THE SHAPE OF SOME WAVELENGTH GENERALIZATION GRADIENTS

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An impressive series of studies, begun by Guttman and Kalish (1956), has brought modern operant techniques to bear on the classical problem of generalization. Most of these papers test hypotheses based on the theories of Hull and Spence. The data have favored some hypotheses, but not others. For example, transposition was successfully predicted from the generalization gradient (Honig, 1958), and discrimination training led to a predicted "peak shift" (Hanson, 1959), although the shape of the shifted curve was not derived in detail. On the other hand, there was no evidence of a relation between discriminability (size of jnd) and the shape of the gradient (Guttman & Kalish, 1956). Hull's ideas on gradient summation were not confirmed (Kalish & Guttman, 1959). The role of motivation seemed more complex than had been hoped (Thomas & King, 1959). Gradients of extinction did not look as expected.²

By and large, the theories behind these predictions are based on scanty data collected under quite different experimental circumstances. Perhaps we should not concentrate too much attention upon the implications of such theories, for in so doing, we may miss the discovery of relationships that no one has ever thought of predicting. If we spend some time exploring, we may later construct our theories at the most favorable spot.

The present experiments explore the shape of the wavelength generalization function in the pigeon and its changes following shifts in the reinforced wavelength.

METHOD

Subjects

Eight young male White Carneau pigeons were used. All were experimentally naive. The birds were maintained at approximately 70% of their free-feeding weights.

Apparatus

Experimental Chamber. The birds worked in a ventilated light-tight aluminum picnic ice-box. The walls of the bird's chamber were painted flat black. The bird struck a circular milk-plastic response key 1 inch in diameter, illuminated from behind by the stimulus light. A solenoid-operated food magazine was located below the response key. A movable mirror reflected the stimulus light down into the magazine during reinforcement, providing magazine illumination of the same wavelength as the stimulus, although dimmer. A loud-speaker in the box supplied white masking noise. Each peck on the response key produced a sharp click from a relay in the box.

Stimulus System. The optical system providing the stimulus and magazine light is shown schematically in Fig. 1. Light from a strip filament lamp run on stabilized voltage at 17A passed first to a Bausch and Lomb grating monochromator ("wavelength control," Fig. 1). Selected wavelengths of 10-m μ band width emerged from this instrument. A motor-driven optical wedge controlled stimulus intensity. The wedge moved to a predetermined setting for each wavelength, so that the light reaching the response key was of relatively constant

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²Personal communication with W. K. Honig, 1959.

Figure 1. The stimulus system.

luminance. The necessary correction was calculated from the sensitivity of the pigeon's eye (Blough, 1957) and the output function of the monochromator.

Control and Recording. Relays, timers, and punched tape programmers controlled the presentation of stimuli and reinforcements. Cumulative records were made of all responses, and counters recorded responses at each wavelength.

Procedure

Training Procedure. Each of eight birds was trained to peck the response key, four at a stimulus wavelength of $550\text{ m}\mu$, two at $570\text{ m}\mu$, and two at $530\text{ m}\mu$. The experimental box was open to room light briefly at the beginning of the first training session. Thereafter, the stimulus supplied the only light in the box except that from the food magazine during reinforcement. Following magazine and key training, the birds were run in experimental sessions that terminated after 2 hours or after 60 reinforcements had been delivered, whichever came first. They received reinforcement according to the following schedules: continuous reinforcement (60 reinforcements); FI 15 seconds (60 reinforcements); VI 30 seconds (30 reinforcements); VI 1 minute (120 reinforcements); VI 2 minutes (2 hours); VI 4 minutes (2 hours); VI 9 minutes (2 hours). During the last 4 hours of training, the stimulus appeared in 30-second presentations, which alternated with 15-second blackouts. During the training sessions, the duration of an individual reinforcement was at first 4 seconds and was then raised to 8 seconds; and finally, when the bird was put on VI 9 minutes, reinforcement time was increased to 12 seconds. At the end of the training period, all of the birds were responding at a fairly regular rate on the 9-minute, variable-interval schedule.

