A METHOD FOR OBTAINING PSYCHOPHYSICAL THRESHOLDS FROM THE PIGEON

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In several recent experiments, I have used a new and rather complex method to measure the pigeon's absolute visual threshold. The published reports of these studies (2, 3, 5, 6) include only brief summaries of this technique. The present paper describes the method in detail and outlines the reasoning behind its various aspects. For the sake of brevity and clarity, I do not attempt to discuss other applications of the technique. Also, I do not add to the previous apparatus descriptions (2, 3, 5), except where such addition is necessary to clarify procedural details.

The method was suggested by Békésy's technique for tracing the human auditory threshold (1). According to Békésy's procedure, the subject listens to a soft tone. When the tone is audible, the subject presses a key. This causes an automatic mechanism to diminish the intensity of the tone gradually. When the tone can no longer be heard, the subject releases the key, whereupon the tone increases in intensity until it is again audible. This process continues and the tone oscillates up and down across the subject's threshold. A continuous chart of the tone's intensity gives a graphic record of the threshold through time.

The novelty of Békésy's method lies in the way that the subject's responses govern the stimulus intensity. Equally important, however, is the control exerted in the opposite direction: the stimulus intensity controls the subject's responses. This "feedback" link in the psychophysical procedure will be my primary concern in this paper. When I refer to "stimulus control," I shall mean this influence which the stimulus has over the subject's responses.

In order to bring the behavior of animal subjects under stimulus control, I have used operant-conditioning procedures developed by B. F. Skinner and his associates. Skinner's techniques are useful not only because they are effective in controlling behavior, but also because the apparatus associated with these procedures is automatic. Thus, it lends itself to a psychophysical method that involves automatic

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[1] **Some parts of this paper are modified from a thesis submitted to the Department of Psychology, Harvard University, in partial fulfillment of the requirements for the Ph. D. degree. An unpublished report by Dr. Floyd Ratliff and me (9) also contains elements of this material. I am indebted to Dr. Ratliff, who directed the thesis research and with whom I worked on other preliminary applications of the general technique.**

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stimulus variation. Furthermore, the enclosed chamber commonly used in operant-conditioning research is ideal for the exact stimulus specification that is necessary in a psychophysical experiment.

The present method combines the procedures of Békésy and Skinner in the following way. The bird is reinforced for pecking one response key (key A) when an illuminated stimulus patch is visible and another (key B) when the patch is dark. These pecks control the intensity of the patch. Pecks on key A reduce the intensity of the patch; pecks on key B increase it. As a result, the stimulus intensity oscillates up and down across the pigeon's threshold, and a continuous record of the stimulus intensity gives a picture of the threshold, just as in Békésy's procedure described above. Figure 1 is a highly schematic picture of the apparatus. Figure 2 contains some sample records that illustrate data obtained in single sessions. The threshold is shown as a function of each of three independent variables.

The use of a single-response key, as in Békésy's original method, might appear to simplify the procedure just described. For example, a bird might be trained to peck a key only when the stimulus patch appears dark. Pecks would increase the stimulus intensity. When the bird did not peck, the intensity would automatically decrease. Such a procedure has one overriding disadvantage: extraneous variables tend to affect the level and variability of the threshold record to a greater degree than when two response keys are used. If the bird stops pecking for some extraneous reason, as it occasionally does, the intensity tends to be driven too low. Deprivation, or reinforcement schedules that raise the response rate, would probably yield a relatively high threshold. As I have argued in another context (4), although two responses may complicate a behavioral analysis, they tend to give a clearer picture of the momentary relation of responses to a stimulus. In the two-key situation, pauses in responding do not affect the threshold record, for stimulus intensity remains unchanged during a pause. Variables known to affect response rate may be expected in most cases to affect the two responses about equally.[2]

STIMULUS CONTROL

Physical Stimulus Conditions

In a psychophysical experiment in vision, the subject's behavior is governed partly by the physical nature of the apparatus. The apparatus is designed to favor a high degree of stimulus control, while it keeps the stimulus at the subject's eye as invariant as possible. In the present case, the pigeon is confined to a light-tight experimental chamber. In order to reach the response keys and food magazine, the bird must place its head through a circular aperture 4.5 centimeters in diameter (Fig. 1). This aperture keeps the bird's head directly in front of the stimulus patch and at a fairly constant distance from the patch. The stimulus is located 4 centimeters beyond the response keys and is viewed through a rectangular aperture above the keys. A silent shutter moves across the stimulus beam to turn the stimulus off. A motor-driven optical wedge in the beam varies the stimulus intensity.

