

INHIBITORY CONTROL AND ERRORLESS DISCRIMINATION LEARNING¹

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Pigeons learned to discriminate between a positive stimulus (white key) and a negative stimulus (red or green key, depending on the subject) via Terrace's fading procedure. Generalization tests, conducted with intermittent reinforcement for key pecking at various wavelengths, yielded minima at the value of the negative stimulus in most "errorless" birds. Terrace's contrary finding of flat gradients in errorless subjects probably resulted from a floor-effect (*i.e.*, virtually zero responding) produced by his extinction-test procedure. The present and other findings do not support Terrace's conclusions that the negative stimulus of an errorless discrimination is behaviorally neutral; inhibition apparently develops to the nonreinforced stimulus even during errorless discrimination learning. A negative correlation between stimulus and reinforcer seems the crucial factor in producing an inhibitory stimulus.

Conventional operant discrimination-learning procedures begin with the reinforcement of a response in the presence of one stimulus (S+). After the response is established, another stimulus (S-) is occasionally presented, during which responding is not reinforced. Responses to S- decrease, whereas responses to S+ continue. Terrace (*e.g.*, 1966a, 1972a) labelled S- responses "errors" and attributed certain byproducts of discrimination learning (*e.g.*, behavioral contrast, peak shift, "emotional" behavior during S-, and inhibitory stimulus control) to the occurrence of errors. More recently, he traced these byproducts to the "active" inhibition of responding during S- (Terrace 1972b). The role of errors remains important, however, as their reduction or suppression produces active inhibition.

Results of experiments in which pigeons mastered discriminations without making errors have provided the main support for Terrace's position. Procedures for training such errorless discriminations generally involve a

gradual increase in the duration and brightness of S-, rather than the sudden introduction of S- at full duration and brightness, as on conventional procedures. This fading technique produces very few errors in some subjects. Terrace reported that when pigeons make fewer than 25 to 40 errors, the byproducts typical of discriminations that are learned with errors fail to develop. For example, when trained to discriminate between either a white vertical line (Terrace, 1966b) or a white homogeneous field (Terrace, 1972a) as S+ and some wavelength as S-, and then tested with several wavelength values in extinction, birds that had made errors showed incremental gradients with minima in responding at or near the former S-; errorless birds, on the other hand, produced flat gradients with virtually zero responding. According to some workers (*e.g.*, Jenkins, 1965; Terrace, 1966b, 1972a), the finding of incremental gradients along an S- dimension orthogonal to dimensions of S+ demonstrates inhibitory control by S-, whereas flat gradients indicate that S- is behaviorally neutral. Therefore, Terrace argued that the flat gradients he obtained after errorless training demonstrate that an "errorless" S- is a neutral stimulus.

Interpretation of Terrace's flat gradients encounters a methodological limitation. Deutsch (1967; see also Hearst, Besley, and Farthing, 1970) pointed out that because Terrace's errorless birds rarely responded to any stimulus

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value during generalization testing, it was not possible to detect whether responding was weaker at S— than at other values along the S— dimension. In other words, Terrace (1966*b*, 1972*a*) may have failed to observe incremental gradients around S— in his errorless birds because of a floor-effect produced by the extinction-test procedure.

The present study employed discriminations (a white S+ versus S— color) and fading procedures very similar to Terrace's. The major new feature was the use of a *resistance-to-reinforcement* procedure during generalization testing. Hearst *et al.* (1970) suggested that testing with nondifferential reinforcement of responding to all stimulus values may be useful for several reasons, but should be particularly appropriate when extinction procedures produce a floor-effect. Continued reinforcement ought to ensure a relatively high response level along the S— dimension.

