	.48	IND	3
	B	$Y=.55X-.18$	.61	IND	3
	G	$Y=.63X-.05$	.99	IND	3
	H	$Y=.93X+.17$	1.00	IND	3
	93	$Y=.80X+.58$	.96	DEP	4
Hollard and Davison (1971)	95	$Y=.66X+.48$	1.00	DEP	4
	119	$Y=.87X+.87$	.94	DEP	4
Lobb & Davison (1975)	21	$Y=.84X-.02$	.93	IND	10
	23	$Y=.86X-.02$	.98	IND	10
	24	$Y=.91X+.05$	.96	IND	10
	25	$Y=.84X+.01$	.94	IND	10
	26	$Y=.67X-.05$	.92	IND	10
	7(1)	$Y=.74X-.01$	1.00	IND	6
Pliskoff & Brown (1976)	(2)	$Y=.66X-.05$	.98	IND	6
	9(1)	$Y=.69X-.29$	.75	IND	6
	(2)	$Y=.68X+.28$	.57	IND	6
	11(1)	$Y=.89X-.05$	.99	IND	6
	(2)	$Y=1.14X+.11$	.97	IND	6
	141(1)	$Y=.88X-.22$	.87	IND	16
Davison & Hunter (1976)	(2)	$Y=.96X+.18$	.90	IND	16
	142(1)	$Y=.73X-.06$	.83	IND	16
	(2)	$Y=.67X+.14$	.59	IND	16
	143(1)	$Y=.84X-.06$	.92	IND	11
	(2)	$Y=.58X+.02$	.82	IND	14
	144(1)	$Y=.68X+.07$	.88	IND	16
	(2)	$Y=.71X+.12$	.85	IND	16
	145(1)	$Y=.65X+.01$	.84	IND	16
	(2)	$Y=.90X+.12$	.90	IND	16
	146(1)	$Y=.75X-.07$	.87	IND	16
	(2)	$Y=.64X-.10$	.78	IND	16
	H1	$Y=.76X+.01$	.90	IND	32
	H2	$Y=.93X+.01$	.87	IND	30
	H3	$Y=.82X+.01$	.90	IND	32
Hunter & Davison (1978)	H4	$Y=.93X+.03$	.88	IND	32
	H5	$Y=.91X+.02$	.81	IND	32
	H6	$Y=.93X+.01$	.93	IND	30
Tustin & Davison (1978)	181	$Y=.68X+.12$	.93	DEP	5
	182	$Y=1.12X-.28$	.91	DEP	5
	183	$Y=.40X-.04$	.81	DEP	5

Table 1 (continued)

Reference	Subject No.	Regression	VAC	IND/DEP	N
	184	$Y = .41X + .12$	.75	DEP	5
	185	$Y = .70X - .13$	.88	DEP	5
	186	$Y = .73X - .25$	.81	DEP	5
<i>4. Arithmetic Schedules: Time Allocation.</i>					
Catania (1963)	117	$Y = .94X - .04$	.95	IND	8
	243	$Y = .76X - .06$	.86	IND	8
	294	$Y = .94X - .04$	.93	IND	8
Silberberg & Fantino (1970)	A	$Y = .87X - .21$	1.00	IND	3
	E	$Y = 1.06X - .18$	.96	IND	3
	C	$Y = .58X + .45$	1.00	IND	3
	B	$Y = .84X - .12$	.99	IND	3
	G	$Y = .97X - .08$	.97	IND	3
	H	$Y = 1.22X - .06$	.96	IND	3
Lobb & Davison (1975)	21	$Y = 1.11X - .07$	.97	IND	10
	23	$Y = 1.07X + .05$	.99	IND	10
	24	$Y = 1.06X - .04$	.97	IND	10
	25	$Y = 1.05X - .06$	.93	IND	10
	26	$Y = 1.03X - .02$	.98	IND	10
Pliskoff & Brown (1976)	7(1)	$Y = .69X - .02$	.97	IND	6
	(2)	$Y = .91X + .04$	.98	IND	6
	9(1)	$Y = .64X - .02$	.93	IND	6
	(2)	$Y = .69X + .10$	.87	IND	6
	11(1)	$Y = .76X - .01$	.91	IND	6
	(2)	$Y = 1.05X + .13$	.97	IND	6
Davison & Hunter (1976)	141(1)	$Y = .93X - .23$	.85	IND	16
	(2)	$Y = 1.03X + .10$	.94	IND	16
	142(1)	$Y = .88X - .05$	.90	IND	16
	(2)	$Y = .85X + .01$	.71	IND	16
	143(1)	$Y = .91X - .12$	.87	IND	11
	(2)	$Y = .92X - .03$	.87	IND	14
	144(1)	$Y = .80X + .14$	.83	IND	16
	(2)	$Y = .82X + .04$	.90	IND	16
	145(1)	$Y = .85X - .07$	.84	IND	16
	(2)	$Y = .97X + .00$	.89	IND	16
	146(1)	$Y = .94X - .10$	.94	IND	16
	(2)	$Y = .73X - .13$	.90	IND	16
Hunter & Davison (1978)	H1	$Y = .85X + .01$	.95	IND	32
	H2	$Y = .89X + .00$	.88	IND	30
	H3	$Y = .92X + .01$	.92	IND	32
	H4	$Y = 1.02X + .03$	.91	IND	32
	H5	$Y = .91X + .00$	.91	IND	32
	H6	$Y = .79X + .02$	.92	IND	30