Reinforcement Contingencies

The discrimination required of the pigeon is the same as that which a human subject makes in a standard visual threshold experiment. In both cases, the subject's

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[2] These arguments hold for human subjects as well as pigeons. I have seen several examples of visual data collected with Békésy's single-key method that show occasional very wide swings in stimulus intensity when "the subject became inattentive."

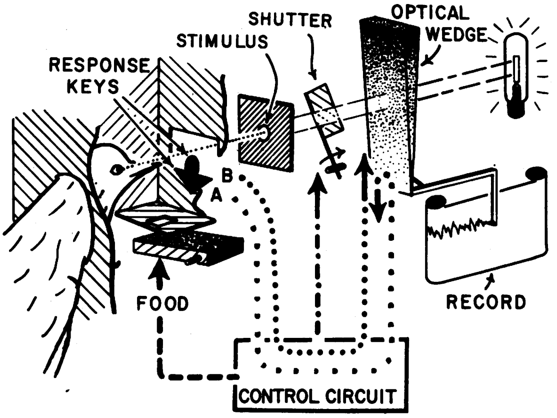

Fig. 1. A schematic picture of the apparatus.

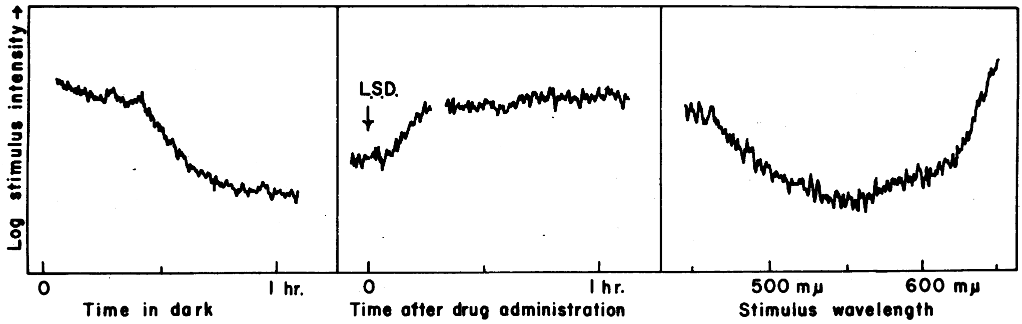

Fig. 2. Sample records from three single sessions. In each case, the higher the curve, the lower the bird's visual sensitivity. Left: A dark-adaptation curve. Center: The effect of a dose of L.S.D. (300 Hg/kg, oral). Right: A spectral-sensitivity curve obtained by increasing wavelength with time. (This curve is not corrected for intensity variation.)

responses are limited to two classes. Each gives one response (peck key A, "yes") when he can see the stimulus, the other (peck key B, "no") when he cannot see the stimulus. However, this stimulus control is maintained differently with pigeons than it is with human subjects. With humans, verbal instructions given at the beginning of a session usually suffice, although the experimenter may employ reinforcement (e. g., "right" or "good" following appropriate responses) if the subject's discrimination is inadequate. With pigeons, reinforcement is used throughout each session to establish and maintain stimulus control. Thus, it is necessary to superimpose a reinforcement procedure upon the essentially simple psychophysical paradigm. It is well to keep this dual nature of the method in mind during the following discussion of reinforcement contingencies. No matter what reinforcement schedule is operative, whenever the stimulus is "on" the bird's responses continuously adjust the stimulus intensity up and down. I shall discuss some details of this adjustment procedure after I have explained the scheme of reinforcement.

Basic Reinforcement Pattern. A trained pigeon makes one response (key A) when the stimulus patch is visible and another response (key B) when the patch appears dark. The response in darkness is maintained by standard reinforcement procedures, but two kinds of "darkness" must be distinguished. I shall use the term "below threshold" to indicate that the stimulus is "on" (i. e., physically illuminated) but is too dim to be visible. The term "stimulus off" will be reserved for the case in which the shutter is closed and no light whatever reaches the stimulus patch. By definition, the pigeon cannot discriminate these two kinds of darkness. Thus, reinforcing responses to key B with food when the stimulus is off keeps the bird responding to key B both when the stimulus is off and also when it is on but below threshold. The bird is never reinforced for pecking key B if the stimulus is on, even if it is below threshold.