METHOD

Subjects

Sixty-one female White Carneaux pigeons were maintained at 75% of their free-feeding weights. Only 31 completed all phases of the experiment. After obtaining an appreciable number (*i.e.*, approximately 20) of subjects that made more than 40 errors ("with-errors" group), we concentrated on filling the "errorless" groups with at least three subjects each, since analysis of errorless learning was the main goal of the present research. Additional birds were dropped from the experiment once they had made approximately 40 errors. A total of nine errorless birds was secured from the original stock of 61 birds. This information is included to indicate the difficulty in obtaining errorless birds, even when we tried to follow Terrace's procedure very closely. Published reports of errorless discrimination learning have rarely, if ever, provided an index of success rates with the procedure.

Apparatus

A Grason-Stadler chamber was modified for pigeons by inserting a black panel 36 cm wide by 32 cm high, with a single response key centered 18 cm from either side wall and 24 cm above the floor. The response key (2.4 cm in diameter) could be transilluminated with ei-

ther white light or light of 630 (red), 590 (yellow), 555 (green), or 490 nm (blue) by an in-line readout projector (I.E.E. 10-0229, with G.E. 44 lamps). Three-second access to grain was through a hole 6.4-cm square, centered 10 cm below the response key. A force of 15 g (0.15 N) on the key was required to register a response. The floor was constructed of bakelite (23 by 36 cm) and covered by white paper during experimental sessions. Dim general illumination was continuously provided by a G.E. 7.5-W bulb located at the back of the chamber and shielded so that the illuminance on the black panel was approximately 0.05 ft ca (measured by a Photovolt Corp. photometer, Model No. 210). Stimulus intensities were manipulated by variation of resistors in series with the in-line readout projector. The only major apparatus difference compared to Terrace's work was use of the miniprojector, rather than a monochromator, to produce various wavelengths.

Procedure

Training. On Day 1, subjects were trained to eat from the magazine and shaped by the method of successive approximations to peck the white response key. Each of the first 30 responses was reinforced. After conditioning of the key peck, discrimination training began. During 30-sec periods when the key was white, responses were reinforced on a variable-interval (VI) 10-sec schedule; during periods when the key was dark, responses were not reinforced. As detailed in Table 1, the duration of the dark-key presentations was increased from 3 to 30 sec on Day 1.

On Day 2, the duration of each S+ (white key) was increased to 60 sec, and the reinforcement schedule was changed from VI 10-sec to VI 30-sec after the second S+ presentation. Duration of the S— wavelength (red or green, depending on the subject) remained at 3 sec throughout this session, but its intensity was increased in 10 steps from completely dark to an intensity equal to S+. Final equalization of S+ and S— intensities, as well as the determination of approximately equal steps by which the intensity of S— was raised, were based on judgments by independent human observers. The corresponding changes in resistance value are shown in Table 1. For this day and for the rest of the experiment, stimulus presentations were separated by 2.5-sec interstimulus intervals, during which the key was dark.

Table 1

Specific variations in intensity and duration of S- during the three days of fading in S-.

| Day | Successive S- Trials | Intensity (ohms) | Duration (sec) |
|-----|----------------------|--|----------------|
| 1 | 1-3 | ↑ | 3 |
| | 4-7 | | 6 |
| | 8-10 | | 10 |
| | 11-14 | Dark | 15 |
| | 15-17 | | 20 |
| | 18-20 | | 25 |
| | 21-30 | ↓ | 30 |
| 2 | 1-3 | Dark | ↑ |
| | 4-5 | 64 | |
| | 6-7 | 47 | |
| | 8-9 | 35 | |
| | 10-11 | 26 | 3 |
| | 12-13 | 22 | |
| | 14-15 | 16 | |
| | 16-17 | 9 | ↓ |
| | 18-20 | 5 | |
| | 21-30 | 0 (i.e., brightness equal to that of S+ key) | |
| 3 | 1-3 | ↑ | 3 |
| | 3-4 | | 6 |
| | 5-6 | | 10 |
| | 7-10 | | 15 |
| | 11-14 | 0 | 20 |
| | 15-17 | | 30 |
| | 18-20 | | 45 |
| | 21-25 | | 60 |
| | 26-30 | ↓ | 180 |

On Day 3, the S+ component of the schedule was increased to 180 sec and the reinforcement schedule was changed from VI 10-sec to VI 30-sec to VI 60-sec over the first two S+ presentations. Equal intensities of S+ and S- were used and the duration of S- was gradually increased from 3 sec to 180 sec, as shown in Table 1. During the first three (fade-in) discrimination training sessions, 30 S+ and 30 S- trials were ordered such that the same stimulus did not appear on more than two consecutive trials.

