*DISSECTING THE CONDITIONED PECKING RESPONSE:
AN INTEGRATED SYSTEM FOR THE ANALYSIS OF
PECKING RESPONSE PARAMETERS*

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The conventional pecking response key, although an excellent transducer of response rate, can provide minimal information on the topography, coordination, or localization of conditioned pecking. We describe the hardware and software components of a system that, in addition to recording response rates, permits simultaneous "on-line" monitoring of head acceleration, jaw movement, terminal peck location, and duration of pecking response. Head movements are monitored with a miniature accelerometer, jaw movements with a magnetosensitive transducer, and peck location with modified touch screen technology. Initial experiments with the system suggest that it will be useful in studies of response differentiation, acquisition and maintenance of complex discriminations, and interaction of conditioned and unconditioned stimuli in the control of pecking response probability and response topography.

Key words: head movement, jaw movement, response duration, response location, response topography, key peck, pigeons

The pigeon's key-pecking behavior is among the most widely used responses in behavioral science. Because of its ubiquity as an index of response probability in studies of animal learning and cognition, the analysis of key pecking has tended to focus on response rate to the exclusion of other response parameters. In nature, however, pecking functions primarily to transport the beak towards biologically significant targets like food or water (peck localization), and to generate jaw-movement patterns (grasping, manipulation, drinking) whose topographies are appropriate to the stimulus properties of the target. The ingestive pecking response thus involves the spatial and temporal coordination of head-transport and jaw-movement components (Klein, Deich, & Zeigler, 1985; Klein, LaMon, & Zeigler, 1983; Zeigler, Levitt, & Levine, 1980).

Conditioned key pecking also involves the coordination of distinct head-transport and jaw-movement components (Deich, Allan, & Zeigler, 1988; Goodale, 1983; LaMon & Zeigler, 1988), but little is known about how these

coordinations are acquired or maintained. Moreover, whether acquired under an operant (Wolin, 1968) or classical (Jenkins & Moore, 1973) paradigm, the conditioned key peck preserves essential topographic features of the unconditioned peck (LaMon & Zeigler, 1984, 1988). Both head-transport and jaw-movement topographies vary with reinforcer type, so that experimental manipulations involving stimulus-reinforcer or response-reinforcer contingencies are likely to affect the topography as well as the probability of the conditioned pecking response. Such considerations suggest that quantification of the topography as well as the frequency of pecking behavior may be useful in conditioning experiments.

The pigeon's pecking response is less than 100 ms in duration (Zeigler et al., 1980), but the availability of microprocessors has removed many of the constraints on the "on-line" measurement and control of such brief responses. Measurement of the head-transport component of pecking requires information on both the spatial and temporal organization of head movement, that is, its initiation, trajectory, kinematics, and termination. Measurement of peck localization should specify the terminal location of the peck in Cartesian (x , y) coordinates. Measurement of the jaw-opening (gape) component requires transduction of variations in jaw movements during the course of head movement. In addition, experimental control of movement parameters requires on-line access to such data so that they may be

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used to program contingencies of reinforcement. Finally, because the interaction among response parameters is of special interest, the head and jaw data must be simultaneously available for measurement and control. Many of these requirements may be met using a combination of movement transducers, touch screen technology, and customized software. For example, Delius and his colleagues have combined head-mounted accelerometers, electrooculography, and videotaping to examine the relation between head and eye movements in the pigeon under a variety of conditions (Wohlschlaeger, Jaeger, & Delius, 1993).

The present report describes instrumentation for the simultaneous monitoring of head and jaw movement, terminal peck location, and contact duration. Information about the temporal organization of head movement (i.e., its initiation, acceleration, and termination) is obtained using a head-mounted miniature accelerometer. Jaw movements are recorded using a magnetosensitive transducer (e.g., Deich, Houben, Allan, & Zeigler, 1985), modified to facilitate its use in conventional conditioning situations. Terminal peck location is monitored using touch screen technology (e.g., Allan, 1992; Allan & Zeigler, 1989). However, although commercially available touch screens are easily incorporated into conditioning setups, they are designed to detect human touches and may therefore fail to detect a substantial proportion of pigeon pecking responses, which have quite different physical parameters. We describe hardware modifications that greatly improve the temporal resolution of a widely used touch screen and also permit precise measurement of peck durations. Finally, we discuss considerations involved in the design of software that can transform a disparate set of transducing devices into an integrated system for the monitoring and control of pecking response parameters. The utility of the system is illustrated by data from an experiment that involved the recording of terminal peck locations and the on-line monitoring of conditioned and ingestive pecking response topographies.