Testing Procedure. All the birds were given a series of three generalization tests, which alternated with reconditioning sessions at their training wavelengths. The procedure during each test was as follows. The key was illuminated for 30-second intervals, alternating with 45-second blackouts. During the first 10 minutes of the session, only the training wavelength appeared, and the bird received three reinforcements on a VI schedule. Then reinforcement ceased, and the stimulus varied among 11 wavelengths: 510 through $590\text{ m}\mu$ in $10\text{-m}\mu$ steps, plus 490 and $610\text{ m}\mu$. These stimuli were randomized within blocks. Each stimulus appeared once in each block, and usually six blocks comprised the session, though a few sessions contained 9 or 12 blocks. During the reconditioning sessions, run on alternate days, the birds returned to the training procedure, VI 9 minutes at their training wavelengths, for 2 hours.

After they had finished their third test run, the four birds trained at 550 m μ went on to an extended series of generalization sessions. First, they had a fourth generalization test as just described. Then, they were trained for 2 hours at a new wavelength, 530 m μ (VI 9), and received another generalization test.

From this point, a new procedure was used. As in the previous generalization runs, the various wavelengths appeared in randomized blocks, each stimulus appeared once in each block, and six blocks comprised a session. However, the sessions were not run in extinction. Pecking at one selected wavelength was reinforced on four out of the six occasions that it appeared during the session. These reinforcements were randomized in time, some coming early in the 30-second presentation, some late. Eating time did not reduce the 30-second opportunity to peck the key.

The birds received three or four runs according to this new plan, with 530 m μ as the reinforced wavelength. Then, they received 2 hours of training with a single wavelength, 510 m μ , presented alone and reinforced on VI 9 minutes. Four or five sessions of the new testing procedure followed, with occasional reinforcements at 510 m μ and stimuli at other wavelengths unreinforced. Next, the birds were trained for 2 hours at 570 m μ on VI 9 minutes, and a series of test sessions followed with 570 m μ reinforced. Similar training and test sessions were run at 610 m μ , and the experiment terminated with a return to the original reinforced stimulus, 550 m μ .

RESULTS AND DISCUSSION

Progressive Changes in the Gradient

What happens to the distribution of the responses over the wavelength continuum when reinforcement shifts from one wavelength to another? Reinforcement was shifted with four birds, and Fig. 2 shows most of the generalization data from one of them, Bird 418. Each curve plots the number of responses given at each of the test wavelengths during a single test session. The curves are numbered consecutively, beginning with the first test session.³ Let us briefly summarize the reinforcement conditions. Sessions 1–3 are generalization tests run in extinction. On each subsequent “training day” (Sessions 4, 9, 14, 20, 30), the bird received about 14 reinforcements on a new wavelength. In the rest of the sessions, the bird received four reinforcements at the designated wavelength.

Several things about Fig. 2 deserve attention. (1) When reinforcement is first applied at a wavelength, a peak appears at that wavelength. This peak is rather broad at first, but sharpens with continued training. (2) When a wavelength is no longer reinforced, the peak at that point falls away in a regular fashion in subsequent sessions. The nature of this change is seen most clearly when the newly reinforced wavelength is far from the old. For example, note the decline at 510 m μ following a shift to 570 m μ (Sessions 15–19), and the decline at 570 m μ following a shift to 610 m μ (Sessions 21–29). (3) When reinforcement is not applied at a given wavelength, responding at that wavelength measures generalization from the stimulus being reinforced at the moment, together with residual effects of training at other wavelengths. Although we cannot clearly separate these two sources of strength, a tentative analysis can be based on the relative rise and decline of responding at the various wavelengths in successive curves. If responding at a wavelength declines rapidly from ses-

³The figure omits the sessions of retraining at 550 m μ that alternated with the sessions labelled 1, 2, and 3. Curve 3 is actually the sum of the bird's third and fourth generalization tests; the bird responded little on each of those days. To save space, several sessions after Day 20 have been omitted from the figure.

