DIFFERENTIATION OF PRESS DURATIONS WITH UPPER AND LOWER LIMITS ON REINFORCED VALUES

DENNIS O. KUCH

MCMASTER UNIVERSITY

Rats received food following lever-press durations between t and $t + t'$ sec where t was 2, 4, or 8 sec and t' was 0.25 t , 0.50 t , or 1.00 t sec. Modal press durations were greater than t but less than $t + t'$ in all cases. Distributions of press durations were lower and broader for larger values of t . Lower t'/t ratios produced lower median press durations and relatively narrower press-duration distributions. Median press duration was a power function of t within a t'/t ratio condition, corresponding to previous results for latency, interresponse time, and response durations.

The differentiation of temporal response properties has been used as a psychophysical method for the study of temporal discrimination (Catania, 1970; Ferraro and Grilly, 1970; Platt, Kuch, and Bitgood, 1973). Approached in this manner, response differentiation is a special case of stimulus discrimination in which the stimuli being discriminated are assumed to be correlated with a parameter of the response. For example, an organism that terminates a response t sec after the response is initiated might be thought of as responding to a temporal stimulus correlated with response duration. If an experimenter requires a minimum response duration of t sec for the delivery of reinforcement, and the organism comes to emit response durations approximating t , the organism can be said to be responding differentially with respect to this temporal stimulus. Functions relating emitted values of temporal properties of responding such as duration, latency, and interresponse time (IRT) to the reinforcement criteria resemble psychophysical functions relating human time estimations to the experimenter's standard stimulus (Catania, 1970). As noted by Catania,

functions from both sources are linear with similar slopes and intercepts when plotted in logarithmic coordinates. This convergence of response and stimulus functions supports the view of response differentiation as a case of stimulus discrimination.

Systematic studies of response duration differentiation are few. Platt *et al.* (1973) studied rats' lever-press durations with reinforcement contingent on durations larger than t , where t varied from 0.4 to 6.4 sec. They found that median press durations approximated t under conditions in which intertrial intervals (ITIs) occurred after each lever release. In a free-operant procedure without ITIs, control of press duration by t was much poorer. Ferraro and Grilly (1970) used t values from 0.1 to 1.6 sec in a free-operant procedure, reinforcing durations between t and $t + 0.2$ sec. They found that mean durations approximated t , even though reinforcement probability decreased precipitously as t increased.

The present study employed a duration differentiation procedure in which press durations longer than t , but shorter than $t + t'$, were followed by reinforcement. A range of t and t' values was used to explore the effects of these variables on press duration. This procedure was used to obtain a more restricted specification of the response durations reinforced than is provided by a schedule in which only t is specified. Specification of a range of reinforced durations allowed assessment of the effects of the range on the precision or variability of press durations, and on the percentage of reinforced responses as well.

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METHOD

Subjects

Twelve experimentally naive male albino rats, between 90 and 120 days old at the beginning of the experiment with free-feeding weights ranging from 348 to 394 g, were maintained at 85% of these weights throughout the experiment by supplementary rations of Purina chow given after each daily experimental session.

Apparatus

Four Gerbrands rat chambers in Grason-Stadler enclosures were each equipped with a Hawley retractable lever requiring a static force of 0.29 N to close its microswitch. The levers could be fully extended or retracted in 1.9 sec. A Foringer pellet dispenser delivered 45-mg food pellets into a cup mounted directly over the lever and recessed into the wall of the chamber. Scheduling and data acquisition were accomplished by means of a computer, and response values were recorded with a resolution of 0.01 sec.

Procedure

Food presentation occurred upon lever release following any press duration between t and $t + t'$ sec. The value of t' was chosen such that the ratio t'/t was either 0.25, 0.50, or 1.00 for any one subject throughout the experiment. Four subjects were tested with each of the three ratios and exposed to t values of 2, 4, and 8 sec in an ascending-descending or descending-ascending order. The order of ex-

posures to t values, the t'/t ratio, and the number of sessions at each t value are summarized for each subject in Table 1.

