FORCE AND RATE RELATIONS IN RESPONDING DURING VARIABLE-INTERVAL REINFORCEMENT¹

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Four rats responded on one-minute variable-interval schedules with several variations in peak-force of response required for food reinforcement. Measures of peak force and rate were taken for the responses, which were the downward exertions of force against a static force-transducing operandum. The analysis distinguished responses, a generic class of measured behavior, from criterion responses, an operationally specified subclass required for reinforcement. Absolute rate of response showed no systematic change, but the rate of responses meeting a newly required criterion of peak-force invariably increased through changes in the absolute rate of response, the relative-frequency distributions of peak force, or some combination of both. The relative frequency of responses meeting an elevated force criterion during variable-interval reinforcement exceeded that maintained with the same criterion with continuous reinforcement. The requirement of more effortful responding for reinforcement does not necessarily reduce response rate. Conformity of the behavior to the requirement for reinforcement is the salient effect.

Key words: response force, response rate, effort, response differentiation, reinforcement criterion, variable interval, lever press, rats

Although the effortfulness of behavior is considered to be an important determinant of the rate at which that behavior is emitted, a conclusive experimental analysis has thus far not been conducted. Problems of definition, methodology, and instrumentation are the major impediments to such an analysis.

Common terminology is often at odds with the dimensions of accepted physical definition. Work is the distance integral ($\int F ds$) of force, and hence the apparent paradox of no work being involved in suspending a heavy weight over one's head, or an animals' exerting force against a fully displaced lever. Notterman and Mintz (1965) proposed the time-integral of force ($\int F dt$), defined by the physicist as "impulse", as a useful measure of organismic energy expenditure. They also suggest renaming this measure "effort", at least for purposes of behavioral research. They provide considerable empirical evidence that the peak force of response is highly correlated with the time-integral of force, and is thus a conve-

niently measured index of energy expenditure, particularly in the context of test situations involving a repetitively emitted operant.

An additional consideration is the definition of the operant itself. Schick (1971) provided a cogent analysis of problems related to defining the operant as "... a unit of behavior defined by a contingency of reinforcement. . . . A class of responses, all members of which are equally effective in achieving reinforcement under a given set of conditions" (Ferster and Skinner, 1957, p. 730). The precedents for such a definition were first stated by Skinner (1938, pp. 3-43). For present purposes, the difficulties in such a definition arise from the requirement to redefine the behavior of interest when the procedure calls for selective reinforcement of some new or different range of behaviors. If responses with peak forces exceeding 5 g are reinforced in one phase of a study, and those exceeding 20 g are reinforced in another, a comparison of the behaviors is confounded by the redefinition of the operant of interest. In the latter case, "behaviors" in the 5- to 20-g range are no longer members of the operant class that identifies the dependent variable in the analysis.

Recognizing the problems that would be involved, Notterman and Mintz (1965) proposed two independent definitions, "response

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threshold" and "reinforcement criterion". The former defines the generic response class, in a sense a reinforcement-independent redefinition of the operant; the latter defines the reinforcement-eligible subclass of the independently defined response. Without such a distinction, response differentiation is impossible except for the always-present differentiation of the reinforced behavior from "other" behavior.

An analysis by Chung (1965) of rate and force relations illustrates the case in point. He measured only those responses that exceeded his force criterion in a series of manipulations involving the requirement for greater forces. Thus, in one condition, a key peck with a peak force exceeding 50 g qualified as a response, and contributed to response rate; in another condition it did not. Rate changes were thus as susceptible to changes in the experimenter's measuring behavior as to changes in the pigeon's key-pecking behavior.

Any procedure that establishes a new criterion for reinforcement and simultaneously changes the method of behavior sampling is subject to confounding. Changed force requirements produced by changing counterweights or springs in an operandum may suffer from such confounding. The subject could continue to behave in exactly the same fashion, yet its rate of response could change considerably, simply because behavior under one condition qualified as responding while in another condition it did not. This possibility has been noted earlier by Kimble (1961, p. 285).

The present concern is the analysis of variations in both the peak force of response and response rate during a series of VI 1-min schedules in which the criterion for reinforcement is based on variations in the peak force of response. Throughout these procedures the definition of response remains constant, with a response beginning whenever the instantaneous force on the operandum exceeds 5 g and terminating when the force falls below this level. Some conditions involve a force band in which the reinforcement criterion is specified by an upper as well as a lower limit for peak force (Notterman and Mintz, 1962).

Our analysis is focused at both rate-force relations and the consequences of differentially reinforcing specified response subclasses under schedules of intermittent reinforcement.