METHOD

Subjects

Four White Carneau pigeons were weighed after each experimental session; if needed, sup-

plementary food was given to maintain them at 80% of their free-feeding weights. Water was continuously available in the home cage. Prior to testing, the birds were anesthetized (Ketamine 100 mg/mL/Xylazine 20 mg/mL), and a platform of dental acrylic was constructed on the skull to serve as a solid mount for the miniature accelerometer. To ensure that the orientation of the accelerometer was constant throughout the experiment and across all birds, its base was glued to a small aluminum plate with screw holes at each end, and two small mounting screws (heads down) and nuts were then inserted in the holes. Next, the pigeon was mounted in a stereotaxic device, the scalp was reflected, the skull was roughened, three jeweler's screws were inserted to serve as skull anchors, and acrylic was piled over the screws to form a platform. While the acrylic was still soft, the stereotaxic carrier was used to position the plate on the platform, perpendicular to the beak axis. When the acrylic was dry, the carrier was raised, leaving the screws embedded in place to serve as guides for mounting the accelerometer plate. Care was taken to maintain sterile conditions in order to prevent infection of the underlying bone.

Apparatus

Training and testing were carried out in a chamber (inside dimensions 23 cm by 29 cm by 42 cm) made of Plexiglas, painted flat black, lit by a 15-W clear houselight, and containing a food hopper. A Gerbrands pellet dispenser, located outside the chamber, delivered a single Bioserv food pellet (94 mg, 4.9 mm diameter) into the hopper, which could be lit by a 6.3-V pilot lamp, on each trial. The front wall contained a rectangular window (16 cm by 16 cm) that gave access to a flat-screen monitor (Zenith Model ZCM-1492). The window occupied the left two thirds of the monitor and provided a stimulus display (16 cm by 16 cm) for the pigeon; the remaining third served as the experimenter's display. A touch screen, described below, was mounted in contact with the surface of the monitor, so that the touch-sensitive surface was accessible through the window. Outputs from jaw-movement and head-movement transducers, also described below, and from the *x* and *y* coordinate systems of the touch screen were amplified and digitized (at 1 kHz) through an analogue to digital (A/D) interface (Keithley Model 570) and

were displayed as separate traces on the experimenter's portion of the monitor. The localization portion of the display was continuously updated during the intertrial intervals so that it contained localization data for all preceding trials. An IBM-compatible microcomputer with an 80286 central processor running at 12 MHz, programmed in software written in Microsoft® QuickBASIC (Version 4.5), was used to control stimulus presentation, reinforcement delivery, and data collection, as well as for data reduction and analysis.

Procedure

Subjects were adapted to the test chamber and were trained to eat from the hopper by repeated activation of the hopper and hopper light for 6 s. Subjects then acquired a conditioned pecking response under an autoshaping procedure. Autoshaping was carried out in daily sessions consisting of 120 to 150 trials, depending on the number of birds to be run that day. Each trial included three components: (a) a variable-time (VT) 60-s intertrial interval (ITI); (b) a 6-s conditioned stimulus (CS), consisting of a red circle (1.2 cm diameter) displayed in the center of the window; and (c) a 6-s unconditioned stimulus (US; hopper activation). A peck at the screen activated the hopper and turned off the houselight and the stimulus display.