Lever-press training consisted of two sessions, during which all presses were followed by two food pellets and a simultaneous 10-sec ITI, during which the lever was retracted and the houselight turned off. When the rats responded quickly after insertion of the lever, t was increased in 0.5-sec increments per session to 2 sec for half the subjects, and in further 1.0-sec increments to 8 sec for the other half. When the first value of t appropriate to a treatment group had been attained, t' was decreased from twice t to the value prescribed by the t'/t ratio for that group. This decrease in t' was accomplished in 0.5-sec decrements for the $t = 2$ -sec condition and in 1.0-sec decrements for the $t = 8$ -sec condition.

During differentiation training, a press duration between t and $t + t'$ sec was followed by two food pellets and a 10-sec ITI. All other press durations were followed by a 10-sec ITI, but no food. Sessions terminated when 50 food presentations had occurred.

Performance was considered stable when the following three criteria were met for three consecutive sessions after the seventh session of exposure to a particular t value: (1) the mean press duration for each of the three sessions was within $\pm 0.05t$ of the three-session mean, (2) the proportion of press durations between t and $t + t'$ for each session was within $\pm 5\%$ of the proportion for all three sessions, and (3) there was no monotonic increase or decrease in mean or standard deviation of the duration distributions for the three sessions.

Preliminary observations indicated that nonoverlapping duration distributions were produced by the reinforcement contingencies so that a single shift from one reinforced duration range to the next led to prolonged nonreinforced responding. For this reason, gradual changes in the t and t' values were scheduled as follows. Movement of t to a higher value was accomplished by setting the t for a session at the eightieth percentile of the previous session's press-duration distribution. The t' value was initially set equal to the t value being approached and was gradually reduced. The reduction in t' was achieved in 0.5-sec decrements for $t = 2$ sec and 4 sec and in 1.0 sec decrements for $t = 8$ sec when the ap-

Table 1

Number of sessions at each t value for each subject, in order of occurrence.

t'/t	Subject	t							
		2	4	8	4	2	4	8	
0.25	1	15	27	10	26	26			
	2	14	11	29	20	10			
	3			13	11	10	11	10	
	4			11	18	10	13	14	
0.50	5	11	15	10	13	11			
	6	11	13	18	12	12			
	7			13	14	11	10	20	
	8			15	16	14	10	12	
1.00	9	12	15	13	24	10			
	10	16	12	12	19	16			
	11			17	14	14	13	17	
	12			20	10	19	16	23	

appropriate t value had been attained. Shifting to a shorter criterion was accomplished by setting t at the value being approached and using the mean press duration of the previous session as the $t + t'$ value until the required t' value was reached.

RESULTS

Data analyses are based on lever presses that occurred subsequent to the fifth food presentation of each of the last three sessions at a t value. Presses before the fifth food presentation were excluded to avoid "warm-up" effects.

Table 2 presents the median press duration and the interquartile range of press durations for each subject at each t value. As can be seen, redeterminations of median and interquartile range were close to the values obtained during original exposure to the t values. Since the second exposure to the t values ensured that exposure to all other t values had occurred and that a greater amount of practice with the schedules had taken place, the summaries below are based on data obtained from the last three t values for each subject.

The mean median press durations for each t'/t group at each t value are plotted in logarithmic coordinates in Figure 1. Standard errors of group means were all less than 0.5 sec and are consequently not shown in the figure. Mean median press duration was directly related to t within a t'/t ratio group so that power functions, presented in the figure, accounted for 97% to 99% of the variance in the individual subject's median press dura-

Fig. 1. Group mean median press durations (T) as a function of minimum duration (t) required for reinforcement, in logarithmic coordinates. The dashed line indicates matching of T and t .

tions. These functions were obtained by computing the linear regression of the logarithm of the median press duration for each subject on the logarithm of the t value under which that median press duration was obtained.