METHOD

Subjects

Four male Sprague Dawley CFE rats acquired from Carworth, Inc., were maintained for several weeks in individual cages with free access to water and food. One week before the experiment began, the rats were placed on a 23-hr food deprivation regimen. The animals were approximately 90 days old when testing was begun.

Apparatus

The rats were tested in a custom-built operant chamber measuring 17.8 cm wide, 25.4 cm long, and 20.3 cm high. The chamber was constructed of Plexiglas except for the end walls, which were aluminum, and the stainless-steel grid floor. A force-transducing operandum was located in the center of one end wall. The contact surface of the operandum was the polished end of a vertically positioned aluminum rod, 1.3 cm in diameter. This horizontal surface was 3.5 cm above the grid floor and approximately tangent to the inside of the cage wall. A protective guard, which limited the application of lateral forces, surrounded the operandum rod. This was an aluminum cylinder, 3.8 cm in diameter, and the contact surface of the operandum protruded 3.0 mm above its top surface. The operandum rod was directly affixed to a Statham UC3 transducer mounted within the protective guard. The effective range of this transducer was 0.0 to 60.0 g and its displacement under maximum load was 0.12 mm. Unlike a conventional operandum, the force transducer is totally silent in operation.

Located on the wall with the operandum were an aperture through which a water tube protruded and a brass food cup into which P. J. Noyes 45.0-mg food pellets could be delivered. These were positioned with their centers 6.2 cm to the right and left of the transducer, respectively.

The test chamber was housed in a sound-attenuated isolation room, approximately 2.0 m long, 1.3 m wide, and 2.0 m high, which was ventilated and illuminated by two 20-W fluorescent fixtures located approximately 1.25 m from the chamber. White noise was provided in the room. The electrical output of the force transducer was conducted from the chamber via shielded cables, where it was amplified and

calibrated to establish an isomorphic relation with force. Thus, a force of 5.0 g applied to the contact surface produced a voltage of 0.5 V while a force of 50.0 g produced 5.0 V. This voltage was monitored by a control unit that established the response threshold. A level of 0.5 V, equivalent to 5.0 g, was the defining threshold of a response. A response began when this level was exceeded and terminated with the descending crossing of threshold. During the course of a response, a storage circuit tracked the peak force attained, providing the basis for peak-force recording following each response. Two additional level detectors could be adjusted to signal when the force exceeded preset limits. These were used to implement suprathreshold reinforcement criteria.

Immediately after termination of each response, the control unit activated a Systron-Donner model 1201 Digital Voltmeter, which digitized the stored peak voltage. The control unit then signalled a Hewlett Packard Model 561 B Printer, which printed the digitized voltage. The digitizing and printing imposed a series of time constraints. A minimum inter-response time of 20 msec was required. In addition, no more than two responses could begin during any 200-msec interval. Behavior affecting the operandum that occurred earlier than permitted by these two limitations was effectively ignored.

Reinforcement contingencies were arranged using Scientific Prototype Reed Relay programming modules. Conventional electromechanical counters recorded total responses, responses meeting suprathreshold criteria, reinforcements, and elapsed time.

The calibration procedures employed were quite similar to those used by Notterman and Mintz (1965). These entailed the use of static weights whose force is derived from the effect of Earth's gravitational field on its mass. We have reported our forces in gram-equivalents to maintain consistency with our calibration procedures, which entailed the use of static weights. (The appropriate conversion to Newtons is approximately $1 \text{ g} = 0.01 \text{ N}$.)

Procedure

On Day 1, each rat was placed in the test chamber for 30 min of response-independent pellet delivery to achieve tray training. Initial conditioning followed immediately thereafter. A self-shaping procedure was employed in

which a food-pellet reinforcer was delivered after every response (CRF) for a total of 60 reinforcements. For all four rats, responding was satisfactorily established within approximately 30 min.

On Day 2, the rats were given 60 food pellets on a CRF schedule. On Day 3, the rats were placed on a VI 1-min schedule with interreinforcement times ranging from 5 sec to 2 min. The peak-force criterion was held at 5 g, the same as the threshold for defining an event as a response. This and subsequent phases were conducted for 20 daily sessions. In the second phase, VI 1-min was maintained and an elevated force criterion was imposed. Thus, following reinforcement eligibility established by the VI schedule, a response meeting the elevated criterion was also necessary for reinforcement. In this phase, the peak-force criterion was 20 g for Rat 1, and 15 g for Rats 2, 3, and 4. In the final phase, Rats 1 and 3 were maintained with their force criteria of the preceding phase but were reverted to a CRF schedule. Rats 2 and 4 were continued with the VI 1-min but had an upper limit of 20 g added to their force requirement, thus imposing a "force band" of 15 to 20 g for reinforcement eligibility. The sequence of procedures can be seen in the left-hand columns of Table 1.