When a pecking response was recorded on the majority of autoshaping trials, a continuous reinforcement (CRF) schedule was introduced. In all CRF sessions, reinforcement (6 s of hopper and light activation) was independent of peck location; that is, it was contingent solely upon the detection of a contact anywhere on the touch screen. A peck at the screen activated the hopper and light, turned off the stimulus display, and was followed by an ITI whose length was determined by the time taken to store the data of the preceding trial. Stimulus position and terminal peck location were monitored on every trial. In the first two sessions of the CRF condition, the stimulus continued to be displayed in the center of the monitor on every trial. In the final sessions, the position of the stimulus varied randomly from trial to trial. A session ended after a maximum of 250 trials, but in most cases it was terminated earlier, when the bird failed to respond to the stimulus for 10 to 15 min. Testing in this condition continued until a sub-

stantial number of responses (>200) had been acquired by each subject.

Transducers

Head acceleration was transduced by a miniature accelerometer (IC Sensors, Model 3031-10) that was attached to the skull mounting platform at the start of each session and removed at its end. The range of this transducer is ± 10 g, with a typical sensitivity of 2.25 mV/g. Other ranges are available from the same manufacturer. The small physical dimensions (7.6 mm by 7.6 mm by 3.6 mm) of the accelerometer ensure that it produces minimal discomfort when mounted on the pigeon. The unfiltered accelerometer signal was conveyed by fine wires to a DC amplifier (Figure 1) that provided an output compatible with the A/D converter.

Variations in gape were monitored by a magnetosensitive (Hall-effect) integrated circuit (IC; from Sprague Model 2UGN3503-U930) that was mounted on the upper beak and a rare earth magnet (Radio Shack Part 64-1895) that was mounted below the tip of the lower beak. The IC generates a voltage proportional to the strength of an applied magnetic field, which is directly related to variations in the interbeak distance (gape). Both the IC and magnet were lightly attached to the beaks at the start of each session, using cyanoacrylate glue, and were easily removed at its end. The mounting did not interfere with pecking or eating. Signals from the IC were conveyed by fine wires to a specially designed amplifier. The use of a Sprague Hall-effect device and the substitution of a constant voltage for a constant current power supply are modifications of the original transducing system (Deich et al., 1985) that greatly improve its sensitivity and stability. (The new Sprague Hall-effect IC is a three-terminal device. The device is powered by a 6-VDC lantern battery with the positive and negative terminals connected to Pins 1 and 2, respectively. The Hall-effect voltage is obtained from Pin 3, and the remaining circuitry described in the original paper is unchanged. All of the circuitry shown in Part A of Figure 2 of Deich et al. can be deleted.)

Terminal peck location was recorded using a touch screen (Duratouch, Model E 274). The device consists of a sandwich of two sheets of mylar, sealed at the edges. Each of the sheets

Fig. 1. Schematic of the accelerometer and DC amplifier. The accelerometer is mounted on the pigeon's skull and connected to a 6-VDC lantern battery and the amplifier via four fine wires. The amplifier portion is powered by ± 15 VDC and the components are mounted on perf-board. Resistors are 0.25 W, 5%, and the potentiometer is a 0.5-W, 10% multiturn cermet trimmer. The AD524CD instrumentation amplifier (Analog Devices) can be programmed for fixed gains of 1, 10, and 100. The inverting amplifier is an LF411 FET input operational amplifier (National Semiconductor).

has a uniform resistive coating on its inner surface, and the two sheets are kept from touching by a matrix of small, evenly spaced dividers. A connector with four contacts attaches to the vertical edges of one of the resistive surfaces and to the horizontal edges of the other surface. This configuration may be viewed as two independent voltage dividers. When a small DC voltage is applied to the vertical edges and the sheets are pressed together by a light touch, a voltage proportional to the x -axis location of the touch may be recorded from the second sheet. Similarly, when the mylar sheet with the horizontal connection is energized, a voltage proportional to the y -axis location may be recorded from the nonenergized sheet.

The detection capabilities of such a device are related to its sensitivity, which is hardware controlled, not readily adjustable by the experimenter, and designed to detect human touches (which tend to be relatively long). For the interface (controller) hardware provided with the Duratouch screen, a contact duration of at least 13 ms was required to generate a readout of the touch location in x and y coordinates. Unpublished observations from our laboratory and some published reports (Rilling, Kramer, & Askew, 1970; Schwartz & Williams, 1972; Whipple & Fantino, 1980) suggested that a substantial proportion of conditioned pecking-response contacts may be less than 10 ms in duration. For this reason, we replaced the commercial controller with a circuit that samples the x , y outputs of the touch

screen at rates sufficient to detect the location of a peck contact with a duration of 2 ms or greater. (Although contacts as brief as 1 ms may be detected, the detection of a location requires specification of both the x and y contacts.)

