Technologies to reliably transduce the topographical details of pigeons' pecks

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Pigeons' pecking has long been a subject of interest in behavioral research, with the response typically being viewed as unitary. Recent experiments done with computer-controlled devices have revealed that this response is at least bipartite in character, with beak opening and response location (head transport) as its components. In addition, experimental work has demonstrated that these response components may be separately influenced and controlled by respondent and operant conditioning procedures. The detailed topographic analysis and technology that have emerged may provide a background for similar work with other behavioral systems.

The pecking behavior of the pigeon is a principal component of the pigeon's ingestive response sequence (Allan & Zeigler, 1989), and it has served as one of the most exhaustively studied conditioned responses. Techniques for the measurement of pecking rate (Ferster & Skinner, 1957), response force (Chung, 1965; Jenkins & Moore, 1973), peck duration (Zeiler, Davis, & DeCasper, 1980), and interresponse times (Galbicka & Platt, 1986) have all contributed to the quantitative analysis of this behavior system in both ingestive and conditioning contexts.

Yet although researchers have measured this behavior along several dimensions, the pigeon's pecking has until recently been considered as a unitary response measured by microswitches and force transducers. These convenient response end points provide measures only of the fact that the head has been transported to a particular location, and there is generally no information about transport sequences that fail to activate the microswitch or transducer. In other words, pigeons may be making many more responses than we experimenters are recording.

Evidence now suggests that both ingestive and conditioned pecks can be decomposed into transport and gape components, and that these components may be differentially affected by stimulus and response contingencies (Allan & Zeigler, 1989; Bermejo, Allan, Houben, Deich, & Zeigler, 1989; Deich, Allan, & Zeigler, 1988; LaMon & Zeigler, 1988).

Early evidence of the bipartite structure of pecking was provided by Wolin (1968) and Jenkins and Moore (1973), who observed that the topography of ingestive and conditioned responses were similar. When pigeons were food deprived, they pecked episodically, with relatively large beak openings, at both food and response keys; when they

were water deprived, their keypeck responding, like their drinking behavior, was characterized by rhythmic jaw movements and small beak openings. These studies identified, qualitatively, the two response components (head transport and beak opening), but the researchers were unable to provide evidence of the response component's potentially separate sensitivity to arranged contingencies. When these researchers ran their studies, the speed of the response (< 100 msec) prohibited on-line arrangement of differential contingencies as a function of responding along one component dimension. In fact, until recently, a quantitative analysis of these response properties would have been prohibitively expensive, if not impossible.

With the advent of microcomputer and integrated circuit chip technologies, these response dimensions have become tractable in real time. This means that both head transport (defined as response location) and beak opening (gape) can be tracked within an experimental session, and that contingencies may be applied as a function of behavior. In this article, I will explore the computer technologies used to measure these separate response systems, and I will present some illustrative data.

RESPONSE LOCATION

In previous studies, response location has been measured with the use of carbon paper, beak-mounted photo cells, pressure-sensitive materials, arrays of multiple keys, and image-processing equipment (Blough, 1977; Dunham, Mariner, & Adams, 1969; Eckerman & Lanson, 1969; Hori & Watanabe, 1987; Jenkins & Sainsbury, 1970; Skinner, 1965). Researchers have also utilized cinematographic and single-frame photographic techniques to localize pecking responses (Goodale, 1983; LaMon & Zeigler, 1984). All of these approaches have one or more of the following limitations: (1) They possess limited resolution; (2) they measure response location in a single dimension; and (3) they involve the collection of location data that must be examined off line. As a result, these techniques are generally not suitable for the programming of con-

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tingencies based on the two-dimensional location of individual responses.

The development of microcomputers has fostered a new generation of displays, with which complex stimuli can be presented at many different locations. In addition, several commercially available peripheral devices allow for the on-line, two-dimensional detection of the location of responses directed at the display device (Allan & Zeigler, 1989; Morrison & Brown, 1990; Pisacreta & Rilling, 1987). In combination, these devices have allowed the development of experiments designed for the examination of factors that control peck localization.

Touch-Screen Technologies

Three classes of location detection devices are often called "touch screens," but the principles of their operation differ. One class of devices consists of arrays of infrared light emitters and detectors arranged in a matrix of horizontal (x) and vertical (y) beams, with x,y intersection points specifying unique response locations (see Figure 1A).

A second class of devices measures response location by monitoring the voltage distribution across sheets of transparent conductive Mylar. Two thin sheets of this material are mounted in a sandwich-like construction, so that when one surface is deflected against the other, an output voltage proportional to the response location is produced (see Figure 1B).

