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Design and evaluation of a touchscreen apparatus for operant research with pigeons

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We developed a touchscreen apparatus for pigeons and conducted a series of experiments that assessed its utility for free-operant procedures. The apparatus incorporated an on-board Windows computer, an electromechanical interface, an amplified speaker, and the touchscreen. We found that merely projecting a virtual key on the screen was insufficient; too many pecks missed the key. Adding a visual target in the center of the key and providing visual feedback for on-key pecks both failed to improve response accuracy. Accuracy was improved by imposing a timeout after off-key pecks or providing a physical boundary around the key. With the physical boundary, response accuracy was comparable to that obtained with conventional plastic keys, and response acquisition via autoshaping also was comparable. Mixing the color elements of the screen's pixels produced color stimuli, but the colors did not function as pure wavelengths of light in tests of stimulus generalization. Both colors and geometric shapes functioned as discriminative stimuli in multiple schedules with variable-interval and extinction components or rich and lean fixed-ratio components. In general, our touchscreen apparatus is a viable alternative to conventional pigeon chambers and increases the experimenter's options for visual stimuli, auditory stimuli, and the number and location of response keys.

Key words: touchscreen, key peck, pigeon

For at least 35 years, video monitors have been used to present stimuli to pigeons and record pecking responses via touchscreens (Clausen et al., 1985). A touchscreen monitor (hereafter, *touchscreen* or *screen*) has significant advantages over the conventional three-key chamber commonly used with pigeons. Because plastic electromechanical response keys are replaced by displays on the touchscreen, software rather than hardware determines the number, size, and location of the virtual keys, as well as an almost limitless array of visual stimuli that can be presented. The flexibility inherent in a touchscreen allows a single chamber to be used in a wide range of experiments without modification.

A review of the literature indicates that touchscreens have been used mainly in studies that arrange reinforcers contingent on a small number of pecks, including discrete-trial match-to-sample (e.g., Clauson et al., 1985; Velasco et al., 2010), image classification (e.g., Levenson et al., 2015), choice (e.g., Stahlman & Blaisdell, 2011), or autoshaping (e.g., Bermejo et al., 1994) procedures, or as part of a larger procedure in which pigeons could exchange tokens by pecking the touchscreen (e.g., Tan & Hackenberg, 2015). In most of these studies, consequences were arranged dependent upon a single peck. We wondered whether touchscreens are suitable for procedures that generate larger numbers of pecks occurring at high rates such as those observed under lean fixed-ratio (FR) schedules. We are aware of two groups of researchers that have used touchscreens in the study of pigeons' behavior using free-operant (Allan & Zeigler, 1989; Jager & Ziegler, 1991; Kono 2017a; Kono & Tanno, 2020) or discrete-trial procedures (Kono 2013, 2017b, 2019a, b) that required multiple responses on a touchscreen. These studies show that touchscreens can be used for free-operant pigeon research, but do not provide an assessment of the practicality of this technology for aspects of procedures

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that are used widely within the experimental analysis of behavior, particularly in free-operant research. This is the focus of the present paper.

Here we describe the design and construction of our apparatus, our initial efforts to use it to establish and maintain responding under discriminative stimulus control, and various refinements that we made to our hardware and software as we gained experience establishing high-rate, accurate pecking.

Design and Construction

We built our touchscreen apparatus by modifying existing pigeon chambers. The interior of each chamber was 51 cm wide, 37 cm high, and 34 cm deep, divided into two compartments by an aluminum panel. The compartment for the pigeon was 30 cm wide, 37 cm high, and 34 cm deep. An electromechanical feeder mounted to the back of panel was retained, as was the houselight on the front of the panel and the chamber's ventilation fan. Our modifications and additions included (a) a single-board computer and an electromechanical interface; (b) a resistive touchscreen mounted on the front panel of the chamber in place of the response keys; and (c) devices for auditory stimuli mounted on the back of the panel. Figure 1 shows photographs and schematic outlines of these features. A complete list of the components and the prices we paid for them is in the appendix. Although we provide specific information about the computer and equipment that we used, it is important to note that any computer operating Windows 10 could be used to operate the equipment and that a resistive touchscreen monitor or infrared touchframe could be used to record pigeon responses.