RESULTS

The major measures of performance for all four subjects are shown in Table 1. The data reported are based on the pooled results of the final three days for each condition. For the VI schedules, every subject shows a substantial increase in the relative frequency of criterion responses during the second VI, as compared with the relative frequency of this response sub-class during the initial VI. In the initial VI, with its 5-g peak-force criterion, all responses were equally eligible for reinforcement. The second VI, with its 20-g criterion for Rat 1, and 15 g for Rats 2, 3, and 4 reflects an effective differentiation of responses meeting this elevated force criterion. The shift to the 15- to 20-g band for Rats 2 and 4 in the third condition shows a very small increase in the relative frequency of in-band responses, which must be considered effectively no change at all. However, Rat 2 does maintain the relative frequency of 15- to 20-g responses with a

Table 1
Experimental Conditions and Response Measures

Subject	Schedule	Force Criterion (g)	Median Peak Force (g)	Per Cent of Total Responses			Response Rate (R/min)			
				Over 15 g	Over 20 g	15-20 g	All R	Over 15 g	Over 20 g	15- 20 g
R1	VI 1-min	5	15.2		33.7		71.6		24.1	
	VI 1-min	20	17.9		47.4		72.4		34.3	
	CRF	20	14.6		41.3					
R2	VI 1-min	5	8.8	18.9		10.2	39.2	7.4		4.0
	VI 1-min	15	12.3	40.9		11.6	49.2	20.1		5.7
	VI 1-min	15-20	11.2	34.6		11.8	71.2	24.6		8.4
R3	VI 1-min	5	11.3	34.2						
	VI 1-min	15	14.7	56.7			67.2	23.0		
	CRF	15	12.5	43.8			61.1	34.6		
R4	VI 1-min	5	7.9	13.8		7.4	38.7	5.4		2.9
	VI 1-min	15	9.6	28.9		11.3	49.2	14.2		5.5
	VI 1-min	15-20	9.7	28.8		11.7	63.6	18.3		7.4

drop in the relative frequency of responses over 15 g.

The data for response rate in Table 1 have been divided into several categories. "All R" indicates the absolute rate of response and is analogous to rate measures that might be obtained on a conventional operandum. The other columns of rate measures show the rates of responses meeting the indicated criteria, both during the schedules when that criterion was in effect and during the other conditions as well. The transition from the 5-g to 20-g criterion for Rat 1 produced no consequential change in the absolute rate of response, but a substantial increase in the rate of responses exceeding the now-required 20 g. Rat 3 shows a similar effect and indeed its absolute rate of response decreased concurrent with an increase in the rate of response meeting the newly established 15-g criterion.

Rats 2 and 4 show a similar effect in the transition from the 5- to 15-g criterion, but both of these subjects produced increases in the absolute rate of response, as well as in the rate of responses over 15 g. The proportional increase in criterion response rate is greater than the proportional increase in absolute response rate for both subjects, and Rat 2 shows an overall increase in criterion response

rate that exceeds the overall increase in absolute rate.

The transition to band criteria for Rats 2 and 4 produced large absolute rate increases and increases in the rate of in-band responses that were small but still proportionately greater than the increase in absolute rate. This corresponds to the very modest further differentiation of 15- to 20-g responses when the band was introduced.

The common feature of all changes in the VI schedules was an increase in the rate of responses meeting a new criterion after that criterion was introduced. These rate increases reflected differentiation of higher absolute rates, differentiation of relatively more-frequent criterion responses, or some combination of these two independent properties of behavior.

The underlined rates of response in Table 1 correspond to the rate of responses meeting the reinforcement criterion in each condition. These reflect a systematic decrease with a more stringent criterion. It is clear, however, that these decreases are not a property of the behavior. These are the rates that would have been attributed to the behavior had our procedures identified only those responses eligible for reinforcement as "responses".

Data for regular reinforcement (CRF) are shown for Rats 1 and 3. Both animals show lower relative frequencies of criterion responses than when reinforcement occurred on VI 1-min in the immediately preceding condition. Rate data were not taken, as the preponderance of time was devoted to the pellet-consummatory sequence of behavior. During CRF, the rate of reinforcement, of course, went up dramatically, from approximately one per minute to well over eight per minute.

Figure 1 shows the relative-frequency distributions of peak force during the first two VI conditions for each subject. All show a similar general effect. The distributions for the VI with the higher force criterion (open circles) reflect a decrease in relative frequency of responses at forces below the new criterion, and an increase at forces above this criterion.

The fulcrum for this distribution shift is remarkably close to the value of the elevated criterion, shown by the dashed-line arrow on the abscissas in Figure 1. The distributions show small frequencies of "under 5 g" responses, technically not responses at all, but included because they were counted as responses in other features of data collection and contingency instrumentation. These were effectively errors in our test system. Essentially, all of these nonresponses that were considered responses were force emissions of 4.9 g.

