FORCE GRADIENTS IN STIMULUS GENERALIZATION¹

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Pigeons were trained to peck with differing force requirements on a key specially designed to measure and control force of pecking without changes in the mechanical threshold. Following training on a key illuminated by a single wavelength, a generalization test was given. Force and rate gradients were obtained. Force gradients were shown to have a form similar to rate gradients. The slope of the force gradients was a direct function of the force of responding at the conclusion of training. Rate gradients were independent of the force of responding.

The force exerted on a response-key by a trained animal may be represented as a distribution of forces, whose statistical properties are a function of the minimum force required for reinforcement. Trotter (1956) and Notterman (1959), investigating the force distribution during acquisition and extinction of bar-pressing by rats, found that the variance decreases during training and increases during extinction. They found that the mean force declined from its initial high level during acquisition to a value approximately twice the minimum force required for reinforcement and returned to the high level during extinction.

In the present experiment, both the force and the rate of responding were studied in relation to stimulus generalization. The conventional experiment on stimulus generalization (e.g., Guttman and Kalish, 1956) investigates only the rate of responding as a function of stimulus value along a designated continuum. Using pigeons originally trained with

a light of a particular wavelength, Guttman and Kalish found that the rate of responding in extinction was a decreasing function of the difference in wavelength between any test stimulus and the original training stimulus. The present study is an extension of earlier studies, adding a new measure of response, the force, and a new manipulation, the force of responding during training. Apart from these changes, experimental procedures do not differ from earlier studies. Gradients of force, as well as gradients of rate, were studied as a function of changes in stimulation and as a function of changes in the force of responding during training.

Subjects

Twelve naive White Carneaux pigeons, 1 to 2 yr of age, obtained from the Palmetto Pigeon Plant, Sumter, S. C., were maintained at approximately 80% of their *ad libitum* weights.

Apparatus

Two experimental chambers with trans-illuminated keys, and associated control and recording apparatus, were used.

The key was of special design. It was hinged at the bottom and the top was connected to two inexpensive crystal phonograph pickups by 1¼-in. lengths of piano wire so that movement of the key activated the crystal. When the key was moved by striking it, foam rubber returned the key to its original position. Any movement of the key broke the connection between a pair of contacts mounted at the top of the key. The key had a low mechanical

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threshold, in that a static pressure of less than 12 g was sufficient to break the contacts.

A pigeon's peck is a quick, ballistic movement; contact with the key at all force levels lasted less than 6 msec. With such a ballistic movement, the force imparted to the key by a peck is a direct function of the peak acceleration of the key, immediately following impact. Since the output of the crystal transducer is a function of the velocity of the key, not its displacement, and since velocity is the time-integral of acceleration, the transducer functions as an integrator of acceleration over time and the peak voltage produced by the transducer is directly correlated with the integral of force over time, *i.e.*, impulse.

The output of the key was recorded on a Texas Instrument Oscillograph and was also used to drive a triggering circuit. The triggering circuit in combination with the break contacts on the key were used to drive a nor-gate which operated a pair of counters, one for all responses above the triggering level, the other for all responses below the triggering level and above the mechanical threshold of the key. These are called "triggering" and "non-triggering" responses, respectively. Only triggering responses operated the grain magazine.

The peak output voltages of the crystals, read in millimeters of deflection on the Oscillograph record, were equated with forces of impact. They were computed in dyne-sec, by releasing a steel ball of known mass, allowing it to roll a measured distance down an essentially frictionless inclined plane of fixed angle, and measuring the peak voltage when it struck the key. The calibration curves resulting from this procedure exhibited an almost linear relation between millimeters of deflection and dyne-sec. The calibration curves for the two keys used in the experiment were of similar slope but different intercept, indicating a slight difference in mechanical threshold. Where it is necessary to compare data from the two boxes, dyne-sec instead of mm of deflection are used. The output voltage of each key for various force levels and the triggering levels for reinforcement were checked daily against the calibration curves. Even under hard usage, the crystals did not significantly vary in output. Repeated tests showed a variability of less than 5%.

The key was trans-illuminated through an enclosed channel by projected light from a Bausch and Lomb grating monochromator, model number 33-86-25. Light to the key was interrupted between trials by a shutter, driven by a pair of solenoids and located in the channel. Key illumination provided the only light in the box, except during reinforcement when the magazine was illuminated with white light. The experimental chamber was 12 in. high by 14 in. long by 16 in. wide. The 1-in. key-hole was located $7\frac{1}{2}$ in. from the floor in the middle of the wall opposite the door. Access to the magazine was through a 2 by 2-in. hole directly beneath the key at floor level. White noise from a loudspeaker in the top of the box masked operation of relays.