The most popular infrared detection system for use in monitoring pigeons' pecking is manufactured by Carroll

Touch Technology (P.O. Box 1309, Round Rock, TX 78680). For Mylar touch screens, Elographics Inc. (Oak Ridge, TN 37830) offers several inexpensive configurations with and without color monitors. If the Mylar screen is purchased separately, the conductive surfaces are laminated to an acrylic plastic backing that can be installed in front of any computer display easily. Allan and Zeigler (1989) provide names and addresses of other infrared and Mylar touch-screen manufacturers.

Both of these classes of touch screens can be used in conjunction with several different stimulus projection devices, including standard in-line projectors, back-projection screens, and high-resolution computer displays. In fact, with VGA monitors, simulated pigeon intelligence panels can be programmed in graphics mode with response keys defined by collections of response locations. Most commercial touch-screen packages include software drivers and routines that allow the user to define contingent response areas.

The third technology computes response position by monitoring forces recorded by strain gauges positioned beneath each corner of the display glass. When the glass is touched, the four strain gauges are differentially activated, and, depending on the relative force at each location, response location is computed as a vector of those forces. This relatively new technology allows only the presentation of stimuli that can be generated on the computer monitor (since this is an integrated device); but the monitor supports VGA, XGA, and 8514A display modes, and the accompanying software drivers and configuration pro-

Figure 1. (A) Schematic of the infrared touch screen positioned behind the front panel of the experimental chamber and in front of an acrylic response surface. This particular response surface is also mounted on microswitches, thereby providing a method of detecting surface contact. A standard in-line projector is depicted as the stimulus presentation device. (B) The Mylar touch screen, positioned in front of a CRT display. Mylar devices are usually flexible and conform to the curved surface of a computer display. A sheet of clear Mylar (not shown) may be used to cover the touch screen's surface, thereby protecting it against repeated beak contacts.

Figure 2. Three-dimensional plots of frequencies of response (for each of 3 birds) at matrix locations identified by an infrared touch screen. The horizontal and vertical dimensions of the touch matrix are labeled, and the z-axis represents frequency of responding. The variable interval (VI) response patterns were produced on a VI 30-sec schedule. The location differentiation schedule presented a stimulus on discrete trials—responses to locations within the stimulus boundaries were followed by a reinforcer delivery, whereas responses off the stimulus were followed by a 5-sec time-out.

grams support each display adapter. Because strain gauges are used to locate touches on the display, up to 256 levels of response force are available as a z coordinate. Simultaneous detection of response location and force suggests several profitable lines of research, in which differential reinforcement contingencies are applied to response dimensions selectively or in combination (e.g., a conjunctive schedule; see Deich et al., 1988). This type of monitor is currently available from IBM at a discounted price of approximately \$1,000 (IBM 8516 Touch Display).

Sample Data from Peck Location Experiments

In Figure 2, illustrative frequency data are presented as a function of response location, collected during use of an infrared touch screen. The horizontal (x) and vertical (y) dimensions of the beam matrix are labeled, and the z-axis provides a measure of response probability at each x,y location. The data are from 3 pigeons trained to peck, on a variable interval schedule, at a 2.54-cm red dot presented on a computer monitor. Each subject produced a characteristic response pattern relative to the position of the projected stimulus. After 20 sessions, a

differential-reinforcement-of-response-location schedule was introduced. Only responses directed at the stimulus were reinforced; all other responses were followed by removal of the stimulus and a 5-sec time-out. Although off-stimulus responding continued for all subjects, the majority of the pecks, after only 5 days of training on this schedule, were directed at the stimulus (see Allan & Zeigler, 1989).

Technological Limitations

The optimal location detection device should (1) detect all generated pecks, (2) unambiguously specify the terminal location of each response, (3) provide location information with a resolution appropriate to the task, (4) be available for use with any stimulus projection system and without stimulus degradation, and (5) allow the programming of contingencies based on the location of individual responses. How well each class of touch screen meets these criteria is explored below.

Response detection. Although touch screens are generally reliable, all three types of device will fail to detect responses if necessary response criteria are not met. For example, if infrared beams in either the x or the y dimension are not sufficiently occluded, a location will not be reported. With the Mylar and strain-gauge devices, if pecking fails to exceed the force required to operate the device, responses will not be recorded. In this respect, the infrared device is superior in that it is capable of recording responses that fall short of the response surface. However, the infrared technology will also report any successful occlusion of beams as a response, even if the beams have been broken by some noncriterion response (e.g., wing flapping).

Terminal response location. Only the Mylar and strain-gauge touch screens provide information about the final location of pecking responses, although not without ambiguity. These devices will only measure the location of the first response that exceeds the operating force threshold, and because food-deprived pigeons peck with an open beak, the actual position of both beaks with respect to projected stimuli cannot be determined. The infrared device, since it must be placed at least 0.5–2.0 cm in front of the response surface (depending on which brand is purchased), really provides a measure of the location of the beak just prior to surface contact (Allan & Zeigler, 1989).