Unfortunately, the response to key A cannot be maintained in the same fashion, that is, by reinforcing it with food in the presence of a single intensity known to be visible to the bird. This procedure will not work because birds can discriminate lights of different intensities. If reinforced at only one intensity, they would become less likely to respond to others. In order to keep a bird pecking key A in the presence of all super-threshold intensities, responses to all of these intensities have to be reinforced. On the other hand, responses to key A must never be reinforced when the stimulus is below threshold, and the threshold is unknown. One way to resolve this difficulty is to choose a reinforcer that is ineffective when the stimulus is below threshold but which becomes effective when the stimulus is above threshold. In the present case, this reinforcer is the disappearance of the stimulus light. Although the onset of darkness is not ordinarily a reinforcer for pigeons, it acquires reinforcing properties here, because reinforcement with food occurs only when the stimulus is off. Responding to key A is maintained by having key A responses turn off the stimulus. A "response chain" is set up. Pecks on key A turn off the stimulus; when the stimulus is off, pecks on key B bring food.

The following, then, is the basic reinforcement sequence: stimulus on → peck key A → stimulus off → peck key B → food presented → ... repeat cycle.... This pattern must be expanded and modified to allow time for variation in the stimulus intensity, to maximize stimulus control, and to provide rapid and continuous responding over long experimental sessions. I shall describe these modifications in the following paragraphs.

Ratio Schedules. If a single response turned off the stimulus and another produced food (i. e., continuous reinforcement on both keys), several undesirable effects would follow. The bird would satiate rapidly, its response could not regulate the intensity of the stimulus, and it could shut its eyes and achieve reinforcement simply by alternating between the keys. Therefore, schedules of intermittent reinforcement on the two keys are necessary.

The desirability of rapid responding and good stimulus control suggests the use of a ratio schedule. Such a schedule, in which reinforcement is contingent upon a certain number of responses, yields high rates of responding (7). Some of my preliminary data also indicate that ratio schedules favor a high degree of stimulus control, and Morse (8) has recently established this result experimentally.

It has been shown that birds can discriminate the number of responses that they have made; and if they are reinforced on a short fixed ratio, they will tend to make responses in bursts approximating the length of the ratio (7). In the present case, this tendency would lead to the same difficulties as those just outlined for continuous reinforcement: probable alternation of bursts on the two keys (regardless of the stimulus), rapid satiation, and minimal control of the stimulus by the bird's responses.

This condition is partially corrected by making reinforcement contingent upon a varying, rather than a fixed, number of responses. The bird can not then tell when to switch keys simply by "counting" its responses. Instead, it must look at the stimulus light.

If an ordinary variable ratio were used on both the keys, however, the bird could still get reinforcement by alternating between the keys, or by some other response pattern unrelated to the stimulus light. For, if the bird receives reinforcement for (e. g.) five pecks on a key, ten pecks alternated between the keys would produce the reinforcement. Alternation is less efficient, because half of the pecks are ineffective; but with short ratios, that is a relatively small matter.

Two "Punishment" Contingencies. To overcome the difficulty just outlined, the bird is "punished" for "false" responses. For this purpose, I have used two arrangements that seem about equally good. In my earlier experiments, "false" responses (defined as pecks on key B when the stimulus is on and pecks on key A when the stimulus is off) wiped out the effect of any preceding correct responses. That is, if a bird made three correct responses out of a total of seven required for reinforcement and then pecked on the wrong key, it had to start over again when it returned to the correct key and peck all seven responses. According to the alternative method, each false peck subtracts only one from the accumulated sum of correct responses. Thus, the delay of reinforcement increases with the number of false pecks, with the limitation that false pecks never increase the required number of correct pecks beyond its initial value.