*Not stated

ported studies (Table 1) of concurrent VI schedule performance. The criteria for inclusion were much the same as used by Baum, except that we excluded studies employing average procedures, studies that failed to report individual-subject data, a study in which deprivation levels may have varied widely (Matthews & Temple, 1979), and a study in which both arithmetic and exponential schedules were used (Trevett, Davison, & Williams, 1972). One whole class of concurrent arithmetic schedule studies was eliminated from the present survey. These were studies using fixed-ratio changeover requirements (Pliskoff, Cice-

rone, & Nelson, 1978; Pliskoff & Fetterman, 1981). Procedurally, these experiments were quite different from those providing the rest of the data analyzed here. The data analyzed were different also, being response counts after the subjects had completed the changeover ratio. Pliskoff et al. (1978) obtained sensitivities to reinforcement of between 1.16 and 1.96 for the three birds they used in replications 1 and 2. If, however, the data are reanalyzed with responses during the changeover ratio added to those after the changeover ratio (the usual case with changeover delays), sensitivity falls to between .58 and .98, well within the

Table 2

Summary statistics of the distribution of the power a in Equation 1 over various experimental reports according to the type of schedules arranged and the measurement taken. N is the number of subjects, SD is the standard deviation, and D_n is the Kolmogorov-Smirnov statistic.

	N	Mean	SD	D_n	Probability
<i>Arithmetic schedules</i>					
Responses	49	.789	.169	.0987	>.2
Time	38	.886	.147	.0808	>.2
<i>Exponential schedules</i>					
Responses	35	.965	.161	.0753	>.2
Time	33	.962	.179	.0807	>.2

usual range. This effect was also reported by Silberberg and Fantino (1970) for changeover delays, rather than changeover ratios. We note parenthetically that had the reanalysis of these two studies been included in the present data set, the mean sensitivity of response ratios to reinforcement ratios for arithmetic schedules (Table 2) would have been decreased by .008.

Table 1 lists the studies we used together with summaries of experimental procedures and the least-squares linear regression line that best described the data for each subject. The experiments were partitioned in a four-way classification according to type of VI schedule used (exponential or arithmetic) and the type of measure (responses or time spent responding).

Table 2 shows the number of data for each of the four categories and the mean and standard deviation of the sensitivities in each. The standard deviations were similar for each category (range .15 to .18), and there was a strong difference in response-allocation sensitivity between arithmetically and exponentially determined VI scheduling (means of .79 and .97). These values can be predicted by a theory that relates sensitivity to reinforcement to inter-reinforcement-time variance.¹ The difference in time-allocation sensitivity, although in the same direction (means .89 and .96), was much smaller.

Figure 1 shows the frequency distributions of values of sensitivity to reinforcement for each of the four categories and also logistic

distributions with the same mean and standard deviation (Table 2). Logistic curves were used for convenience. Over the central parts of the distributions they are similar in shape to normal distributions, so little is lost by using the logistic here. The fit between the theoretical and empirical distributions was assessed using the Kolmogorov-Smirnov statistic (Siegel, 1956), and the obtained values of this statistic, D_n , and the probability of rejecting the null hypothesis, are shown in Table 2. In no case could we reject the hypothesis that we sampled the empirical data from the theoretical distributions. The same test rejected the hypothesis that the response sensitivities on arithmetic and exponential VI schedules came from the same distribution ($\chi^2 = 13.8$, $df = 2$, $p < .01$). We could not reject the same hypothesis for time-allocation sensitivities.