DISCUSSION

Much of our results could have been anticipated from rather basic and well-known consequences of reinforcement: the frequency of reinforced behavior increases. The manifestation of this principle in our study was quite clear. The interesting feature was the route to its achievement. Response rate and the peak force of response would appear to be independent and independently differentiable properties of behavior. Increases in the rate of a newly reinforced behavior may derive from changes in either or both behavioral properties. Our procedures generated specimens of most of the possible routes to the fundamental rate-increasing effect of reinforcement.

The present data provide some suggestive evidence regarding what form of differentiation will actually occur. When the change in schedule required a peak-force variation that

was previously relatively rare, large increases in the absolute rate of response ensued. When the new criterion corresponded to a relatively frequent response variation, absolute rate of response showed no change or a reduction. The present study provided only a few instances to make this assessment and then largely in across-animal comparisons. However, it seems reasonable that an effect of this sort would take place. A change to a more-stringent criterion reduces reinforcement frequency. Those changes in behavior that increase the rate of criterion responses tend toward restoring reinforcement frequency. The changes that produce this most rapidly experience the most rapid selective strengthening. It is possible that the animals may restore reinforcement frequency most rapidly as a consequence of modulations in response rate when the peak-force variation is rather rare. On a VI schedule, when temporal eligibility for reinforcement has been established, a burst of rapid responses may substantially reduce the waiting time for a response meeting the peak-force criterion. Although reinforcement follows a particular interresponse time and a particular peak-force, the effectiveness of rate variation may be more discriminable. When the peak-force variant is already relatively frequent, changes in peak force may come in contact with differential reinforcement sooner than rate variations. In a sense, the animal has concurrent reinforcement contingencies for two different properties of its behavior. Differentiation of one or the other presumably depends on the rapidity with which variations in each affects an improved reinforcement frequency.

The rate of reinforcement declined for all of our animals immediately following the changes to more-stringent criteria in the sequence of VI schedules. However, every animal restored reinforcement frequency so well that we dispensed with a planned control phase for the presumed reduction in reinforcement frequency that would follow the introduction of more-stringent criteria. Interreinforcement time did not differ in any consequential magnitude among the criterion variations employed.

The present data show less-effective maintenance of criterion responses by CRF than VI. The two rats shifted from the VI 1-min to CRF with an unchanged reinforcement cri-

Fig. 1. Relative-frequency distributions of peak force of response for four rats under VI 1-min reinforcement schedules each under two different peak-force criteria for reinforcement. The vertical arrows on the X-axis indicate the minimum force required in each condition. Data are based on three 1-hr test sessions; the total number of responses under each condition is indicated in the keys. Y-axis scales vary among subjects.

terion showed a drop in the relative frequency of responses meeting the criterion. This might be surprising since in CRF, nonreinforcement unequivocally corresponds to sub-criterion responding. In VI, the vast majority of responses are unreinforced with no differential consequences for criterion and sub-criterion responses. However, the change to CRF produced an enormous increase in the proportion of responses reinforced, and in the rate of reinforcement. The contingencies for reinforcement in CRF provide relatively little effective cost for a sub-criterion response in terms of the rate at which reinforcement occurs or in terms of the gross trade-off between energy expenditure and reinforcer acquisition. Responses are rapidly made and one or several sub-criterion responses provide very little delay in reinforcement. Similarly, the proportion of total energy expenditure is probably only modestly affected by the emission of a quantity of sub-criterion responses. Although we have not measured it directly, other behaviors such as locomotion, operandum approach, *etc.*, undoubtedly constitute a major source of energy expenditure. The difference between, say, 50% and 100% reinforcement does entail a factor of two in operandum-oriented energy expenditure, but a much smaller factor with regard to the total behavioral output maintained by the reinforcement. Thus, the "cost" of errors in the form of noncriterion responses is relatively small where cost has as its dimensions either time or energy expenditure.

The distinction between "response" and "reinforcement criterion" has been maintained in the present analysis. Were this not done, and the definition of response in each condi-

tion depended on the reinforcement criterion, every rat would have shown a response-rate decrease with the imposition of a more-stringent reinforcement criterion. Such an erroneous conclusion would derive from confounding the unit of sampled behavior with the reinforcement requirement. Two of the four rats in this study showed large rate increases, one showed essentially no change, and one showed a rate decrease when the sampling unit was held constant across the phases of the study that increased the force requirement. The essential importance of the definitional arguments is considerable when matters of definition can lead to anithetical observations regarding the nature of behavioral change. A reinforcement-criterion-independent definition of the dependent variable is essential in the experimental analysis of behavior.

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