Procedure

The pigeons were first trained to eat from the magazine and then to peck at the key with the triggering circuit set at minimum force, just above the mechanical threshold of the key. The experimental session was divided into 30-sec periods followed by 10-sec blackout. The session was terminated after 60 reinforcements. Each reinforcement consisted of 4-sec access to grain. The illumination of the key throughout training was a light of 550 $m\mu$. Next, the force requirement was raised, as rapidly as the animal's responding permitted, until the force requirement for a given experimental condition was reached. All triggering responses were reinforced. Four final force requirements were used: 75, 90, 105, 175 dyne-sec, with each bird at only one force requirement. When the criterion was reached that 50% or more of the responses in a day's session were triggering responses, reinforcement became intermittent. Frequency of reinforcement was gradually decreased until the birds were working on a VI 18 sec schedule. To reach this point in training without extinction required about nine days, with some birds taking as much as 18 days and some as little as four days. The birds were first given VI 18 sec for three days and then directly transferred to VI 30 sec for six days.

Immediately after the sixth day of VI 30 sec, the pigeons were tested for four days in extinction. During each day, a set of 11 test stimuli, ranging from 500 $m\mu$ to 600 $m\mu$ in steps

of $10m\mu$, was presented five times, but randomized so that each stimulus was presented once in each 11 trials. Each 30-sec trial with one of the 11 wavelengths was followed by a 10-sec blackout. The sequence of stimuli was the same for all birds for all sessions.

Data are presented for 12 birds, three for each force requirement.

RESULTS

Before the force requirement was raised, the pigeons pecked with low mean force, about 40 dyne-sec, and within a narrow range, about 10-80 dyne-sec. The mean force rose during acquisition and fell during extinction. The range of forces also rose during acquisition

and fell during extinction. Examination of the Oscillograph records suggests that the coefficient of variation was approximately constant.

Table 1 gives the average force for each bird at the conclusion of training, as well as the force requirements for reinforcement. As measured by the percentage of triggering responses, force remained stable over the last nine days of the training procedure. Even though the pigeons had reached a stable pattern of responding, it is apparent from Table 1 that the average force is not closely correlated with the force level. A Kruskal-Wallis one-way analysis of variance by ranks shows no significant effect of force requirements ($H = 0.74$ with 2 df).

Fig. 1. Force distributions for individual birds. Dashed line indicates the force requirement. By taking percentage of total responses, the scales are adjusted so that the area under each curve is the same.

Table 1
Force Requirement and Average Force of Responding
on Last Day VI 30 sec in Dyne-sec

Force Requirement	Bird	Average Force
175	Fd 50	300
	Fd 54	96
	Fd 48	135
105	Fd 52	173
	Fd 42	108
	Fd 60	151
90	Fd 49	337
	Fd 53	105
	Fd 57	285
75	Fd 51	129
	Fd 41	135
	Fd 59	171

Figure 1 shows the force distributions for individual birds on the last day of VI 30 sec. These are drawn as frequency distributions, *i.e.*, the percentage of responses of a given spike height, using 3-mm categories. These distributions differ markedly in shape from bird to bird, from quite sharp unimodal distributions, *e.g.*, Fd 53, to approximately rectangular distributions, *e.g.*, Fd 60. Many of these distributions, *e.g.*, Fd 48 and Fd 49, can be interpreted as bimodal with the lower mode at 9-12 mm and the upper mode at various force levels. The mode for the unimodal distributions also falls at 9-12 mm. Since a peak in the force distributions occurs

at 9-12 mm, independently of the force requirement and independently of the mean force at which the bird was pecking, the peak may be a response to the mechanical threshold of the key. If the mode at 9-12 mm is a response to the mechanical threshold of the key, most birds learned the mechanical threshold, although some, *e.g.*, Fd 53, did not learn the force requirement for reinforcement at all. The average force distribution for all birds is unimodal with its mode at 9-12 mm. This is consistent with the assumption that most birds show a mode at this point with some showing an additional mode at higher force levels.

Figure 2 gives the gradients of average force per stimulus and average number of pecks per stimulus for all birds during extinction. Averaging across subjects was done by first expressing each individual gradient as a set of percentages of the force or number of responses to the middle stimulus and then averaging the percentages. The gradient for number of responses represents the average rate gradient, since the total exposure time to each stimulus in extinction was the same.