After Day 3, S+ and S- always remained equal in intensity and duration, and were presented in a quasi-random order, 15 times during each session; no more than three consecutive trials could be of the same stimulus. Throughout training, responses during S- delayed the offset of S- by resetting the S- timer.

All subjects with S- (red) and the first nine subjects with S- (green) experienced the above fading procedure. However, errorless learning proved extremely difficult to obtain with a

green S- (26 birds were used without success); therefore, the procedure for introducing S- was modified for the last 10 birds. On Day 1, S+ was 30 sec, as before, but both the duration and the intensity of S- were increased within the session. Over the first 10 S- trials, duration of the dark key was increased from 1 to 30 sec; for the second 10 S- trials, duration was reduced to 1 sec and intensity was increased over the same 10 steps as for previous subjects; for the final 10 S- trials, duration was gradually increased so that by the end of Day 1, S+ and S- were the same intensity and duration. Over the next two days, both stimuli were gradually increased in duration until each was 180 sec long.

Testing. Following 14 days of additional training (15 days for one "with-errors" bird), with S+ and S- at their full intensity and duration, each subject was tested for stimulus generalization along the wavelength dimension. Test values included 630, 590, 555, and 490 nm. The S+ was not presented during the test. Each test was, however, preceded by a warm-up of four S+ presentations (with VI 60-sec reinforcement) and four S- presentations according to the same procedure used in training. Generalization test stimuli were presented in 12 randomized blocks of four stimuli, and each stimulus presentation was 60 sec in duration. Each bird received one of four different test-stimulus sequences.

On subsequent days, subjects received additional generalization tests (with a variety of different sequences, but otherwise the same procedure). Only the first test was preceded by a warm-up.

For the first 12 birds (all trained with a red S-, including errorless Birds 71, 2337, 2643, and 7897 in Figure 3) the test began with a presentation of S-, which remained on until the subject responded. The first two responses were reinforced, after which this stimulus remained on for an additional 60 sec while reinforcement was available on a VI 30-sec schedule. This schedule remained in force until the bird had completed one block of four stimuli in which each reinforcement that became available during a stimulus presentation was collected during that presentation. The schedule was then changed to VI 60-sec for the remaining stimulus blocks. During generalization sessions after the first test, reinforcement was always available on the 60-sec schedule.

If a subject did not respond to the first test stimulus (S⁻) within 2 hr, several free reinforcements were given and the method of successive approximations was employed to shape key pecking to the test stimulus. Thus, these first 12 birds each obtained at least two response-contingent grain deliveries at the red S⁻ before other test stimuli were introduced. This training at S⁻ was omitted for all remaining birds, however, because we felt that it unnecessarily complicated the experiment.

For the remaining subjects, therefore, the first test stimulus was not necessarily the former S⁻. Reinforcement was initially available on a VI 30-sec schedule, which was changed to VI 60-sec, as for previous subjects. All test-stimulus presentations were 60 sec long, and no attempt was made to shape responding to the former S⁻.

Before testing, each bird was classified as either "with-errors" or "errorless", according to the general criteria offered by Terrace (1966a and personal communications). Only responses to the illuminated S⁻ were considered errors; responses on the dark key on Day 1 and interstimulus-interval (ISI) responses during later sessions were not counted as errors. In addition, responses during the first second of S⁻ that followed (very infrequent) responses during the 2.5-sec ISI were not counted as errors because such S⁻ responding appeared to be a "spillover" from ISI responding. This additional criterion was suggested by Terrace (personal communication) and is analogous to one employed in his early work to discount S⁻ responses that appeared to represent a spillover from an immediately preceding S⁺. A bird was classified as errorless if it made fewer than 35 errors to S⁻. Generally, once a bird made a burst of responses, or even more than three or four responses during one S⁻, it continued making errors on subsequent S⁻ presentations and exceeded the 35-error criterion. This limit is also consistent with the general criteria followed by Terrace (personal communication).