Figure 2. Gradients from successive, individual test sessions of Bird 418. The bird was trained first at 550 $m\mu$, then shifted to other wavelengths. A vertical line below each curve indicates the reinforced wavelength. Note omission of several days' data.

sion to session, we assume that the current reinforcement conditions have relatively little effect at that wavelength. If responding rises or stays high at a wavelength, we assume that it is receiving a strong contribution from the current reinforcements. For example, reinforcement at 570 $m\mu$ does not maintain responding noticeably at 510 $m\mu$, for the curve at

510 $m\mu$ falls rapidly during the sessions of reinforcement at 570 $m\mu$ (Sessions 15–19). Reinforcement at 570 $m\mu$ does maintain responding at 560 $m\mu$ and 580 $m\mu$ throughout the same series of sessions. Similarly, training at 530 $m\mu$ seems to raise responding more to the left (490, 510 $m\mu$) than to the right (550, 560 $m\mu$). Viewed as measures of generalization, these effects agree with the “primary” generalization gradients yielded by birds trained from the first at 530 $m\mu$ and at 570 $m\mu$ (see below). In two cases, generalization spans a wide range: training at 510 $m\mu$ lifts responding at 610 $m\mu$ somewhat (Sessions 10–12), while training at 610 $m\mu$ brings a substantial rise at 490 $m\mu$ and 510 $m\mu$ (Sessions 27, 29).

In addition to Bird 418 (Fig. 2), three other birds were reinforced on the series of different wavelengths. The general effect of the reinforcement shift was similar in all the birds, but there are several noteworthy differences. The data of Bird 418 were chosen to appear in detail because the process of change was clearest in this bird: the curves responded readily to reinforcement shifts, but discrimination did not occur so fast that the curves became very sharp at the reinforced wavelength before the broader generalization effects were visible.

Summary curves for the other three birds are shown in Fig. 3. The “550 $m\mu$ ” curves represent means of the first three test sessions. The other curves all represent the fifth test session at each of the reinforced wavelengths. Each bird shown in Fig. 3 reacted in its own way to the reinforcement shifts. Bird 130 discriminated rapidly; its gradients had grown quite sharp by Day 5, and it is hard to see the nature of generalization effects in its data. Bird 372 was the opposite; its response distribution shifted but slowly with reinforcement. Large humps at previously reinforced wavelengths still appear in its curves on Day 5 at each

Figure 3. Summary curves of three birds trained first at 550 $m\mu$, then shifted to other wavelengths. The 550 curve is the mean of three tests; the other curves represent in each case the fifth test session following a shift of the reinforced wavelength.

new wavelength. Bird 098 also shifted slowly. However, more striking than this is the peculiar shape of the gradients from this bird, a point that will receive further comment below.

Individual Differences

Guttman and Kalish (1956) gave each of their birds two generalization tests. They mentioned that individual birds tended to reproduce characteristic curves, and suggested that "averaged gradients are not entirely representative of the generalization phenomenon for the single S." The present data confirm this finding. Figure 4 shows the first three generalization tests from each of six birds. Two birds were trained at 550 m μ , two at 530 m μ , and two at 570 m μ . The gradients produced by each bird are similar and can be distinguished

Figure 4. The first three gradients from each of six birds. Two birds were trained at 530 m μ , two at 550 m μ , and two at 570 m μ . Note individual differences.

from the curves of the other bird trained at the same wavelength. Three of the birds generalized rather broadly, giving some responses throughout the entire test range (Birds 098, 755, 951). The other birds responded in a more limited portion of the stimulus range (Birds 130, 818, 6454). Figure 4 also suggests a few other differences; perhaps the most striking is that between Birds 130 and 098. Bird 130 follows the "average" asymmetrical pattern for birds trained at 550 m μ . The two other birds trained at 550 m μ gave gradients similar to these (Birds 372, 418; Fig. 2 and 3). Bird 098 gave a few more responses to the longer wavelengths than to the shorter, but its gradients are much more symmetrical and tend to come to a sharper point at the training wavelength.