The controller circuit (Figure 2) alternately energizes the touch screen in the vertical and horizontal directions, amplifies the signal from the touch screen, and provides separate x and y voltages that can be read by an A/D converter. The 1-ms square wave input to the circuit may be obtained from a digital input/output computer interface card, or by alternately sending codes for 0 V and 5 V to a digital-to-analogue (D/A) converter. The outputs, labeled " x -axis read" and " y -axis read," are attached directly to two channels of an A/D converter as single-ended inputs. The 6.2-V level applied to the screen by the UDN2981A driver is supplied by the voltage regulator circuit shown in the inset of Figure 2. Voltages in excess of this level may damage the resistive coating of the touch screen. Two 5-k Ω variable resistors are used to adjust the maximum output of the circuit to match the range of the A/D converter (0 to 5 V in our configuration). The 200-k Ω trimmer is used to adjust the voltage level of the 0, 0 coordinate. Acquisition of one coordinate pair from the touch screen requires a programmed sequence of events. When the D/A converter is instructed to output 0 V, touch screen terminals $x1$ and $x2$ are energized and the voltage at the point labeled " x -axis read" will represent the

Fig. 2. Schematic of the touch screen controller/amplifier. All amplifiers and drivers are integrated circuits (ICs) that can be mounted easily on perf-board. The two surfaces of the touch screen are represented by the shaded area connected to Points X1, X2 and Y1, Y2. Resistors are 0.25 W, 5%, and potentiometers are 0.5-W, 10% multiturn trimmers. The LF411 amplifiers (National Semiconductor) are powered by a ± 15 -VDC supply. The remaining drivers and inverters are powered by a +5-VDC supply. The 74LS04 is a hex inverter IC (Motorola). The UDN2981A is an eight-gate source driver IC and the ULN2003A is a seven-gate peripheral driver IC (Motorola; Sprague). The model LM317T voltage regulator (Motorola) shown in the inset should be adjusted to provide 6.2 V.

x coordinate. The voltage is read by the computer by sampling from the A/D converter connected to this point. After a 1-ms delay, the D/A converter is instructed to output 5 V, touch screen terminals y_1 and y_2 are energized, and the y coordinate may be read by sampling from the A/D converter connected to the point labeled "y-axis read." In the absence of contact with the screen's surface, both the x and y values will be approximately 0 V.

Calibration

The accelerometer may be calibrated by mounting it firmly (e.g., in a stereotaxic instrument) and rotating it from a horizontal to a vertical orientation. The change in voltage recorded during this 90° rotation equals the sensitivity per 1 g (9.8 m/s²).

The magnetosensitive transducer was calibrated by inserting, between the beak tips, a tapered aluminum rod with a base diameter of 20 mm, decreasing in 2-mm steps to a tip diameter of 2 mm. This produced a series of gapes of known values. The voltages recorded

for each gape were converted to digital values, using specially written software that was the equivalent of a look-up table. Calibrations were carried out at the start and end of each session. The two sets of digital readings were stored and their average subsequently used to generate a calibration curve for the conversion, by linear interpolation, of gape data obtained during the session.

For calibration of the touch screen, a box was displayed on the monitor equal in area to the desired touch-sensitive surface. (This may be of any size, up to and including the total area of the monitor.) The upper left corner of the box was touched with a stylus, and the voltage for the corresponding x and y coordinates was recorded. Touching the lower right corner of the box provided a second coordinate pair for calculating the distance along the vertical and horizontal edges of the box. Because the output of the touch screen is a linear function of distance, the location of intermediate touches can be obtained by interpolation. In our current experiments, the active area of the