As a result of this procedure, patterns of responding unrelated to the stimulus are unlikely to produce reinforcement. There is an exception to this conclusion, however. If bursts of responses exceeding the maximum ratio occur in alternation on the keys, reinforcement will follow. Although long ratios would reduce this difficulty, the desirable length of the ratio is limited. The limit becomes evident when one recalls that pecks on key A drive the stimulus patch dimmer, and that when the stimulus goes below threshold the well-trained bird will switch its pecking to key B. The ratio required on key A must not be so long that the bird's responding to key A is always cut off by the disappearance of the stimulus before the ratio can be completed.[3]

This limit on the ratio became a practical problem when, after long training, one bird began to alternate long runs of responses on the two keys. The bird pecked a swift series of responses on key A and then without pause continued its run on key B, often regardless of the intensity of the stimulus. The bird's threshold began to wander from the regular pattern established in previous sessions.

A characteristic of the bird's behavior suggested a way to cope with this difficulty. The bird did not pause as it switched from key A to key B. It was as if the bird did not "bother" to observe the stimulus patch, for the fact that the patch is above and beyond the keys makes it difficult for the bird to observe the patch without pausing between pecks. Birds under stimulus control peck in bursts interspersed with pauses, during which they presumably look to see if the light is on or off. When looking competes with pecking, looking is more likely to occur if pauses in pecking are mandatory. Accordingly, a timer was introduced into the circuit which made it impossible for pecks on key B to bring food if they followed pecks on key A by less than about 0.2 second. If the stimulus was off when such pecks occurred, the shutter opened and the stimulus came on again. Thus, if a bird did not pause as it switched keys from A to B, not only did it not obtain food but also it had to start responding on key A all over again in order to turn the stimulus off. Under these conditions, the spurious chaining rapidly dropped out and stable thresholds were re-established.

Additional Reinforcements on Key B. It would be well to recall at this point that pecks on key A are reinforced by closing the shutter, which turns off the stimulus. Pecks on key B are reinforced with food only if the shutter is closed and the stimulus is off. If the stimulus is on but below threshold, pecking on key B does not bring food. Early in the development of the present method, I neglected one contingency. After each food reinforcement, the shutter opened and the bird was expected to peck the keys once again, depending on whether or not the stimulus patch was visible. However, since the stimulus was on, the bird was never reinforced for pecking key B at this time. It was always necessary to peck key A first, in order to close the shutter. Thus, the bird soon came to peck only on key A at this time, whether the stimulus patch was visible or not. To get rid of this spurious discrimination, it was necessary to reinforce some responses on key B immediately after reinforcement. In order to do this, I changed the control circuit in such a way that the stimulus remained off (shutter closed) after about one reinforcement in every five. With this arrangement, the pigeon can get food again one time in five by pecking a short ratio on key B immediately after eating. The stimulus controls pecking at this time: if the stimulus is visible, the bird must peck key A; but if it appears dark, pecking key B is likely to bring food immediately.

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[3] As this discussion implies, the method makes use of moment-to-moment variability in the absolute threshold. If the threshold intensity were exact and unvarying, a single peck on key A would send the stimulus below threshold and a peck on key B would send it above once more; a bird under stimulus control would not complete a ratio longer than one. Experiments with human subjects show a systematic effect that probably has its counterpart in the present procedure: a light of decreasing intensity disappears at a lower intensity than that at which a light of increasing intensity first appears.

Interval Schedule on Key A. Under the reinforcement schedules described up to this point, birds are reinforced very frequently. Also, the stimulus is off a relatively large proportion of the time. When the stimulus is off, the wedge that regulates the stimulus intensity does not move and no data are collected. For these reasons, an interval component is added to the reinforcement schedule in effect on key A. Following most food reinforcements (those after which the stimulus comes on), a variable-interval timer is started. While this timer is operating, no amount of pecking will close the shutter or raise the food magazine. Pecking has no effect other than to dim the stimulus (key A) or make it brighter (key B). When the timer completes its cycle, the ratio schedules and "punishment" contingencies described above become effective. Because the timer operates for an interval varying between 1 and 45 seconds, the bird never "knows" when its pecks begin to be effective. A discrimination based on time following reinforcement is thus prevented.

Feedback Clicks. Experience has indicated that higher rates of responding are maintained if the effective response produces a characteristic stimulus "feedback." In the present situation, as an aid to discrimination, each key produces its own loud and characteristic "click" when it is pecked.