We may conclude that even at a given training wavelength, there is no curve that could be called the "generalization gradient" for all birds. Training wavelength also seems to contribute to the shape of the gradient; we turn next to this relationship.

Shape as a Function of Training Wavelength

There is no reason to expect generalization gradients to show symmetry or constancy of shape when plotted on a wavelength base line. We use the wavelength scale by convention,

but an arbitrary transformation of this scale—to “frequency,” for example—would yield a new set of shapes. However, Guttman and Kalish (1956) report a good deal of regularity among curves plotted on the wavelength continuum, and only confusion resulted when an attempt was made to plot the data on “rational” scale with units representing jnd’s for hue (Guttman, 1956).

Can any order be found in the shapes of the present gradients? Figure 5 shows the average of the initial gradients collected around 530, 550, and 570 $m\mu$. These curves summarize the data shown in Fig. 4, plus the results of two more birds at 550 $m\mu$. The gradient centered at 550 confirms the now well-established finding (e.g., Guttman & Kalish, 1956; Guttman, 1956; Hanson, 1959; Thomas & King, 1959) that the average gradient around this point is strongly asymmetrical. Most birds trained at 550 $m\mu$ peck more at wavelengths longer than 500 $m\mu$ than at wavelengths shorter than 550 $m\mu$.

Figure 5. Mean gradients around each of three training wavelengths. The figure includes only gradients around the first training wavelength. Six birds contribute—two at 530 $m\mu$, four at 550 $m\mu$, and two at 570 $m\mu$.

The gradient centered at 570 $m\mu$ is rather rounded and symmetrical; it looks much like the Guttman and Kalish (1956) gradient at 580 $m\mu$. The gradient centered at 530 $m\mu$ is high on the left, and thus contrasts with the Guttman and Kalish gradient at 530 $m\mu$, which is high on the right. Clearly, more data are needed here, but one factor favors the present data as the more representative. It has been shown elsewhere (Blough, 1959) that a drop in stimulus intensity may slow down responding considerably. The brightness of the Guttman and Kalish stimulus system, which was uncorrected, undoubtedly fell rapidly with decreasing wavelength below 530 $m\mu$, with less change in the longer wavelength regions. This may have abnormally depressed responding below 530 $m\mu$ and distorted the gradients in this region.

It is informative to compare these tentative findings on the shape of the gradients with the data of the birds trained at a succession of wavelengths. Figure 6 shows the mean gradients at each wavelength from Bird 418 (mean at 550—all tests; 530, 510, 570—2nd and 3rd tests; 610—5th and 6th tests). The dotted lines suggest the curves as they might be in the absence of previous reinforcement. As with the “primary” gradients just discussed, the curve at 530 is asymmetrical to the left and the curve at 570 $m\mu$ is rounded and symmetrical. With a good eye and a trusting heart, one can detect these phenomena in data of Birds 130 and 372, though in these birds, as we saw above, sharpening due to discrimination and flattening due to previous reinforcement make such analysis very chancy.

The curves of Bird 098 (Fig. 3) defy classification with the others. They are quite reliable—e.g., the bird produced a curve similar to that labelled 530 repeatedly. They also tend

Figure 6. Gradients around a succession to training wavelengths in a single bird, summarized from Fig. 2. Dotted lines suggest "correction" for residual effects of previous training. Compare with appropriate curves in Fig. 5.

to be consistent as a group, showing steepness in the vicinity of 550 $m\mu$, flatness in the regions 510–530 $m\mu$ and 570–590 $m\mu$.

Such consistencies in the data of individual birds, together with the suggestive shapes of the mean "primary" gradients, revive the possibility that there are regions along the spectrum within which generalization readily occurs. Trained near the middle of such a region, the bird would generalize within the region, producing a symmetrical, flat-topped gradient. Trained at the edge of such a region, the bird would generalize into the region; in the other direction its curve would fall more rapidly, to yield an asymmetrical gradient. At the moment, the best case can be made for such a region centered near 570 $m\mu$. Perhaps, another, centered at 515 $m\mu$, would account for a leftward asymmetry in the 530- $m\mu$ gradient, and a third would complete the bird's "color circle," accounting for the strong generalization between 490 $m\mu$ and 610 $m\mu$, the extremes of the spectrum used in this work.