A **B** **C**

Fig. 3. Schematic representation of the experimenter's display after a single autoshaping trial. (A) Conditioned pecking: The three traces represent jaw movements (Gape), head movement (Accel), and contact duration (Contact). The data are aligned with respect to the moment of touch-screen contact. (B) Localization: locations on the touch screen of a population of pecking responses made to a 1.2-mm circular stimulus. Each small circle represents a single terminal peck location, and the localization display was updated after every trial. (C) Consummatory response: gape and acceleration traces recorded during the period following delivery of reinforcement. The gape record illustrates jaw movements during the ingestive sequence. (An upward deflection in the gape record indicates a jaw-opening movement.) An opening or grasping response is

monitor was 400 by 400 pixels. The horizontal and vertical size controls on the monitor were adjusted to display this area as a box measuring 160 mm wide by 160 mm high. Trim potentiometers were adjusted to provide a resolution of 50 μ m in both directions. For data analysis, the unit of measurement is a single pixel (1 pixel = 0.4 mm on a side).

Software Considerations

Using a microcomputer with an 80286 central processor, we had no difficulty sampling analogue data from four separate input channels; one each for the accelerometer and magnetosensitive devices and two for the touch screen. On occasion we have added an additional channel of electromyographic (EMG) data. We have been able to present stimuli, sample each channel at a resolution of 1 kHz, store up to 20 s of data per trial, and control reinforcement contingencies. Sampling from a large number of channels normally requires a tradeoff between sampling frequency and data storage. That we were able to avoid such constraints reflects both some properties of the behavior studied and the use of certain programming strategies that allowed us to store all the data of interest while minimizing the amount of data stored.

Constraints on the storage of consummatory response data were minimized by the fact that the response is brief (<1 s) and is elicited at very short latencies by reinforcer delivery, so that the data storage window was both short (3 to 5 s maximum) and well defined. However, for conditioned pecks made on the CRF schedule, the data storage window—from stimulus onset to touch screen contact—could be of indefinite length. To deal with this situation, we combined a circular array and a Schmitt trigger function. In the interval prior to contact, data from the accelerometer and magnetosensitive devices were stored in a circular array containing the most recent 500 data

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followed by three high-velocity "stationing" movements that serve to position the food pellet, and then by a jaw movement mediating intraoral transport of the pellet. The acceleration record indicates the presence of two periods of fixation, the second of which is followed by head acceleration (peck initiation) and deceleration (peck termination or contact), followed by the head movements accompanying stationing and intraoral transport.

samples. This number of samples is sufficient to capture both the beginning of head movement and the entire jaw-opening movement. In the absence of a peck, the array was continuously refreshed. Contact with the touch screen activated the Schmitt trigger to switch to a continuous data collection mode, utilizing an array that stored data from all the input channels during the period following contact—the reinforcement period. (A Schmitt trigger is a hardware or software device that is preset to “trigger” when some criterion event occurs. In our system, the Schmitt trigger was a very fast, machine-language software function that monitored one of the touch screen channels for a change in value. The same result may be achieved more easily in hardware, by connecting the touch screen output to a hardware interrupt channel.) Data from both the circular and the continuous arrays were stored in random access memory and were saved to disk during the intertrial interval, a time when processing demands are minimal. Under the conditions of the present experiment, more than 10,000 data points could be saved to the hard disk in about 5 s.

Some special programming requirements are associated with the data from the x and y channels of the touch screen. Ideally, the data resemble two square pulses, where pulse height corresponds to the distance from the origin to the x or y coordinate of the contact and pulse width corresponds to contact duration. In practice, perturbations in beak movement during sustained contact generated noise in the signal waveforms, producing pulses with a slow rise and decay and with somewhat ragged tops.

To facilitate analysis, the data (in pixels) were first smoothed by dividing by 10. To deal with the noise problem, we used two simple algorithms in calculating location and duration values. The algorithm used to define the duration of the contact identifies the first time at which the voltage exceeded the resting level and the last time at which the voltage returned to the resting level. This algorithm is applied to both the x and y axes, generating four time values. The difference between the smallest and largest of these values defines contact duration. The algorithm used to define contact location is designed to extract a single representative value from an array of points, each of which represents an independent estimate of the location at that time. Because the form

of the contact may differ in different experiments, it may not be useful to specify a single “general” algorithm. (The algorithm used to extract the data shown in Figure 4, as well as other relevant software, is available from the authors.)