The gradient for force shows that the average force of responding is a decreasing function of the distance of the test stimulus from the training stimulus, as is the gradient for rate. The gradient for force, however, is much flatter than the gradient for rate. The relative force of responding in the presence of stimuli

Fig. 2. Average relative force and rate gradients.

distant from the training stimulus is greater than the relative rate to the same stimuli. Both gradients are asymmetrical, *i.e.*, both force and rate fall off less rapidly to distant

stimuli above 550 $m\mu$ than below. This asymmetry of rate gradients about 550 $m\mu$ is frequently reported in generalization studies, *e.g.*, Guttman and Kalish, 1956.

Fig. 3. Force and rate gradients, Fd 50, Fd 54, Fd 48. The force requirement for each bird was 175 dyne-sec. Scales have been adjusted so that the force or number of responses to the 550 $m\mu$ stimulus falls the same distance above the origin for each curve.

Figures 3, 4, 5, and 6 show the gradients of force and rate for individual birds. To allow for more accurate comparison of the shapes of individual gradients, the curves have been constructed with the force and rate of responding to 550 m μ set the same

Fig. 4. Force and rate gradients, Fd 52, Fd 42, Fd 60. The force requirement for each bird was 105 dyne-sec. Scales have been adjusted so that the force or number of responses to the 550 m μ stimulus falls the same distance above the origin for each curve.

Fig. 5. Force and rate gradients, Fd 49, Fd 53, Fd 57. The force requirement for each bird was 90 dyne-sec. Scales have been adjusted so that the force or number of responses to the 550 $m\mu$ stimulus falls the same distance above the origin for each curve.

distance above the origin for all birds. Mm deflection and number of responses are given in the marginal scales. The gradients for force are much more irregular than the gradients for rate.

Although the gradients for rate are similar to one another, the gradients for force range from quite sharp to essentially flat. The slopes of the force gradients are steeper for birds responding with high force; the slopes of rate

Fig. 6. Force and rate gradients, Fd 51, Fd 41, Fd 59. The force requirement for each bird was 75 dyne-sec. Scales have been adjusted so that the force or number of responses to the 550 $m\mu$ stimulus falls the same distance above the origin for each curve.

gradients are independent of force and independent of the force gradients. To compare the slopes of the gradients with the force of pecking, the following measure was constructed. The number of responses or the average force per stimulus was expressed as a percentage of the number of responses or the average force to the 550 $m\mu$ stimulus. These percentages per stimulus for rate or force were multiplied by the number of steps its stimulus was from the training stimulus and the products were summed for each bird. Finally, this weighted sum was inverted and multiplied by 10^4 . The resulting number, called a slope index, increases as the gradient steepens and decreases as the gradient flattens. Table 2 gives the slope indexes for force and rate, together with the average force, the average force for the middle stimulus, and the total number of responses.

The slope index for force gradients is directly correlated with the force of pecking during training ($r_s = 0.72$, $p < .01$). As might be expected, a similar direct correlation holds between force of responding to 550 $m\mu$ in extinction and the slope index for force gradients ($r_s = 0.75$, $p < .01$). The slope index for rate gradients, however, is not significantly correlated with either of these measures ($r_s = 0.10$ and 0.14 , $p > .05$).

Force of responding to 550 $m\mu$ during extinction is not correlated with the force requirements. The Kruskal-Wallis one-way analysis of variance by ranks shows that force of responding to 550 $m\mu$ in extinction is not significantly different for different force re-

quirements ($H = 0.74$ with 2 df). The force of responding to 550 $m\mu$ during extinction is, however, highly correlated with the force of responding on the last day of VI 30 sec ($r_s = 0.89$, $p < .01$).

Both force and rate decline during the course of extinction. Figure 7 shows the average force and rate gradients for each day of extinction. The major decline in both force and rate occurs between the first and second day of extinction, with rate dropping much more rapidly than force. Both force and rate gradients sharpen during extinction. Using the slope index described, slope indexes for the average force gradients increase from 4.88 to 7.11. Over the same period, slope indexes for the average rate gradients increase much more drastically, from 8.25 to 31.96.

DISCUSSION

The results of the present experiment are in sharp contrast to the results of Notterman's studies with rats (Notterman, 1959). Unlike the rat, the pigeon begins responding with low mean and low variance. The coefficient of variation is approximately constant, so that when high force is learned, the variance increases during acquisition and decreases during extinction. This finding severely restricts the generality of Notterman's results, which may obtain only for those organisms that initially respond with high mean and high variance. (Comparison may be improper, since the present experiment used force integral instead of peak force.)