The computer, operating under Windows 10, was used to present virtual response keys and stimuli on the touchscreen, record pecks on the screen, and control the houselight, feeder, and auditory stimuli. We programmed the computer with the free Express edition of Visual Basic 2010, although other general purpose languages could be used. The computer communicated with the touchscreen through a USB port; the screen was approximately 9 cm high and 15 cm wide, and had a resolution of 480 pixels by 800 pixels. Another USB port was used to connect the computer to the electromechanical interface, which had relays that allowed our programs to control three 28-V devices: the houselight, feeder, and a relay serving as a feedback clicker. Operation of the touchscreen monitor and electromechanical interface required three software drivers; information about obtaining and installing these drivers is in Supplementary Materials A on the publisher's website.

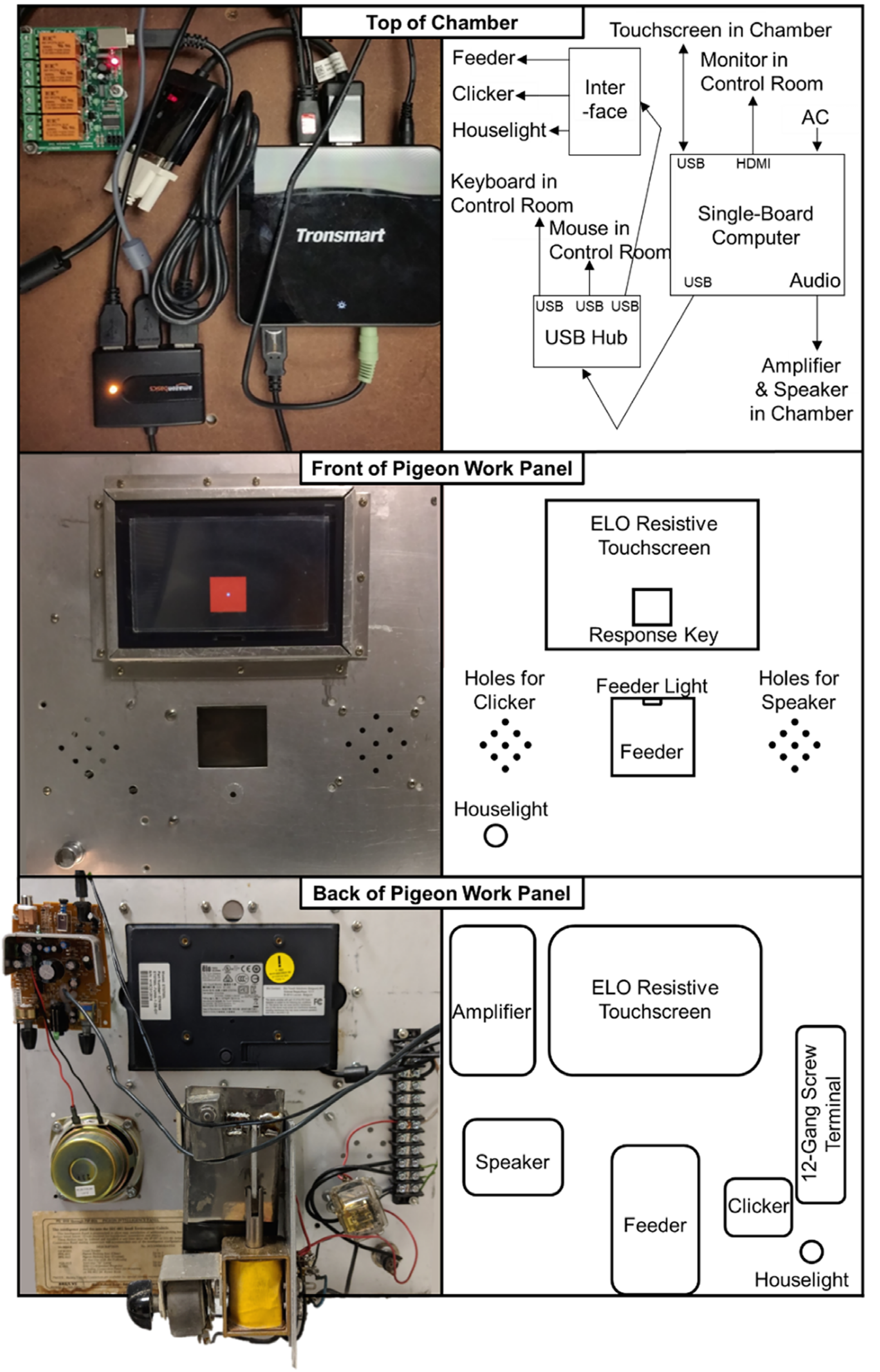
To provide auditory stimuli such as white noise generated by our software, the computer was connected via audio jack to an amplified computer speaker inside the chamber. The computer, USB hub, and electromechanical interface were mounted to a board (30 cm square) that sat on the outside top of the chamber, insulated from the chamber by rubber feet.