There were some procedural differences from Terrace's experiments. In his interdimensional discrimination experiments, Terrace used either 30-sec or 60-sec stimulus durations. However, because we found errorless performance difficult to maintain with 60-sec durations, we used 180-sec stimuli, as in Terrace's earlier experiments (see Terrace, 1966a). Our correc-

tion procedure (rarely experienced by errorless birds) also differed somewhat from Terrace's: S-responses reset our S⁻ timer; in Terrace's experiments, they stopped the timer for 30 to 45 sec.

RESULTS

Of the S⁻ (red) subjects, 13 learned with errors, making between 46 and 1178 errors. Six birds made between one and 22 errors and were considered errorless. Nine S⁻ (green) subjects made between 73 and 528 errors, whereas three made between 30 and 33 errors, meeting our criterion for errorless performance.

Group data for S⁻ (red) subjects during the first day of generalization testing are shown in Figure 1. The two groups displayed very similar relative gradients. The absolute gradients, however, show that with-errors subjects made many more responses during the test than did errorless subjects. This difference in total generalization-test responses was statistically significant ($t = 2.18$, $df = 17$, $p < 0.05$, two-tailed).

Similar findings are shown in Figure 2 for the S⁻ (green) subjects. As in Figure 1, relative gradients had very similar shapes, and with-errors birds responded more during the tests than did errorless birds. For these subjects, however, this difference in total generalization-test responses was not statistically significant ($t = 1.28$, $df = 10$, $p > 0.20$), perhaps due to the small number of errorless birds.

Gradients for individual errorless subjects are presented in Figure 3. All the S⁻ (red) birds, except 7897, showed maximal responding at the wavelength value (490 nm) farthest from S⁻, but a clear minimum at S⁻ was present in only three of the six birds. Subject 7897 made eight responses during the first test stimulus (shaping was not necessary) but, even though the first two of these were reinforced, it made only one other response (to 490 nm) during the rest of the test. Figure 4 shows that during further sessions of generalization testing, this bird also exhibited a clear-cut gradient around S⁻. Gradients for Birds 2337 and 2643 were irregular during further testing and are not shown; these were two of the three birds whose pecking to the red S⁻ had to be shaped at the start of generalization testing. All three S⁻ (green) birds produced clear incremental gradients around S⁻. Thus, dimensional control by S⁻ was found for at least seven of the nine errorless birds.