The Keithley 570 A/D converter, like those of other manufacturers, includes subroutines to be called from programs written in high-level languages (e.g., Microsoft® QuickBASIC, C, Pascal). However, these subroutines are not needed because interface hardware of any type may be directly and rapidly addressed using BASIC in conjunction with the instructions provided by the manufacturer. Most students and technicians have some level of acquaintance with BASIC, and transfer to this specific system is rapid.

The hardware requirements of the system are relatively modest. They include an 80286-based microcomputer running at 12 MHz or more, a 12-bit multichannel A/D converter, a digital I/O board, a touch screen, and the electronic components needed to construct the transducer amplifiers and the touch screen controller. All are commercially available, off-the-shelf items, and their total cost, exclusive of the computer, is well under \$1,000.

RESULTS

Figure 3 reproduces the experimenter's portion of the computer screen display at the end of an arbitrarily selected training (autoshaping) trial. The three traces shown in the top panel plot the gape, acceleration, and contact duration of the conditioned pecking response for that trial, aligned with respect to the time of contact with the touch screen. The chosen time base permits plotting of the entire conditioned response. The center panel schematically illustrates the distribution of terminal peck locations with respect to the position of the circular stimulus. Because the display was updated after every trial, the small circles provide a record of peck locations on each of the preceding trials of the session. The bottom panel plots, for the latest trial, the gape and acceleration data recorded during the 800 ms following reinforcer delivery, using a time base that permits viewing of the entire consummatory response. The segregation of conditioned and consummatory peck data for each

Fig. 4. Top: Frequency distribution of pecking-response contact durations for each of the 4 subjects, summed across all the CRF sessions for each subject: 9170, six sessions; 9172, six sessions; 9226, four sessions; 9229, five sessions. Bottom: Analogue voltage traces representing the waveforms generated via the touch screen for three different types of pecking response contacts in a single subject. The location data are plotted in pixels (1 pixel = 0.4 mm on a side).

trial facilitates subsequent analysis of the different data sets.

The top portion of Figure 4 presents illustrative frequency distributions of contact durations for each of the 4 pigeons, summed across all CRF sessions. Although the distributions differ with respect to the extent of their bimodality, each of them contains a substantial

number of pecks less than 10 ms in duration. To illustrate the topography of pecking-response contacts, the bottom portion of the figure presents, for 1 subject, the waveforms (single axis only) of three representative touches. Previous cinematographic analyses of the pigeon's pecking response (Smith, 1974) suggest that the first waveform represents a brief peck

Fig. 5. Scatter plots illustrating the relation between variations in the position of the projected circular stimulus and variations in the terminal locations of the pecking response. For each bird, plots are based upon all the CRF sessions in which the position of the stimulus was varied on each trial. The range of locations reflects the dimensions of the display (160 by 160 mm). Distances are millimeters from the x axis. Data are presented for only one axis (x), because those for the other axis are almost identical.

involving contact with only one beak; the second, successive contacts with two beaks, and the third a sustained contact with both beaks.

Figure 5 plots, for each bird, the relation between the position of the projected circular stimulus on a given trial and the terminal location of the pigeon's pecking response on that trial. The data are summed across the CRF sessions with random placement of the stimulus. The correlation coefficient serves as an index of the precision with which stimulus location controls response location in the testing paradigm. Note that all birds "track" the

location of the stimulus, although there was no specified contingency between reinforcement and terminal peck location.

Finally, to assess the reliability of the modified touch-sensitive device as a detector of conditioned pecking responses, the pecking behavior of 2 birds was observed with the aid of a video camera. For the first 100 trials of a CRF session, the number of head thrusts initiated was compared with the number of contacts recorded. For the 1st subject, the proportion detected was 100%; for the 2nd, the proportion was 98%.