We are tempted to identify such regions of generalization with the "hues" or "unitary colors" of human perception, for our "hue" is our generalization in the use of a color name over a restricted part of the spectrum. The data suggest that the "hues" of pigeon and human do not coincide; the pigeon's "yellow" seems too broad, and its "red-blue" (represented by generalization between the ends of the test spectrum in this study) has no human counterpart. However, this latter generalization between what we report as "orange-red" and what we report as "greenish-blue" is possibly an artifact of the testing procedure. These spectral regions are complimentary for the human, and each produces the other as an after-image. If, during training at one spectral region, the pigeon frequently "saw" the complimentary as an after-image, it might in effect be getting trained at both and respond accordingly during testing.

Such remarks imply that the generalization procedure might help to clarify problems of color vision in animals. For example, in this context, the data suggest that Bird 098 might have anomalous color vision. Its curve at 550 m μ seems to fall between two rather broad generalization regions (Fig. 3). Perhaps it is a "dichromat," with a weak "yellow" process!

The present data support the conclusions of Guttman and Kalish (1956) on the relationship between the pigeon's wavelength generalization and discriminability functions. Assuming the correctness of the generalization data, we must either reject the common notion that there is some sort of inverse relation between the two functions (i.e., the steeper the gradient at a given wavelength, the smaller the jnd at that point), or we must reject the only available data on wavelength discriminability in the pigeon (Hamilton & Coleman, 1933). For example, we have seen that the generalization gradient is relatively flat around 570 m μ . That implies a large jnd in this region. Hamilton and Coleman report a *minimum* jnd at about this point, similar to the human minimum to be found near there. However one feels about this dilemma, the need for more discriminability data is pressing. It is certain that pigeons can discriminate much more finely than the Hamilton and Coleman data indicate. For example, these authors show a pigeon "jnd" at 550 m μ of about 17 m μ . The present author has trained birds to discriminate 550 from 559 m μ in less than 1 hour (successive presentation), setting a maximum of 9 m μ on the jnd. Hanson (1959) reports a significant discrimination of 1 m μ at 550 m μ ; this is the same order of magnitude as the human jnd at that point. Despite such discrepancies, the Hamilton and Coleman data may still correctly indicate *relative* discriminability across the spectrum (cf., Kalish, 1958). Their data showed good agreement among three subjects. The absolute size of the jnd is a function of many variables (amount of training, testing procedure, etc.) that may have worked against them.

SUMMARY

Eight pigeons were trained to peck a disk illuminated by one of several wavelengths (530, 550, or 570 m μ). The birds generated generalization functions by pecking, in extinction, at eleven wavelengths presented in random order. Four of the birds were then trained at a series of new wavelengths and tested with a modified procedure.

The major results are:

- (1) Regular reproducible gradients were obtained from all birds. With shifts in the reinforced wavelength, the gradient shifted and responding centered around the new wavelength. The characteristics of the gradients could be interpreted in terms of (a) generalization from the reinforced wavelength, (b) residual effects of previously reinforced wavelengths, and (c) discrimination effects resulting from differential reinforcement at the training wavelength.

- (2) There were clear individual differences among the gradients of birds trained at the same wavelength.

- (3) The data suggest that gradients around different training wavelengths are not similar, when plotted on a wavelength base line. Some gradients are rounded, some pointed, some asymmetrical. There may be regions along the spectrum within which generalization most readily occurs. One such region appears to be centered near 570 m μ , another to include the ends of the test spectrum (490 and 610 m μ); there may be a third centered near 515 m μ . There seems to be no meaningful relation between such regions and available data on the pigeon's hue discrimination (jnd) function, but the jnd data are open to question.

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