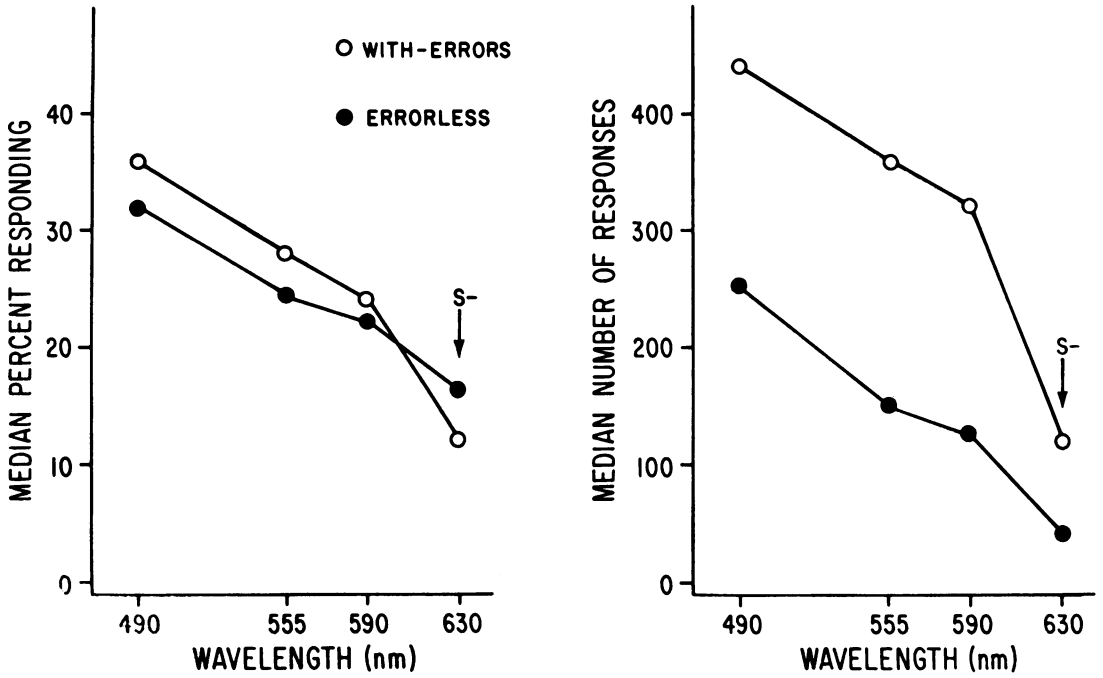


Fig. 1. Group gradients of relative and absolute wavelength generalization obtained on Day 1 of generalization testing for six errorless and 13 with-errors birds after training with a white S+ and a 630-nm (red) S-.

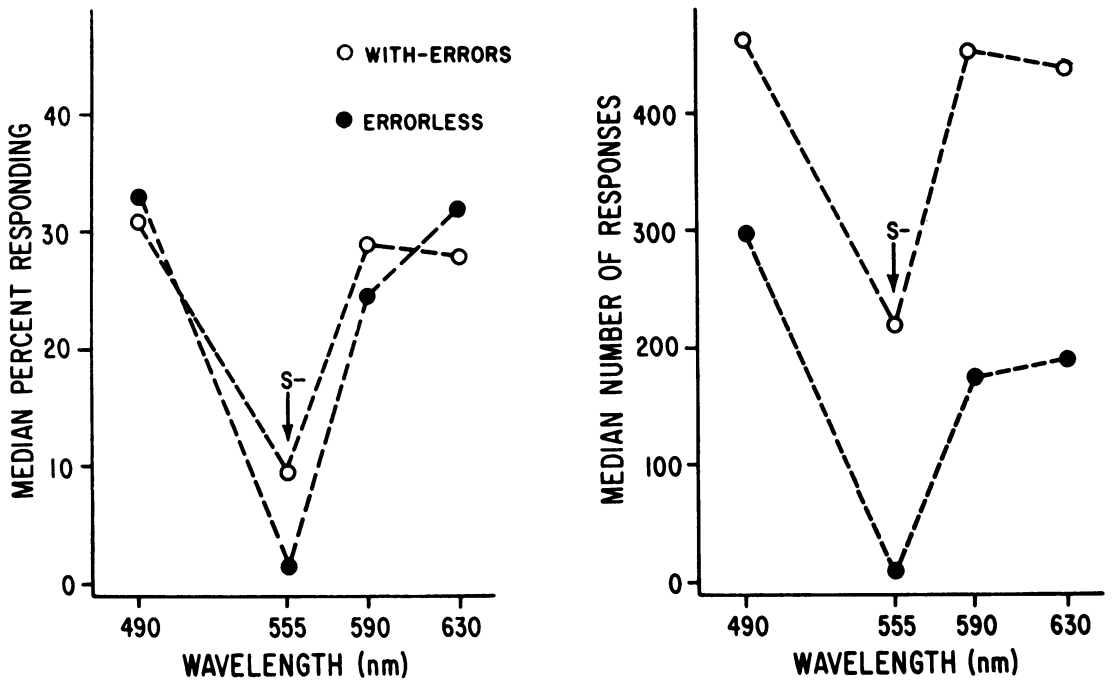


Fig. 2. Group gradients of relative and absolute wavelength generalization obtained on Day 1 of generalization testing for three errorless and nine with-errors birds after training with a white S+ and a 555-nm (green) S-.