Table 2
Force, Total Responses, and Slope Indexes. Force in Dyne-sec

Force Requirement	Bird	Avg force 550 $m\mu$	Avg force all stim.	Total responses	Slope index force	Slope index rate
175	Fd 50	300	138	1583	6.18	12.22
	Fd 54	76	96	2810	3.43	14.67
	Fd 48	96	97	1448	4.71	30.66
105	Fd 52	130	100	3076	4.92	13.88
	Fd 42	52	28	3818	4.66	11.77
	Fd 60	128	104	1682	6.01	10.23
90	Fd 49	220	204	1003	5.51	10.69
	Fd 53	54	71	1568	4.69	7.35
	Fd 57	141	126	1247	6.12	15.16
75	Fd 51	98	93	2733	3.67	12.66
	Fd 41	124	120	1688	4.02	9.85
	Fd 59	98	97	2132	3.50	7.68

Fig. 7. Force and rate gradients for each day of extinction averaged across all subjects. Scales have been adjusted so that the force and rate to the 550 $m\mu$ stimulus for the first day of extinction falls at about the same distance above the origin.

The average force gradients obtained in the test for stimulus generalization have been shown to have a form similar to average rate gradients. The slopes of individual force gradients, however, have been shown to be a direct function of the force of pecking at the end of training, whereas rate gradients are independent of force. Examination of the extinction data suggests that if the pigeon is to peck the key, it will peck with some minimum mean force well above zero. A minimum mean force of pecking may explain the correlation between the slope of the force gradient and the force at the end of training. If this force is close to the minimum force, the resulting force gradient would be nearly

flat. The minimum mean force may result from learning the mechanical threshold of the key, *i.e.*, the minimum force necessary to move the key. The pigeon will cease to peck a key that does not move, even under continuous reinforcement (Hefferline, Birch, and Gentry, 1961), indicating that pecking such a key may be aversive. In the present experiment, the mechanical threshold of the key may have been learned through avoidance conditioning.

In the narrow sense determined by the equipment, all birds learned a force requirement for reinforcement: all birds learned to respond in such a way that they received about the same frequency of reinforcement. Yet it is clear from the different forms of the force distributions that different birds learned quite different things. In the present experiment the force requirement was complicated by two factors to be discussed below: (1) The nature of the feedback from the force requirement, (2) The use of a VI schedule.

The force of impact required for reinforcement was controlled by the electrical output of the key independently of its mechanical loading. Since mere movement of the key is not a sufficient criterion for the required force, as it is in the standard pigeon key, the sensory feedback related to the force requirement for reinforcement is drastically reduced. Since the mechanical threshold was held constant and did not change with changes in the force requirement, changes in the way the key moved could not be used as a cue for the required force of pecking. This reduced feedback may explain the length of time required for force training. With the standard pigeon key, a change in the force requirement produced by a change in the spring loading of the key, is learned within one session, instead of taking the average of nine days required in the present study.

Since reinforcement was available only intermittently, the frequency of reinforcement could be unchanged if only a small percentage of the pecks exceeded the force requirement. For example, the frequency of reinforcement for Fd 54 was the same as the other birds even though at the conclusion of training, less than 50% of its pecks were made with a force greater than the triggering level.

As far as the information available to the bird is concerned, there is a serious ambiguity

between the force requirement and the VI schedule. The same consequence follows if the bird is responding too lightly or if reinforcement is not yet available, *i.e.*, no reinforcement. A decrease in the frequency of reinforcement could be the consequence of either an increase in the force requirement or a change in the schedule. With the high rate of responding normal to a VI schedule, the difference between these conditions could be detected only if the bird increased the force of its pecks. This change in force of responding, however, works against the response system of the organism, since a decrease in the frequency of reinforcement tends to produce a decrease in the force of responding (Skinner, 1938).

The ambiguity between force and schedule is brought out sharply in the behavior of a group of birds run in a previous pilot study. They were trained on a VI schedule *before* they were given force training. Every attempt to raise the force requirement led to a decrease in the frequency of reinforcement, which in turn led to a decrease in the force of responding, which led to a further decrease in the frequency of reinforcement, and the bird invariably spiraled into extinction. Even following a shift to force training on continuous reinforcement, only two of the 12 birds in this group could be taught the force requirement.

From an adaptive point of view, the pigeon may not be designed to deal well with force contingencies, at least with respect to the pecking response. This might be expected from the usual function of this response, *i.e.*, picking up objects. For this use, the important parameter to the organism would not be the force of the peck, but the distance of movement. Thus it may be distance cues, rather than pressure cues, to which the pigeon is responding when confronted by a force requirement. This would provide a further basis for the learning of the mechanical threshold of the key and explain the difficulty in learning a force requirement with the present key.

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