So that experimenters could start and observe sessions from the nearby control room, the computer's HDMI port was used to connect it to a desktop video monitor that duplicated the touchscreen's display, and USB ports were used to connect the computer to a keyboard and mouse. When we tested our first chamber, the connections to the control room equipment were made directly, as shown in Figure 1. When four touchscreen chambers were in operation, the connections were routed through a KVM (Keyboard-Video-Mouse) switch. This allowed us to control and monitor the four touchscreens with a single keyboard, monitor, and mouse.

Inside the chamber, the touchscreen was centered on the pigeon's side of the aluminum panel with the bottom of the screen 19 cm above the floor. A Mylar sheet protected the screen from damage. At different stages in the evolution of our design, we also used adhesive rubber, a stainless-steel faceplate, or a frosted window film in combination with the touchscreen. These materials are described in more detail below. A rectangular aperture, 6 cm wide and 5 cm high, was centered 10.5 cm above the floor (measured from the bottom of the aperture) and provided access to food reinforcers when the feeder was operated. The aperture was lit with a 28-V bulb during the food presentations. General illumination during the sessions was provided by the houselight in the lower left corner of the work panel A set of nine holes arranged three by three (approximately 5 cm wide and 5 cm high) were drilled into the panel on each side of the aperture, 10 cm from the floor (measured from the lowest hole). The speaker was mounted behind one set of holes and the feedback clicker behind the other set.

Figure 1

Equipment and Layout of Touchscreen Chambers



Note. Shown here are pictures and schematics of the outside top of the chamber (top panel), the pigeon's side of the aluminum panel (middle), and the equipment side of the aluminum panel (bottom).

General Method

Subjects

A total of 15 White Carneau pigeons (14 males, 1 female identified as Pigeon 4089) served as subjects. The pigeons were maintained at 80% (± 2%) of their free-feeding weights by food pellets delivered during the sessions and, when necessary, supplemental feeding at least 30 min after sessions. Water was freely available in the home cage, which was kept in a temperature-controlled room with a 12:12 hr light/dark cycle. Five pigeons had experience pecking plastic keys in conventional operant chambers on fixed-ratio (FR) schedules (Pigeons 88, 90, 1108, 1156, and 1424), eight were experimentally naive (Pigeons 9202, 12749, 12777, 12890, 12894, 12903, 15327, and 15390), and two had unknown experimental histories (Pigeons 363 and 4089). The treatment of the pigeons complied with a protocol approved by the West Virginia University Animal Care and Use Committee.

Procedure

Sessions were conducted 7 days per week at approximately the same time each day. After the pigeon was placed into the chamber, a 5-min delay preceded the start of the session to minimize the effects of transportation from the vivarium and handling. During the delay, the chamber was dark and silent (except for the sound of the ventilation fan). At the start of the session, the houselight and the white noise (80 dB) were turned on. During a reinforcer delivery, the houselight and keys were turned off and the food aperture was lit. Each key peck on a virtual key on the touchscreen produced auditory feedback consisting of a click lasting 100 ms.

The color of the virtual response key was varied across the evaluations. On a computer screen, color images are created by manipulating the red, green, and blue elements of each pixel. The intensity of each color element has 256 levels, from 0 (off) to 255 (fully lit). Colors are defined by an RGB code that specifies the intensities of the red, green, and blue elements of the pixel (e.g., pure blue would have an RGB code of 0,0,255). Colors defined by wavelength of light can be translated into RGB codes; conversion calculators are available online (e.g., https://www.johndcook.com/wavelength_to_RGB.html). For example, our programs produced a white key using the RGB code of 255,255,255, a red key using 255,0,0, and a yellow key using 255,223,0. The black space around the key—the blank screen—had a code of 0,0,0 (i.e., none of the color elements were lit). See Supplementary Materials B for a list of RGB codes used in each of the evaluations described below.