The mean interquartile range of press durations increased with t as shown in Figure 2. At $t = 2$ sec and $t = 4$ sec there was also a direct relationship between mean interquartile range and t'/t ratio, such that the dispersion of emitted durations increased as the range of reinforced durations increased. This relationship

Table 2

Median press duration $\pm$ interquartile range of press durations for each subject in order of schedule occurrence.

Subject	<i>t</i>						
	2	4	8	4	2	4	8
1	2.14 ± 0.41	4.06 ± 0.46	7.90 ± 2.61	4.13 ± 0.92	2.08 ± 0.42		
2	2.04 ± 0.38	4.34 ± 0.54	8.35 ± 4.37	4.31 ± 0.74	2.14 ± 0.40		
3			8.56 ± 0.98	4.23 ± 0.55	2.11 ± 0.41	4.22 ± 0.42	8.30 ± 1.39
4			8.43 ± 1.20	4.26 ± 0.58	2.11 ± 0.35	4.28 ± 0.44	8.76 ± 1.23
5	2.14 ± 0.32	4.58 ± 0.66	8.71 ± 1.32	4.25 ± 0.52	2.24 ± 0.46		
6	2.07 ± 0.37	4.52 ± 0.55	8.98 ± 2.10	4.22 ± 0.80	2.44 ± 0.63		
7			8.30 ± 2.27	4.82 ± 0.70	2.38 ± 0.36	4.66 ± 0.79	9.45 ± 3.79
8			8.27 ± 1.63	4.49 ± 0.69	2.28 ± 0.39	4.52 ± 0.69	8.48 ± 1.77
9	2.58 ± 0.44	4.79 ± 0.89	9.39 ± 1.94	5.27 ± 0.88	2.43 ± 0.50		
10	2.33 ± 0.44	4.85 ± 0.87	10.28 ± 1.56	6.46 ± 1.09	2.89 ± 0.52		
11			8.95 ± 2.19	4.90 ± 0.95	2.46 ± 0.79	4.86 ± 0.95	9.43 ± 1.77
12			10.18 ± 2.37	5.17 ± 1.45	2.68 ± 0.62	4.88 ± 1.04	9.78 ± 3.72

did not hold at $t \geq 8$ sec. The large within-group variability in mean interquartile ranges at that t value exceeds the between-group differences, making any conclusion as to between-group relationships tenuous. The disproportionately high dispersion measures at $t = 8$ sec may be attributed to the occurrence of disproportionately large low peaks in the duration distributions, rather than to any increased dispersion around the primary peaks. As is shown in Figures 4 and 5, almost one-fourth of the durations of Subjects 2 and 7 were shorter than 4 sec at $t = 8$ sec, producing very high interquartile ranges and inverting the relationship between interquartile range and t'/t ratio at $t = 8$ sec.

Dividing the interquartile range of press durations by the median press duration provides a measure of response variability relative

to the absolute magnitude of press duration. These variance coefficients are presented in Figure 3. The coefficients increased with t'/t ratio at $t = 2$ and $t = 4$ sec. This relationship was reversed at $t = 8$ sec, although the group overlap prevents a clear conclusion as to ordering of the groups. The variance coefficients for all groups were lower at $t = 4$ sec, and higher at $t = 8$ sec, than at $t = 2$ sec.

Figures 4 and 5 present the press duration distributions obtained during the last three sessions at each of the last three values for each subject. Solid bars represent presses followed by reinforcement. These distributions were generally bimodal, with a primary peak between t and $t + t'$ and a secondary peak below 1.0-sec duration. The primary peak was broader and flatter for longer values of t . There was also a tendency for the primary peak to be narrower and higher for subjects tested on schedules with lower t'/t ratios. No systematic effects of t and t' on the secondary peaks were observed.

The proportion of response durations meeting the reinforcement criterion is pre-

Fig. 2. Group mean interquartile ranges of press durations as a function of minimum duration required for reinforcement. Vertical lines are $\pm 1/2$ standard error of group mean.