Baum (1979) noted that response-measured sensitivity to reinforcement was generally smaller when measured in Davison's laboratory (a modal value of .80) than when estimated in his laboratory (a mode of 1). The present reanalysis explains the difference as Davison has normally used arithmetically determined VI schedules, whereas Baum has used exponentially based VI schedules. Baum also noted that there were no differences between time-allocation sensitivity determined in the two laboratories, and the present reanalysis showed no significant differences in time-allocation sensitivity between arithmetic and exponential VI schedules. In view of the significant difference in response-allocation sensitivity between schedule types, the non-significant difference in time-allocation sensitivity is puzzling. The answer may lie in the way that time allocation has conventionally been measured from changeover to changeover or from the first response on a schedule to the first response on the other. The following argument demonstrates the problem.

If the total output in a session is k pecks, then on a two-key concurrent schedule, this total comprises P_1 pecks on key 1, P_2 pecks on key 2, and P_0 pecks-equivalent to nondefined reinforcement sources. These measures exhaust the possibilities under Herrnstein's (1970, 1974) definition, and the three categories are non-overlapping. We can realize this theory empirically by measuring P_1 and P_2 , though we cannot normally measure P_0 . If the duration of the session is T sec, this will theoretic-

¹Copies of a theoretical paper that predicts the difference in sensitivity to reinforcement between arithmetic and exponential schedules are available from R. J. Taylor.

Fig. 1. Empirical relative frequency distributions of the value of a in Equation 1 for the studies listed in Table 1. The data were categorized by type of schedule and type of measure. Panel A shows exponential-schedule time measures; Panel B shows exponential-response measures; Panel C shows arithmetic-schedule time measures; and Panel D shows arithmetic-schedule response measures. The solid curves are logistic distributions with parameters as shown in Table 2.

cally comprize T_1 sec emitting P_1 , T_2 sec emitting P_2 , and T_0 sec emitting P_0 . Again, these quantities exhaust the session time, and they are non-overlapping. But in conventional time-allocation measurement, T_1 commences with P_1 and T_2 commences with P_2 , and these two measures alone exhaust the session time. Thus, the empirical measures of T_1 and T_2 both contain, to some extent, T_0 . If we call the parts of T_0 , occurring within the empirical measures of T_1 and T_2 , T_{01} and T_{02} respectively, then T_{01} is the time after emitting P_1 before emitting more P_1 or emitting P_2 . T_{02} is likewise defined. This is sufficient to show that the empirical measures of T_1 and T_2 are imprecise absolute measures of the time spent emitting P_1 and P_2 . The log ratio of these measures may be an accurate estimate of the ratio of times spent responding, but only under precise conditions (namely, $T_{01} = jT_1$ and $T_{02} = jT_2$, where j is a constant for an experimental con-

dition). If these precise conditions are not met, conventionally measured log time ratios will be an incorrect estimate of the log ratio of times spent responding. For example, if pausing (emitting P_0) always occurred after responding on the higher reinforcement-rate alternative, time-allocation sensitivity would be overestimated. Some evidence for just this effect has been collected in this laboratory (Al-diss, 1982). There is, therefore, a question mark over the adequacy of conventional time-allocation measures, and a refinement of the method of measuring time allocation might equate response- and time-allocation sensitivities both within arithmetic and within exponential scheduling procedures.

Response-allocation sensitivity is affected by differences in the way reinforcements are distributed in time. The same conclusion was implied by Davison's (1982) study of concurrent fixed-ratio (FR) VI schedules, which showed

that response-allocation sensitivity was 1.0 for variations in the FR schedule and .7 for variations in the arithmetic VI schedule. Davison also reanalyzed Lobb & Davison's (1975) data on concurrent fixed-interval (FI) VI performance. Sensitivity to FI schedule variations was .41, and to arithmetic VI schedule variations it was .78. It is clear that the sensitivity parameter of the generalized matching law (Equation 1) can precisely handle schedule differences, and the implication may be that sensitivity increases with increases in interreinforcement time variance.

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