Resolution. Clearly the infrared screen has a limited resolution because of the physical dimensions of the emitter and detector units and because of restrictions upon how closely these units can be spaced and aligned (generally 1.5 beams per centimeter: for a 13-in. monitor, resolution can be as high as 50 [x] × 40 [y]; for most infrared detectors, these resolutions are doubled—when two adjacent beams are broken along one dimension, an intermediate location is reported). Both Mylar and strain-gauge touch devices generally maintain an adjustable resolution that is a function of the A/D conversion process as well as of software conversion routines; the resolution of these devices, however, is 10–100 times higher than that of a

comparable infrared device (e.g., for a 13-in. monitor, resolution can be as high as $4,096 \times 4,096$, or approximately 150–200 locations per centimeter).

Stimulus presentation and degradation. Because infrared and Mylar touch screens are available as peripheral devices, they may be used with any stimulus projection system. The strain-gauge technology is presently available only as an integrated part of an IBM computer monitor, although high-resolution graphics and even stimuli of photographic quality can be presented on this display.

Infrared touch screens do not occlude projected images or introduce parallax error (parallax occurs when the stimulus image is projected on a surface behind the response surface). Comparable Mylar devices, because the device surfaces are coated, will result in noticeable stimulus degradation and, because the response surface is separate from the stimulus projection surface, they can generate response locations that are a function of parallax. The strain-gauge monitor effectively reduces both stimulus degradation and parallax, because responding is recorded on the stimulus projection surface itself.

Programming contingencies. Even with these drawbacks, all devices are capable of providing researchers with relatively clear information about response location. Because this information is available in real time, the programming of response contingencies is a relatively simple matter (it typically involves a single line of programming code). Several preliminary studies suggest that pecking location can be affected by both respondent and operant contingencies (see above; see also Allan, 1990; Allan & Zeigler, 1989; Rilling & LaClaire, 1989). Further analysis of the location of the pigeon's peck should provide useful information on the control of response systems for which location is an important parameter. Indeed, other measurement systems have been employed to track the location of pigeon's pecking and locomotive behavior (e.g., Pear, Silva, & Kincaid, 1989). In combination, these devices may provide profitable data on the control of behavior.

GAPE RESPONDING

Previous studies of beak opening (gape) during ingestive and keypeck responding have involved off-line analytic techniques—chiefly, high-speed cinematography (LaMon & Zeigler, 1984; Smith, 1974). Analysis of the data from these experiments, which is a laborious task at best, prohibits the manipulation of consequences as a function of changes in gape.

Deich, Houben, Allan, and Zeigler (1985) and Deich et al. (1988) have presented data collected with a computer-monitored device that allows for the on-line measurement of gape responding. Figure 3A provides a schematic view of the apparatus as it is positioned on the beaks of the pigeon. A small integrated circuit package (an inexpensive linear Hall-effect device manufactured by Panasonic; another, comparable chip is available from Sprague) designed to measure magnetic flux density was glued to the

upper beak, with the signal and power leads held in place on the top of the pigeon's head by a small piece of tubing glued to the dorsal feathers of the head (not depicted in the figure). A magnetic field was generated by a small neodymium magnet glued to the lower beak. Figure 3B depicts the continuous voltage output of the Hall-effect device over time, as a function of beak opening or gape. The voltage was amplified (with a custom-built, but rather inexpensive, amplifier), digitized through a commercial A/D interface, and recorded by a computer at the rate of 250 samples per second.

Figure 4 presents sample gape records taken from food- and water-deprived subjects exposed to an autoshaping procedure in which a keylight was present for 6 sec, on the average once every minute, followed by delivery of the appropriate food or water reinforcer. The records show the pattern and extent of beak opening during key-

Figure 3. (A) Diagram of the Hall-effect chip assembly, depicting electrode wires, Hall-effect integrated circuit chip glued on the upper beak, and a neodymium rare-earth magnet glued on the bottom beak. (B) A sample gape record over time, taken with the Hall-effect device during a bout of keypecking.

Figure 4. Autoshaping trial gape records taken when individual birds were either food or water deprived (as indicated). The conditioned stimulus (CS) and unconditioned stimulus (US, or reinforcer) periods are indicated, and a time scale is provided. The three records (numbered 1–3) during presentation of the food US (three 6.4-mm pellets) whose opening times seem relatively long illustrate consummatory responses. The extended opening period is due to pellet masticulation.

Figure 5. Gapes directed at a response key during autoshaping trials for 3 different birds, each receiving a differently sized pellet as a reinforcer (diameter indicated by the dashed lines and the number above each dashed line). For each subject, three gape records are superimposed to show the stereotypy of gape responding directed at the response key. There is a tendency for gape to track, but generally overshoot, the size of the reinforcer.

light and food or water presentations. It is clear, as Jenkins and Moore (1973) discovered, that how a pigeon gapes in a particular conditioning situation is largely controlled by the type of reinforcer offered.