Fig. 3. Group mean variance coefficients—interquartile range divided by median press duration—as a function of minimum duration required for reinforcement. Vertical lines are $\pm 1/2$ standard error of group mean.

Fig. 4. Relative frequency distributions of lever-press durations with various reinforcement requirements. Shaded bars represent presses followed by reinforcement and filled circles are overage classes. Partly filled bars indicate that the class interval overlaps reinforced and nonreinforced durations. Class intervals are 0.2-sec wide and the abscissa labels are upper limits of the class intervals. For the first two rows $t'/t = 0.25$, for the next two $t'/t = 0.50$, and for the last two $t'/t = 1.00$. These subjects received a 2-4-8-4-2 series of t values.

Fig. 5. See caption of Fig. 4. These subjects received a 8-4-2-4-8 series of t values.

sented in Figure 6. The proportion of response durations falling between t and $t + t'$ was generally lower at $t = 8$ sec than at either $t = 2$ sec or $t = 4$ sec. The effect of the t'/t ratio on

criterion response proportions was monotonically ordered, with larger t'/t ratios being associated with higher proportions at all t values. Twelve of the 24 redetermined criterion

response proportions fell within 10% of the original values. Of the remaining 12 proportions, seven were greater than, and five were less than the first determinations.

DISCUSSION

Changes observed in the press-duration distributions with changes in the reinforcement criteria conformed to the generally accepted view of response shaping, according to which differential reinforcement of a tail of a response duration distribution shifts the distribution in the direction of differential reinforcement. Reinforcing response values in the tail of the distribution increases the size of the response generalization gradient in the region of reinforced response values. Simultaneously with the movement of the reinforcement criterion, other response values are moved relatively farther from the reinforced values and

undergo extinction. These processes of generalization of reinforced responses and extinction of distant response values shift the whole distribution in the direction of reinforcement. A corollary of this analysis is that reinforcement of a narrower range of response values should cause less response generalization and produce narrower distributions of response values. As seen in Figures 4 and 5 and at $t = 2$ and 4 sec in Figure 2, this was generally the case in the present study.

Procedures similar to the present ones were used by Malott and Cumming (1964) in a series of studies of IRT differentiation. Their results for IRTs paralleled those found here for response duration, insofar as modal IRTs approximated t and the IRT distributions were flatter for higher values of t . Malott and Cumming also concluded that a decrease in the t'/t ratio tended to produce flatter IRT distributions, although inspection of their figures suggests that the relationship between kurtosis and t'/t ratio was probably nonmonotonic in the range of ratios from 0.1 to 1.0 that they used. The smaller range of t'/t values in the present study precludes a more detailed comparison.

The relationship between mean median press duration and t bears a close resemblance to relationships observed in studies of response latency, IRT, and in other studies of response duration. Catania (1970) demonstrated that the relationship of central tendency of pigeon and rat latency and IRT to t on differentiation schedules could be well described by power functions with coefficients between 1.0 and 2.0, and exponents slightly less than 1.0. Although linear functions would have fit the present data adequately, and the three points derived from these data did not allow subtle distinctions, the two functions lead to different predictions for responding at t values longer than those employed here. Linear functions fitted to the present group data would have had slopes greater than 1.0, calling for increased overshooting of t as t increased. Power functions for these data predict convergence and eventual crossing of the emitted and minimum required values of duration.

The functions describing the data reported here (Figure 1) had coefficients that decreased from 1.38 to 1.07 as the t'/t ratio decreased and exponents that increased from 0.948 to

Fig. 6. Group mean proportion of responses meeting the reinforcement criterion as a function of minimum duration required for reinforcement. Vertical lines indicate $\pm 1/2$ standard error of the group mean. The dotted line connects points obtained under a constant 2-sec range (t') of reinforced duration values.