RESPONSE CONTROL OF STIMULUS INTENSITY

The goal of the foregoing reinforcement procedures is to make the pigeon peck in such a way that the stimulus intensity is adjusted back and forth across the bird's absolute threshold. Whenever the stimulus is on, this adjustment proceeds without interruption. Responses on key A reduce the stimulus intensity and responses on key B increase it. Periodically, as determined by the reinforcement schedules, pecks on key A turn off the stimulus. While the stimulus is off, the optical wedge that adjusts intensity does not move. When the stimulus comes on after reinforcement, it has the same intensity that it had when it went off. The stimulus also remains at a constant intensity when the pigeon does not peck. Thus, on the data records a horizontal line indicates either that the bird did not respond or that the shutter was closed during the period in question.

Pecks on the two response keys change the intensity of the stimulus patch by means of a simple electromechanical system. The response keys operate relays. These in turn control a small reversible motor, which moves a variable-density optical wedge in the path of the stimulus beam. A rotary solenoid moves the shutter across the optical path, producing the "off" condition of the stimulus. These movements are of course silenced so that they can provide no discriminative cues for the bird.

Although the speed and magnitude of the stimulus changes do not seem to be very critical, several considerations establish an optimal range for these factors. The intensity should not change for too long following a given response, for the intensity may wander further up and down than necessary, producing a record of variable appearance. Also, stimulus control may be weakened if the consequences of a response extend over too long a time.

Within a given time interval, the stimulus intensity will vary much or little, depending on the characteristics of the optical wedge and the speed of the wedge motor. The intensity must change quickly enough to keep up with any threshold variations. A relatively high rate is also desirable, so that the disappearance of the stimulus below threshold looks like its sudden disappearance when the shutter closes. On the other hand, the intensity variation following a peck must not be so great that the bird sends the stimulus below or above threshold with a very few pecks. As in the case of an overly long ratio-reinforcement schedule, the bird in this situation would have difficulty completing the necessary number of pecks on key A before the disappearance of the stimulus would cause it to switch to key B.

REVIEW OF PROCEDURAL DETAILS

The aim of the procedure is to produce a stimulus-intensity record that oscillates up and down across the pigeon's absolute threshold. To achieve this, the bird must peck key A when it sees the stimulus and key B when the stimulus appears dark. When the stimulus is on, these pecks control the stimulus intensity; pecks on key A make it go down and pecks on key B make it go up. On random schedules, key A pecks turn off the stimulus and then key B pecks bring food reinforcement.

Schedules of reinforcement are introduced on the two keys to maximize the control of the light stimulus over the bird's behavior, to minimize the influence of other stimuli or contingencies, and to maximize the continuity and length of experimental sessions.

A ratio component added to the schedule increases response rate and improves stimulus control. The ratio is variable to prevent discrimination based on the number of responses emitted. False responses cancel the accumulation of correct responses toward completion of the ratio. Stimulus control is improved by requiring the bird to pause briefly as it switches from key A to key B. Additional reinforcements on key B reduce an undesirable correlation between a food reinforcement and the subsequent correct key. A variable-interval component in the schedule on key A prevents rapid satiation and increases the proportion of stimulus "on" time. Characteristic clicks from the two keys increase the response rate and aid the discrimination. Several factors place bounds on the optimal rate of stimulus intensity change.

Figure 3 summarizes a typical sequence of events between two food reinforcements. The figure is divided by vertical lines into three "stages," the first while the interval timer is operating, the second while the ratio on key A is being completed, and the third while the ratio on key B is being completed. For simplicity, no instance is shown of "punishment" for failure to pause while switching from key A to key B. Also, there is no case of additional reinforcement on key B. The latter may be viewed as repetition of Stage 3. Arbitrary values illustrate the variable-interval and variable-ratio schedules.

THE METHOD IN USE

Preliminary Training

Preliminary training, like the initial "shaping" of a response, is largely "played by ear." It is a matter of gradually introducing the bird to new conditions and more difficult schedules. It is possible to specify the training steps only approximately, because individual birds adapt and learn at different rates. In the following paragraphs, I shall describe the training procedure I have followed with several birds.

The pigeon was first starved to about 70% of its free-feeding weight. On its first day in the experimental box, the bird found grain in the brightly lighted magazine. After one or two sessions, the bird had learned to come and eat as soon as the magazine was raised. Next, the bird was trained to peck the keys; a peck on either key turned on the magazine light and lifted grain within reach for about 5 seconds.