Evaluations

Test A: Autoshaping

Our first effort was to establish pecking a virtual key via autoshaping, a widely used procedure in free-operant research to develop initial key-peck responses toward localized light (Brown & Jenkins, 1968). Pigeons 363, 1108, and 4089 served as subjects. All had been trained to eat from the feeder promptly upon its operation. The response key was a white square. The size of the key (2.7 cm x 2.7 cm) was matched to the diameter of the plastic keys in our conventional chambers. The key was centered horizontally on the pigeon work panel and the bottom of the key was about 23 cm above the floor.

The autoshaping procedure was based on the one described by Brown and Jenkins (1968). A trial began by lighting the key. After 8 s, the key was darkened and access to food was delivered for 4 s. If the pigeon pecked the key while it was still lit, the key was darkened and the food was delivered immediately. Pecks on the touchscreen outside the key (off-key pecks) were recorded but had no programmed consequences. The trials were separated by variable intervals with a mean of 60 s (range: 45-75 s) during which the houselight remained on.

We planned to continue autoshaping until the pigeon pecked the key on 10 consecutive trials. Only Pigeon 1108 met this acquisition criterion, and it took 659 trials. The other two pigeons also pecked the key: Over 560 trials, Pigeon 363 pecked the key 50 times and Pigeon 4089 pecked it 18 times, but these pecks never occurred on 10 consecutive trials. Off-key pecks were common, comprising 77% of the total pecks by Pigeon 1108, 86% by Pigeon 363, and 46% by Pigeon 4089. The autoshaping procedure appeared to be effective in generating pecks on the screen, but too many pecks landed outside the boundaries of the response key.

After abandoning the autoshaping procedure with Pigeons 363 and 4089, we exposed them to an FR 1 schedule. The white key was on screen throughout the session, except during reinforcers. Pigeon 363 took 18 min to peck the key 50 times; Pigeon 4089 took 46 min. As before, off-key pecks occurred often, totaling 195 times (80% of pecks) for Pigeon 363 and 16 times (24% of pecks) for Pigeon 4089.

In our experience with conventional chambers, autoshaping is normally completed within one or two sessions (i.e., 60 to 160 trials); only rarely does a pigeon fail to acquire the response. It is possible that the noncontingent delivery of food in autoshaping trials led to adventitious reinforcement of off-key pecks on our touchscreen, a notion supported by the high rate of off-key pecks. When the FR 1 schedule was initiated, food reinforcers necessarily followed a peck on the key, and responding was established within a single session. We were successful in establishing responding, but the autoshaping failures and high rates of off-key pecking were causes for concern.

Test B: Response Accuracy and Response Rates

In the next test, we made changes to our hardware and software to reduce off-key pecks, that is, to increase pecking accuracy. We arranged eight conditions to evaluate the effects of punishing off-key pecks with timeout, adding a target to the center of the key, adding visual feedback for key pecks, and placing a physical border around the key. The three pigeons in the first test served as subjects. Their pecks on a red key were reinforced with 4-s access to food on FR schedules. The location and dimensions of the key were the same as before. Sessions lasted until 40 reinforcers were delivered or 4 hr elapsed, whichever came first. Each condition lasted until response accuracy, defined as the proportion of pecks that were on-key, was stable over five consecutive sessions by visual inspection. Figure 2 shows each pigeon's response accuracy over the five stable sessions of each condition and Table 1 shows mean response rates in those sessions.

Timeout Punishment of Off-Key Pecks. In Condition 1, responding was reinforced on an FR schedule that was made leaner over several sessions from FR 1 to 5 in steps of one and from FR 5 to 15 in steps of two. Each off-key peck resulted in a timeout: The key was darkened for a minimum of 5 s and until 5 s elapsed without an off-key peck. The leftmost panel of Figure 2 shows that response accuracy was moderately high: Averaged over the last five sessions, accuracies were .65, .92, and .86 for Pigeons 363, 1108, and 4089, respectively. The leftmost column of Table 1 shows that the rate of key pecking exceeded 80 responses per minute for two of the three birds; these on-key response rates are within the range we have observed under similar FR schedules in conventional chambers.