DISCUSSION

Although the standard pecking key is an elegant solution to the problem of transducing response rate, it can provide only limited information about response topography and is uninformative with respect to response coordination. Furthermore, the physical properties of the key and switch may seriously distort the accurate measurement of peck duration. The relatively inexpensive system described in this report permits simultaneous monitoring of conditioned pecking-response topography as well as the terminal location and duration of the conditioned peck. Although the present data were gathered using rather simple conditioning paradigms (autoshaping, CRF schedule), the system may also be used with more complex reinforcement contingencies, including those involving time-costly components. By using the programming strategies described in this report, such contingencies may be implemented while maintaining the high-resolution monitoring of response parameters.

The quantitative descriptions of ingestive and conditioned pecking-response topographies acquired using the present system (Figure 3) are consistent with those previously acquired using photography (Klein *et al.*, 1985; LaMon & Zeigler, 1988; Zeigler *et al.*, 1980; see also Siemann & Delius, 1992). Control of pecking response location by stimulus-reinforcer contingencies (Figure 5) has been reported earlier, using a "feature-positive" paradigm (e.g., Goodale, 1983; Jenkins & Sainsbury, 1970).

In previous studies of pecking response duration, contact duration was measured either as the duration of displacement of a standard pecking-response key (e.g., Schwartz & Williams, 1972; Whipple & Fantino, 1980) or by using force transducers, which provide a voltage analogue representation of the force-time function (LaMon & Zeigler, 1984; Rilling *et al.*, 1970). The waveforms and the distributions of touch screen contact durations shown in Figure 4 reflect the direct measurement of contact duration, independent of pecking force. The present system thus minimizes interactions between the topography of the response and the physical properties of the force transducer. Moreover, our data on pecking-response contact durations suggest that commercially available touch screens may fail to

detect a significant number of pecks. For example, the hardware associated with a widely used commercial touch screen (Duratouch) requires a minimum contact of 13 ms to record a touch. As Figure 4 indicates, however, such a criterion may exclude a substantial proportion of the pigeon's conditioned pecking responses.

Although the focus of this report has been on the monitoring of topographic parameters, data on more traditional measures of pecking response probability (frequency, rate, latency) are easily obtainable. Thus, the present system should prove to be useful in a variety of experimental settings in which measurement and control of the pigeon's pecking response is a central concern. The modified touch screen controller will provide localization data for those pecks which, because of their physical properties (e.g., location, duration, force), might not be detected either by standard pigeon keys or by commercially available touch screen controllers. This property may be important in studies in which many responses terminate off the key, either as a result of a specific behavioral strategy (e.g., omission experiments) or the disruption of visuomotor processes (e.g., Jaeger & Zeigler, 1991). The increased sensitivity of the touch screen would also be critical for paradigms requiring that each peck in a specified sequence of pecks at (i.e., contacts with) the target must be registered to produce reinforcement, such as ratio schedules or sign or goal-tracking experiments (Blough, 1992).

System components may be used to bring one or more pecking response parameters under associative control, using response differentiation procedures. Thus, the increased sensitivity and high spatial resolution of the modified touch screen will facilitate differentiation studies of peck localization (e.g., Allan & Zeigler, 1989; Jaeger & Zeigler, 1991). The system also permits the arrangement of reinforcement contingencies related to contact duration. Moreover, by converting deceleration at the moment of contact, the accelerometer output could serve as a measure of relative force and be used to control reinforcement contingencies in force differentiation studies.

The novel and potentially most useful feature of the system is its ability to monitor several parameters of the conditioned pecking response simultaneously. The ability to examine

interactions among the different response components of conditioned pecking should be useful both in studies of motor control and in the analysis of conditioning processes. For example, the simultaneous monitoring of head acceleration, gape, and terminal peck location would provide temporal landmarks for studies of the coordination of the head- and jaw-movement systems and for the analysis of feedback and feedforward mechanisms. Monitoring of head and jaw movements during the course of conditioned response acquisition could clarify the extent to which the different responses are similarly affected by manipulations of CS or US variables (e.g., LaMon & Zeigler, 1988). Finally, the system described in this report makes it possible to explore, within a single subject, the effect of varying CS or US properties upon measures of both pecking response strength and pecking response topography.