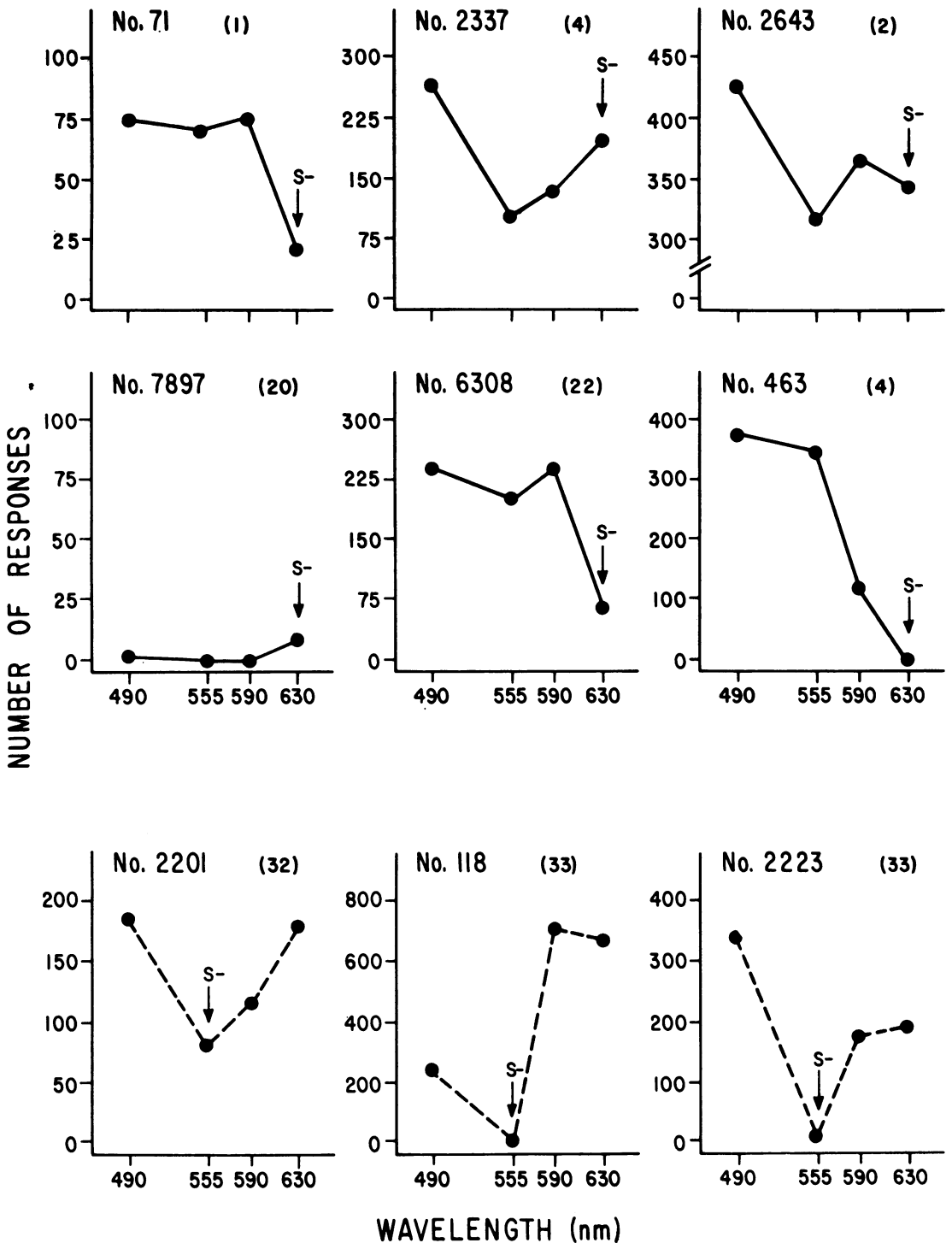


Fig. 3. Gradients of absolute wavelength generalization obtained on Day 1 of generalization testing for all errorless birds. The upper six graphs are for subjects trained with a 630-nm (red) S-. The lower three graphs are for subjects trained with a 555-nm (green) S-. For each bird, the number of errors is indicated in parentheses.