In Condition 2, we removed the timeout contingency and continued to reinforce key pecks on an FR 15 schedule. Pigeon 4089's accuracy was unaffected, whereas Pigeon 363's accuracy was reduced by about 8 % and Pigeon 1108's near-perfect accuracy was reduced by about 41%. Response rates decreased for two pigeons and increased for one.

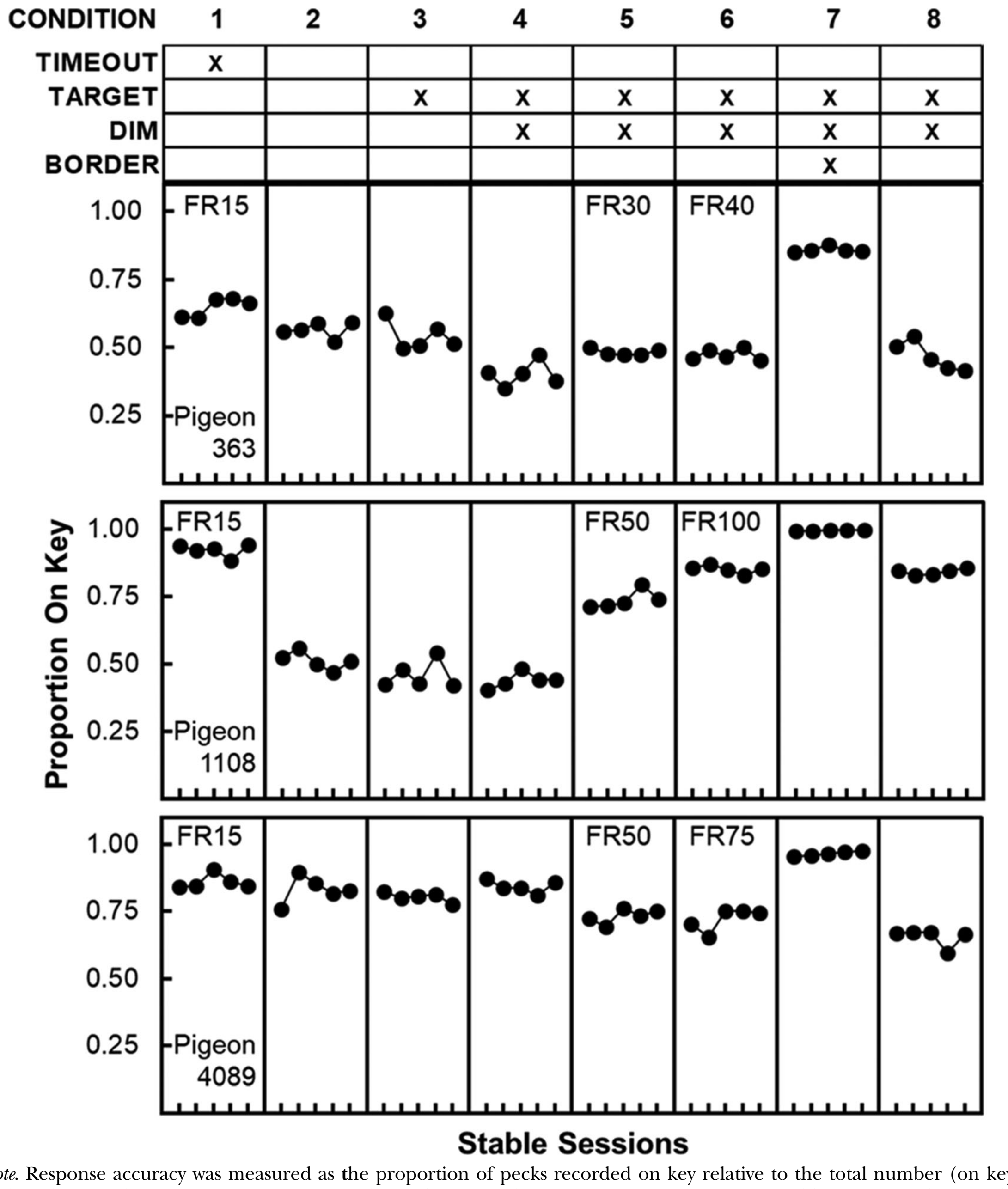
Added Target. In Condition 3, we put a white square (10 pixels x 10 pixels) in the center of the red response key. The idea was to provide a small target to increase accuracy (Pliskoff & Gollub, 1974). The FR 15 remained in effect. The target did not affect accuracy or response rates systematically.