REFERENCES

- Allan, R. W. (1992). Technologies to reliably transduce the topographical details of pigeons' pecks. *Behavior Research Methods, Instrumentation and Computers*, 24, 150-156.
- Allan, R. W., & Zeigler, H. P. (1989). Measurement and control of peck localization in the pigeon. *Physiology and Behavior*, 45, 1215-1221.
- Blough, P. M. (1992). Detectability and choice during visual search: Joint effects of sequential priming and discriminability. *Animal Learning & Behavior*, 20, 293-300.
- Deich, J. D., Allan, R. W., & Zeigler, H. P. (1988). Conjunctive differentiation of gape during food-reinforced key pecking. *Animal Learning & Behavior*, 16, 268-276.
- Deich, J. D., Houben, D., Allan, R. W., & Zeigler, H. P. (1985). A microcomputer-based system for monitoring of jaw movements in the pigeon. *Physiology and Behavior*, 35, 307-311.
- Goodale, M. A. (1983). Visually guided pecking in the pigeon (*Columba livia*). *Brain, Behavior, and Evolution*, 22, 22-41.
- Jaeger, R., & Zeigler, H. P. (1991). Visual field organization and peck localization in the pigeon. *Behavioral Brain Research*, 45, 65-69.
- Jenkins, H. M., & Moore, B. R. (1973). The form of the autoshaped response with food or water reinforcers. *Journal of the Experimental Analysis of Behavior*, 20, 163-181.
- Jenkins, H. M., & Sainsbury, R. S. (1970). Discrimination learning with the distinctive feature on positive or negative trials. In D. I. Mostofsky (Ed.), *Attention: Contemporary theory and analysis* (pp. 239-273). New York: Appleton-Century-Crofts.
- Klein, B. G., Deich, J. R., & Zeigler, H. P. (1985). Grasping in the pigeon: Final common path mechanisms. *Behavioral Brain Research*, 18, 201-213.
- Klein, B., LaMon, B., & Zeigler, H. P. (1983). Drinking in the pigeon: Response topography and spatiotemporal organization. *Journal of Comparative Psychology*, 97, 178-181.
- LaMon, B., & Zeigler, H. P. (1984). Grasping in the pigeon: Stimulus control during conditioned and consummatory responses. *Animal Learning & Behavior*, 12, 223-231.
- LaMon, B., & Zeigler, H. P. (1988). Control of pecking response form in the pigeon: Topography of ingestive behaviors and conditioned responses for food and water reinforcers. *Animal Learning & Behavior*, 16, 256-267.
- Rilling, M., Kramer, T. J., & Askew, H. R. (1970). A preliminary analysis of the dynamics of the pecking response in pigeons. *Journal of the Experimental Analysis of Behavior*, 13, 267-278.
- Schwartz, B., & Williams, D. R. (1972). Two different kinds of key peck in the pigeon: Some properties of responses maintained by negative and positive response-reinforcer contingencies. *Journal of the Experimental Analysis of Behavior*, 18, 201-216.
- Siemann, M., & Delius, J. D. (1992). Variability of forage pecking in pigeons. *Ethology*, 92, 29-50.
- Smith, R. F. (1974). Topography of the food-reinforced key peck and the source of the 30 millisecond inter-response times. *Journal of the Experimental Analysis of Behavior*, 21, 541-551.
- Whipple, W. R., & Fantino, E. (1980). Key-peck durations under behavioral contrast and differential reinforcement. *Journal of the Experimental Analysis of Behavior*, 34, 167-176.
- Wohlschlaeger, A., Jaeger, R., & Delius, J. D. (1993). Head and eye movements in unrestrained pigeons (*Columba livia*). *Journal of Comparative Psychology*, 107, 313-319.
- Wolin, B. R. (1968). Difference in manner of pecking a key between pigeons reinforced with food and water. In A. C. Catania (Ed.), *Contemporary research in operant behavior* (p. 286). Glenview, IL: Scott Foresman.
- Zeigler, H. P., Levitt, P., & Levine, R. R. (1980). Eating in the pigeon (*Columba livia*): Response topography, stereotypy and stimulus control. *Journal of Comparative and Physiological Psychology*, 94, 783-794.

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