Figure 5 provides further evidence of the control of gape by the reinforcer. Three birds were offered different pellet sizes as reinforcers in an autoshaping preparation. During the keylight period, each subject produced many gapes, over many trials, whose peak values approximated or generally exceeded the size of the indicated food pellet. This tracking of pellet size by gapes produced during presentation of the keylight stimulus occurred in the absence of any explicit contingency with respect to gape.

As is true with response location, gape may be affected by both respondent (see the autoshaping evidence pre-

sented above) and operant contingencies. Figure 6 presents gape records from a single subject who was either food or water deprived (10 sessions under each deprivation condition) while pecking on a variable-interval 30-sec schedule. In these operant conditions, and without any constraint on the size of emitted gapes, there was a clear tendency for the pigeon to gape at the key as it did when engaged in the appropriate ingestive sequence. When the pigeon was deprived of food, it pecked with a rather large peak gape, and when it was deprived of water, its pecks were accompanied by smaller gape values. These records provide relatively concrete evidence of Wolin's (1968) observation that food- and water-deprived pigeons emit operant pecks with different beak openings.

Deich et al. (1988) have provided evidence that if reinforcers are made to be contingent on either increases or decreases in gapes produced during keypecking, appropriately sized beak openings will be produced. Figure 7, taken from Figure 3 of the Deich et al. (1988) paper, shows data from 1 bird. When key contact was detected by the computer, the previous 45 digitized gape samples were scanned, and the highest value was selected. That number (the peak gape) was compared to a criterion value set by the experimenter. During the *up* condition, if the peak gape exceeded the established criterion, a reinforcer was delivered; otherwise, a time-out was imposed. During the *down* condition, if the peak gape was less than the criterion, reinforcement was arranged. During baseline sessions, the average peak gape was monitored non-contingently, although reinforcers were still contingent on keypecking. In relation to the baseline, both *up* and *down* conditions produced appropriate shifts in the distribution of gapes at key contact.

Figure 6. Superimposed gape records taken during operant variable-interval performances for a single bird that was either food or water deprived during different phases of the experiment. Without any imposed contingency on gape size, there is a clear tracking of the reinforcer type by gape size. Deprivation state is indicated on the x-axis, and a 50-msec time scale is provided.

Technological Limitations

When properly calibrated, the Hall-effect system is reliable. However, the data are only as precise as the calibrations allow, and with a nonanesthetized bird, it is frequently difficult to obtain consistent calibration values. With con-

Figure 7. Frequency distributions of peak gapes taken during differential reinforcement of gape size. Peak gapes were determined by waiting for key contact and then scanning the previous 45 digitized gape samples and selecting the highest value. Because both key contact and gape were required to complete the contingency, behavior may be said to have been maintained on a conjunctive schedule. Emitted gapes had to be greater than an experimenter-selected criterion in the Up condition, and less than a criterion in the Down condition. Criteria were adjusted during the experiment in order to move gape values up or down. Baseline data was taken when key contact was the only required response component (from Deich, Allan, & Zeigler, 1988).

siderable practice (on the part of the pigeon and the experimenter), reliable calibrations and data can be obtained.

Because the gaping response is so rapid (< 100 msec), the computer must sample at rates generally greater than 250 Hz. The amount of data produced under continuous monitoring conditions is enormous—megabytes of data can be collected in a single session. In addition, the problem of real-time analysis of the recorded topographies is not trivial (cf. Zeigler, Levitt, & Levine, 1980; Zweers, 1982). Without the convenience of a microswitch closure to define a "response," specification of the beginning and end of a response sequence typically requires a relatively complex algorithm.

In the original Deich et al. (1985) paper on the Hall-effect measurement system, the authors described attaching the Hall-effect sensor and small magnet with screws set in the beaks and 5-min epoxy coating the entire preparation. Subsequent work with this device indicates that both the Hall-effect assembly and the small magnet may be attached to the beaks with cyano-acrylate glue for the duration of the session. The apparatus may then be removed at the end of the session, allowing a single assembly and magnet to be used on several subjects each day.

(See Deich et al., 1985, for further discussion of the Hall-effect system and its use.)

CONCLUSIONS

The methods and data presented here suggest somewhat separate and flexible roles for the transport and gape components of the pigeon's peck. The standard keypeck response, which has typically been considered a response unit, now adduces itself as at least a two-component response system, with each component being differentially sensitive to respondent and operant contingencies. The intricate character of this response system and its minimally bipartite character can be efficiently analyzed only with current computer technology. Indeed, the detailed topographic analysis that has emerged holds the promise of future analyses and manipulation of other behaviors in real time.

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