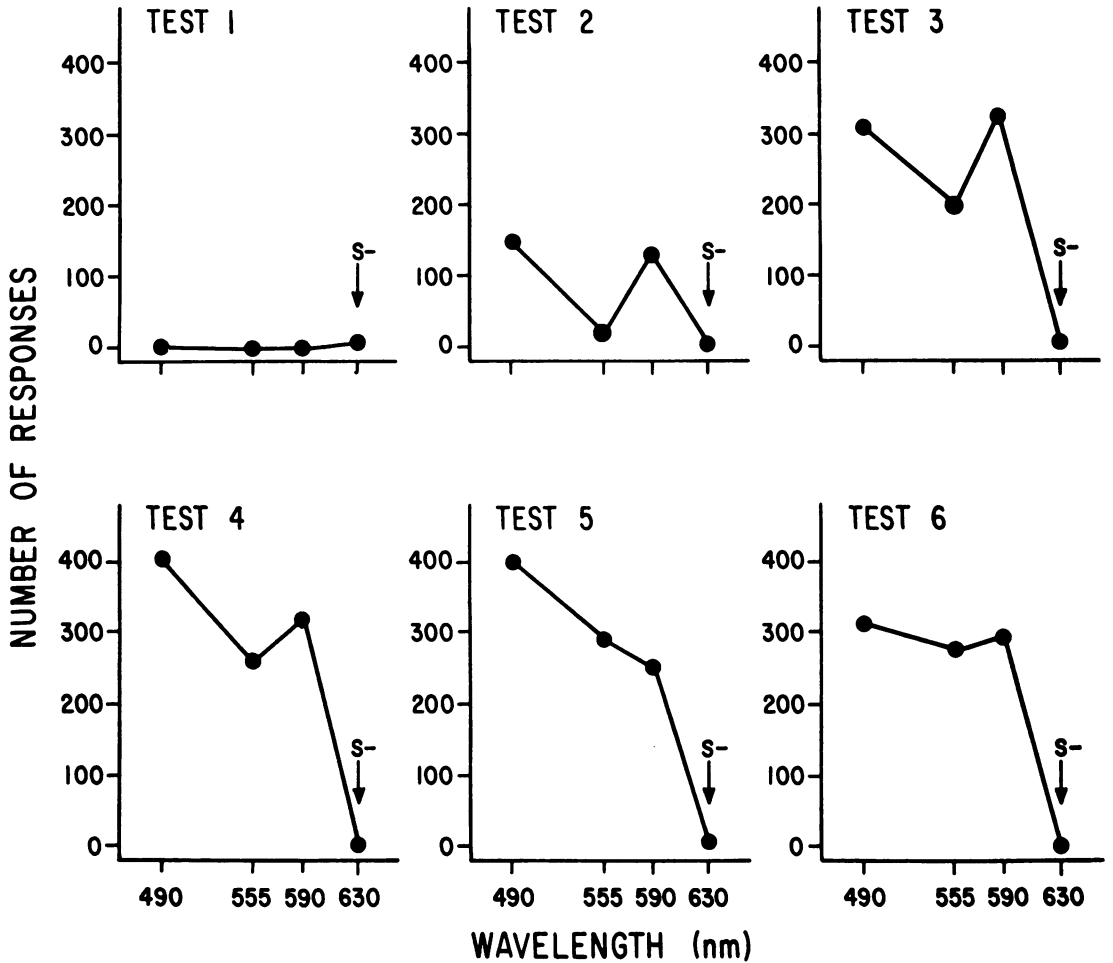


Fig. 4. Generalization gradients obtained on six successive days after errorless discrimination learning in Bird No. 7897. Control by the S- value (630 nm) was not apparent on the first day, but a clear gradient emerged with continued testing.