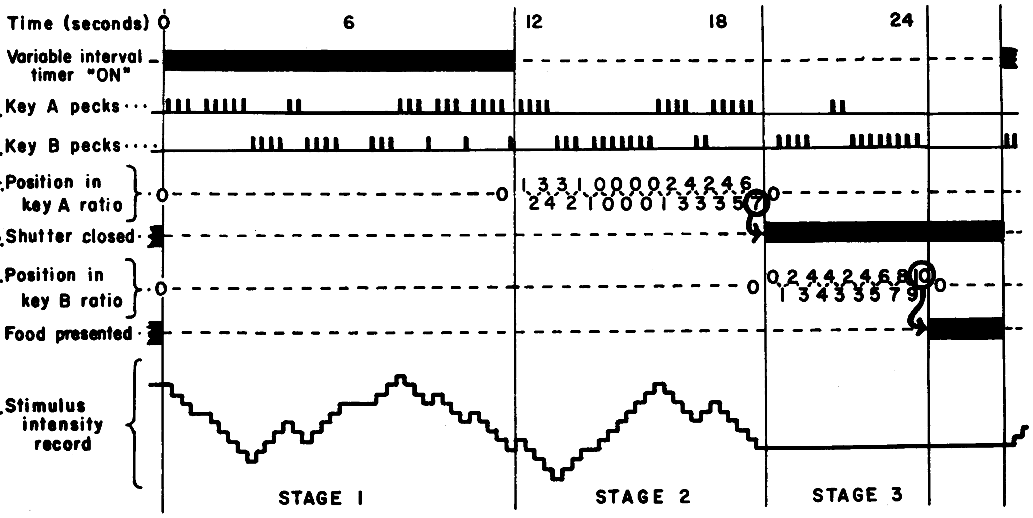

Fig. 3. A simplified diagram of events between two food reinforcements. During Stage 1, the variable timer operates (line 1), and pecks (pips on lines 2 and 3) serve only to change the stimulus intensity (line 8). In Stage 2, the interval timer has stopped, and key A pecks accumulate to the total required (in this case, 7) to close the shutter. The double row of numbers in line 4 indicates the momentary sum of these pecks. Key B pecks subtract from this sum. Stage 3 begins with shutter closure and continues until key B pecks have accumulated to the total required (in this case, 10) to bring food. Key A pecks subtract from this sum. The intensity record does not change during Stage 3 or during presentation of food.

After about 50 reinforcements had been delivered, the stimulus patch, previously dark, was strongly illuminated. A peck on key A now turned off the stimulus; a peck on key B when the stimulus was off brought food for 5 seconds. After the bird had eaten, the stimulus usually reappeared and the cycle was repeated. However, after an average of one reinforcement in five, the stimulus remained off; the bird had only to peck key B to be reinforced again. The bird quickly learned to peck key A when the stimulus was on and key B when it was off.

Up to this point, two lights other than the stimulus patch were used. One ("house light") illuminated the box, and the other ("magazine light") illuminated the grain from below during reinforcement. During the remainder of preliminary training, these two lights were first made red, then dimmed, and finally extinguished. The intensity of the stimulus was also slowly reduced.

The reinforcement schedules were introduced gradually. The number of pecks required on each key was raised to two or three, then increased further. After these ratios had been built up and the "punishment" contingencies introduced (see above), the interval schedule on key A was initiated and its length gradually increased.

The final step was to place the stimulus intensity under the control of the bird's responses. This was done after about 16 daily sessions of 30 minutes to 2 hours.

The bird was now working under the conditions described in the earlier sections of this paper. It was allowed to practice until its threshold records became stable, and then experimentation began. During experiments, the bird's response rate gradually increased and it received more reinforcement. As this improvement occurred, the ratio and interval schedules were correspondingly lengthened.

Values of Parameters

In describing the method in the preceding pages, I have introduced a number of experimental parameters. As I have suggested, most of these parameters appear to have an optimal range of values. The following values are ones that I have found effective in birds that have had considerable experimental experience.

Deprivation: 75 to 85% of free-feeding weight, plus at least 1 day hungry.
Duration of food-magazine cycle: 2 to 5 seconds depending on bird.
Key A schedule: variable interval, mean 15 to 30 seconds; plus variable ratio, mean 4 to 8 responses.
Key B schedule: variable ratio, mean 9 responses.
Delay required between pecks on A and pecks on B: 0. 25 second.
Proportion of reinforcements repeated without turning on stimulus: 1 repeat to 4 nonrepeat (programmed randomly).
Duration of stimulus change per single peck: about 0. 3 second.
Intensity change per peck: about 0. 02 log unit.