0.990 as the ratio decreased. The decreasing coefficients indicate that the median press duration more closely approximated t as the range of reinforced duration values decreased. The increasing exponents suggest that the median function approaches linearity as the reinforced range decreases, and indeed the lowest t'/t ratio produced the function closest to the matching relationship $T = 1.0t^{1.0}$, shown by the dotted line in Figure 1. These results also fit in nicely with those of Platt *et al.* (1973) who found a relationship between median press duration and t described by a power function with a coefficient of 1.32 and an exponent of 0.92. In their study, only a minimum value of press duration was specified for reinforcement, so that t'/t was infinite.

The placement and precision of press durations in the present study depended upon the particular reinforcement contingencies in effect. A larger range of reinforced duration values produced a higher median press duration, and at $t = 2$ and 4 sec, a larger interquartile range of press durations. This dependence on reinforcement contingencies of what have been considered analogues of temporal judgments (Platt *et al.*, 1973) illustrates the importance of such factors in the determination of psychophysical functions. The median press duration produced by a particular set of contingencies may represent a compromise between maximizing reinforcement probability by placing the median press duration well within the criterion range, and minimizing response effort by producing the shortest reinforceable press duration. The increased dispersion of the press-duration distributions with increased t'/t ratio may have been a result of the greater response generalization and lessened extinction of distant response values afforded by a larger range of reinforced press durations.

The variance coefficients presented in Figure 3 provide an index of the relative dispersion at various t values. From a purely sensory point of view, these variance coefficients should be invariant across t and t'/t , representing a constant proportionality between variability and magnitude of response, independent of criterion magnitude and reinforcement contingencies. Catania (1970) reported that variance coefficients (standard deviation divided by mean in this case) of pigeon's key-peck latencies on latency dependent reinforce-

ment schedules were relatively stable over a range of t values from 1.27 to 24.4 sec. Similarly, Platt *et al.* (1973) reported nearly constant variance coefficients (interquartile range divided by median as in the present study) for rats' press durations over a range of t values from 0.8 to 6.4 sec. Ferraro and Grilly (1970) used a procedure similar to the present one with t' fixed at 0.2 sec as t varied from 0.1 to 1.6 sec. They reported a stable variance coefficient (interdecile range divided by $t + 0.1$) for t values from 0.3 to 1.6 sec, even though t'/t decreased from 0.67 to 0.125 over this range. As shown in Figure 3, the variance coefficients in the present study clearly depended on both the criterion magnitude and the range of reinforced duration values. These effects, although systematic, are quite small relative to the within-group variability, and do not constitute a strong rejection of the possibility of invariance of the coefficients with differences in treatment conditions. The overall mean variance coefficient was 0.21, a value comparable to that reported by other investigators (Platt *et al.*, 1973).

The effect of t on the dispersion of press durations generally corresponded with the effect of t on the proportions of press durations meeting the reinforcement criteria. Criterion response proportions were negatively correlated with variance coefficients within a t'/t ratio group so that higher criterion response proportions were associated with relatively narrower distributions. The lack of constancy of the criterion response proportions across t values is thus primarily a reflection of differences in the relative variability of response durations across t values. However, it is clear from Figure 6 that the effect of t'/t ratio on criterion response proportions is much greater than the effect of t within a t'/t condition. The dotted line in Figure 6 connects the points obtained under a constant 2-sec range of reinforced duration values across all three t values. The decrease in criterion response proportions from $t = 2$ sec to $t = 8$ sec was 0.35. The largest decrease observed with t'/t ratio held constant was 0.10 in the $t'/t = 0.50$ condition from $t = 2$ sec to $t = 8$ sec. Figure 6 also suggests that the effect of t on criterion response proportion decreased, and the criterion response proportion approached invariance across t , as t'/t increased. These results should be useful in designing investigations of

trade-off relationships between response and reinforcement parameters in choice situations. Only minor modifications in the t'/t ratio at different values of t should be necessary independently to manipulate reinforcement probability or density and response effort or duration on concurrent duration differentiation schedules.

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