To compare the proportions of with-errors and errorless birds that showed incremental gradients, *i.e.*, a definite minimum at S-, we determined the number of subjects that showed a gradient on one or more of the first four tests. Sixteen of 22 with-errors birds (72.7%) and seven of nine errorless birds (77.8%) showed such gradients. Thus, errorless performance produced incremental gradients at least as often as did with-errors performance.

DISCUSSION

According to the generalization assay for inhibition used by Terrace (1966*b*; 1972*a*), the present finding of incremental gradients

around S- suggests that an errorless S- is an inhibitory stimulus. Furthermore, the results of our tests with maintained intermittent reinforcement at all stimulus values imply that the flat gradients Terrace obtained in very similar experiments were due to a floor-effect brought about by his extinction-test procedure. An example of such a floor-effect occurred in the present experiment (Figure 4), in which a bird that made only 20 errors during training responded very infrequently during the first session of testing and produced a flat gradient. During further sessions of testing, however, a clear incremental gradient emerged.

Hearst (1972) suggested that incremental gradients may be obtained even when the stimulus producing minimal responding is not in-

hibitory. For example, a stimulus could merely be less excitatory than the other test stimuli and the obtained gradient would be hard to distinguish from one around an inhibitory stimulus. Hearst proposed that several tests for inhibition, *e.g.*, combined-cue and retardation-of-learning tests (*cf.* Rescorla, 1969), are necessary to determine if a particular training paradigm produces an inhibitory stimulus. Although the present experiment employed only generalization tests, and was therefore inconclusive according to Hearst's argument, the additional evidence required to establish that an errorless S- exerts inhibitory control comes from other investigators. For example, Lyons (1969) and Johnson (cited by Hearst, 1972) reported that when the S- of an errorless discrimination is superimposed on the S+ from the same discrimination (combined-cue test), large decrements in responding are observed. Although Lyons' procedure for training errorless discriminations (response prevention) differed from Terrace's, Johnson did use Terrace's fading procedure. In experiments involving discriminations established in an autoshaping situation, Wilkie and Ramer (1974) showed that an errorless S- is inhibitory via a retardation-of-learning test; Wessells (1973) found that an errorless S- is inhibitory via both a combined-cue test and a retardation-of-learning test; Rilling (*in press*) obtained incremental gradients around an errorless S-. Thus, there is good evidence, obtained with a variety of assays, to indicate that S- is inhibitory after errorless learning.

Terrace's (1972a) argument that reduction or suppression of responding during S- is necessary to establish incremental gradients around S- fails to handle the present results. In fact, one bird (No. 71) made only one error and still showed an incremental gradient. Our generalization gradients obtained from errorless subjects, and the evidence supplied by Lyons, Johnson, Rilling, Wessells, and Wilkie and Ramer indicate that the negative correlation of a stimulus with a reinforcer is crucial in endowing a stimulus with inhibitory properties. Such a negative correlation produces an inhibitory CS- in Pavlovian conditioning (Rescorla, 1969). We suggest that the relationship between a stimulus and a reinforcer is as important in operant conditioning as it is in classical conditioning, and we propose that it is such relationships that mainly produce in-

hibitory (and excitatory) control, rather than specific-response reduction or suppression (in the inhibitory case), as suggested by Terrace.

In summary, we have argued that Terrace's (1966b, 1972a) failure to obtain incremental gradients around S- after errorless learning was probably due to a floor-effect, and that findings from our and other experiments indicate that in operant discrimination learning, a stimulus bearing a strong negative correlation with the delivery of reinforcers becomes inhibitory even when discrimination learning occurs with almost no responses to S-.

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