I should emphasize that I have not attempted to study systematically the effects of varying these parameters. The values listed were arrived at by trial and error. To some extent, it seems advisable to use different values for different birds. Therefore, although these values have worked in practice, they all may not be optimal.

Difficulties and Remedies

Symptom: No Responding. As in other operant-conditioning work a major cause of failure to respond appears to be insufficient deprivation. Without special training, birds tend to roost in the dark, so that the use of high deprivation (e.g., 70%) is advisable, at least in early sessions. An overweight bird often fails to start responding in the apparatus, or prolonged pauses in responding occur during the experimental session.

Insufficient reinforcement is a second cause of failure to respond. The birds learn to eat in the dark with varying degrees of efficiency. One of my birds regularly gained weight when its only food was obtained during an hour's session. A bird that gained little weight during experimental sessions and paused frequently during its runs was much improved when it was given access to the food magazine for twice as long as the other birds.

A schedule of reinforcement adequate for one bird may result in extinction with another. This variability can be largely attributed to variations in individual response rates. A rapidly responding bird obtains more reinforcements than a slowly responding one. Thus, a slowly responding bird may require shorter interval and ratio schedules.

Symptom: Wandering Threshold. How does one know when the stimulus loses control and the bird's record wanders from the "true" threshold? One indication is a marked departure from the threshold picture established in previous runs, or earlier in the same run. A good way to detect a loss of stimulus control is to increase or decrease the intensity of the stimulus by a known amount and see if the bird adjusts its intensity control to compensate for the change. Figure 4a shows a sample record obtained during dark adaptation in which a 0.7-log unit filter was placed in the optical path at the point indicated by the arrow. In this case, the bird promptly increased the intensity by just 0.7 log unit, compensating for the filter and indicating that the stimulus was in control. Figure 4b shows that this procedure had no effect on the record of a bird that was not under stimulus control and was working well below its previously established threshold. Note also the great variability of this record, another indication of loss of control.

My approach to the correction of the "wandering threshold" has been twofold. First, I have tried to increase the influence of the stimulus over the bird's responding. Second, recognizing that a stimulus near threshold intensity may never acquire very powerful control, I have tried to balance the tendencies to respond to each of the two keys, so that weak stimulus control will be sufficient to determine which response will be made. These two approaches are, of course, not entirely separable, but involve differences in emphasis.

In my experience the pigeon rarely pecked the keys in such a way that the stimulus intensity wandered above the threshold established by previous runs. This condition may be considered the result of an overbalance of pecking on key B. It has occurred once or twice when the reinforcing mechanism broke down and the bird began to extinguish. As would be expected, responding to key A dropped out first under extinction, presumably because it is the farthest removed from food reinforcement. A similar result has occurred when the bird received relatively little reinforcement because too many correct responses were required. This situation was corrected by shortening the interval and ratio schedules on key A.

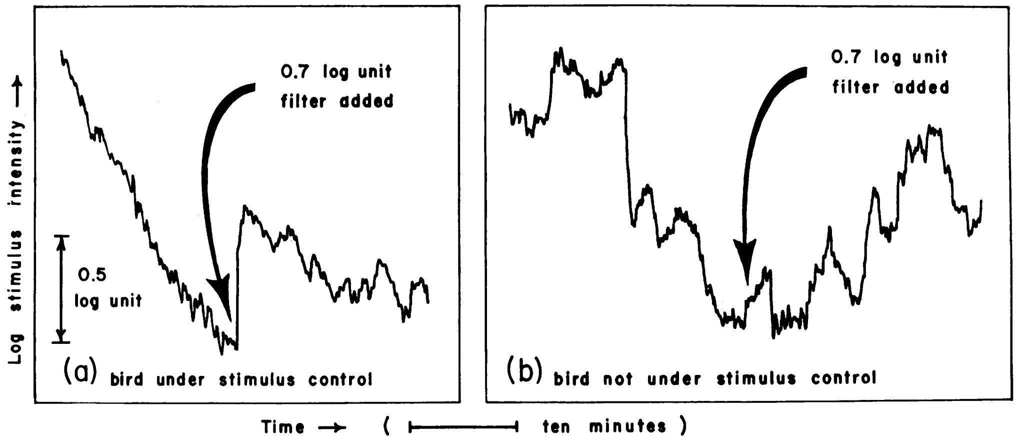

Fig. 4. Results of a test for stimulus control. (a) The bird compensates for a sudden decrease in the intensity of the stimulus. (The falling curve results from dark adaptation.) (b) Changing the stimulus intensity has no effect on the record.

The case in which the pigeon pushes the stimulus intensity below threshold has occurred more frequently. Here, responding on key A is no longer under stimulus control, for it occurs when the patch "appears dark." This situation arises when the schedule is "too easy." That is, the bird obtains reinforcement following a more or less random series of pecks unrelated to the stimulus patch. The stimulus tends to run to low intensities in this case, because relatively more key A pecks occur when the stimulus is on and the intensity is changing. This is true because key A pecks turn off the stimulus, while key B pecks turn it on.

When the threshold wanders downward, the following procedures may help.

(1) Increase the length of the interval, or the ratio, or both, effective on key A. This makes reinforcement less likely to follow a short run on key A.

(2) Increase the length of pause required when the bird shifts from key A to key B. This may help to re-establish an "observing response."

(3) Increase the proportion of times when the stimulus remains off after a reinforcement. It will be recalled that in this case, pecking key B brings reinforcement again immediately. This procedure strengthens the key B response relative to the key A response and thus tends to push the intensity up.

APPLICABILITY OF THE METHOD

The present method, with appropriate modifications, appears to be applicable to a variety of animal subjects and sense modalities. There are limitations, however, to the types of psychophysical problem that may be studied. Briefly, the method is applicable, in principle, to problems where: (1) the stimulus can be varied on some physical continuum, and (2) values of the stimulus fall into two classes, one of which is not discriminable from some stimulus Sx. When the method is applied, one class of responses is primarily reinforced (e. g., with food) in the presence of Sx and another class is reinforced secondarily by producing Sx. The resulting measure might be called the "threshold of equivalence." To stimuli along the continuum on one side of this threshold, the subject gives the same response as to Sx. To stimuli along the continuum on the other side, a different response occurs.

Both absolute and differential thresholds may be studied as special cases of this "threshold of equivalence." For the absolute threshold, Sx is "stimulus off," and the class not discriminable from this includes stimuli below threshold intensity. Other examples following this paradigm are critical flicker frequency (Sx is a "steady light") and certain acuity measures (e. g., the stimulus continuum is the breadth of a line, and Sx is "line absent"). For differential thresholds, such as those for pitch, wavelength, or intensity, the stimulus has two parts. At Sx, the parts are physically equal. The stimulus varies along a continuum from greater to lesser inequality between the two parts.[4]

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[4] For example, to find a pigeon's differential threshold for color, one side of a split field might be held at a constant wavelength, while the bird's responses varied the other side in small wavelength increments. Pecks on key A would decrease the difference between the sides, while pecks on key B would increase the difference. If small enough increments were used, the bird would not drive the stimuli to physical equality, but would cause the wavelength of the variable side to oscillate around the "threshold of equivalence." On random schedules, pecks on key A would produce equal fields (Sx), and then pecks on key B would bring food. Two thresholds could be obtained, one above and the other below the constant wavelength.

Many psychophysical problems may be reduced to the determination of a "threshold of equivalence" along a particular "attribute" of a stimulus. For example, one may ask within what range of intensities a green stimulus has the same brightness as a red stimulus. Acting under instructions, a human subject "abstracts," "attends to," or "is under the control of" primarily the brightness of the stimulus. As a result of his instructions, the subject excludes the discriminable "color" aspect. The present method does not have this effect. It applies only if one class of stimuli is indistinguishable in all respects from a reinforced stimulus Sx. The reinforcement contingencies that serve as the animal's "instructions" invite it to use all available cues, though care is taken to make the appropriate stimulus continuum the only effective source of these cues.

This does not mean that reinforcement techniques cannot be applied to problems in animal psychophysics that require "selective attention." There is much to be done. The fundamental methodological problem at present appears to be a further refinement of our methods of stimulus control. We also need continued behavioral analysis of that fascinating hodgepodge involving "abstraction," "concept formation," and "attention."

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