Visual Feedback. In the first three conditions, auditory feedback—an audible click—was presented after each key peck. In Condition 4, we added visual feedback: After each key peck, the color of the key was dimmed for 100 ms by reducing the RGB values by half (from 255,0,0 to 128,0,0). The FR15 schedule and the target were left unchanged. The visual feedback did not affect accuracy or response rates systematically, even though Pigeon 363's accuracy decreased by about 14%.

Leaning the FR Schedule. As the number of responses required for reinforcement is raised, the effective penalty for inaccurate responding also is raised. For example, a pigeon with an accuracy of .75 would peck off-key an average of five times in the course of completing an FR 15 but 25 times in the course of completing an FR 100. We reasoned that raising the FR would promote a more efficient topography. Conditions 5 and 6 evaluated whether raising the FR would increase response accuracy. In Condition 5, the FR was raised in steps of two from FR 15 to 25 and in steps of five from FR 25 to 50 or until signs of ratio strain

Figure 2

Response Accuracy per Pigeon in Stable Sessions of Test B



Note. Response accuracy was measured as the proportion of pecks recorded on key relative to the total number (on key and off key) in the five stable sessions of each condition for the three pigeons. The FR was held constant within conditions, and across conditions except where labeled.

appeared. Upon reaching FR 50 (Pigeons 1108 and 4089) and FR 30 (Pigeon 363), responding was allowed to stabilize. For Pigeon 1108, accuracy increased from an average of about .44 to .74 and response rates from 61 to 138 pecks per minute. There was a small increase in Pigeon 363's accuracy and a small reduction in Pigeon 4089's accuracy.

In Condition 6, the FR was raised further in steps of five until either FR 100 was reached or

Table 1

Response Rates per Pigeon in Test B

Pigeon	Response	Measure	Condition 1	2	3	4	5	6	7	8
363	On Key	Mean	25	39	22	26	28	29	92	19
		SD	(10)	(3)	(3)	(5)	(6)	(3)	(1)	(7)
	Total	Mean	41	70	41	66	59	61	109	40
		SD	(14)	(6)	(9)	(10)	(12)	(7)	(2)	(14)
1108	On Key	Mean	148	62	51	61	138	160	196	149
		SD	(8)	(5)	(8)	(3)	(6)	(10)	(7)	(4)
	Total	Mean	163	122	111	138	188	188	198	178
		SD	(8)	(7)	(6)	(10)	(2)	(9)	(7)	(5)
4089	On Key	Mean	82	62	80	72	65	65	103	78
		SD	(12)	(8)	(4)	(2)	(5)	(5)	(5)	(6)
	Total	Mean	97	75	101	86	89	90	107	119
		SD	(13)	(8)	(5)	(2)	(8)	(4)	(4)	(5)

Note. Conditions were as follows: 1, Timeout; 2, No timeout; 3, Target; 4, Dimming Feedback; 5, Leaning FR; 6 Leaning FR; 7, Border; 8, No Border. Response rates per pigeon (on-key and total pecks per minute) were aggregated across the five stable sessions of each condition.

signs of ratio strain emerged. Upon reaching FR 40 (Pigeon 363), FR 75 (Pigeon 4089), and FR 100 (Pigeon 1108), responding was allowed to stabilize. These FR requirements were used throughout the remainder of the conditions in Test B. Under these FR requirements, accuracy and response rates increased for Pigeon 1108 and remained relatively unchanged for Pigeons 363 and 4089.

Key Border. In a conventional pigeon chamber, the plastic keys are recessed behind a circular hole in the work panel. The metal of the work panel surrounding the key creates a physical border for each key. In Condition 7, we put a physical border around our virtual key. It was made of black rubber, 5 mm wide and 3 mm thick, and glued to the Mylar screen protector. Pecks on the border were recorded as off-key pecks. Accuracy increased to its highest levels, averaging .86, 1.00, and .96 for Pigeons 363, 1008, and 4089 respectively, as did response rates, 92, 196, and 103 pecks per minute. Removing the border in Condition 8 led to marked reductions in accuracy and response rate in every pigeon.

To describe the effects of the border in a more molecular way, Figure 3 shows the screen location of each peck in the last session of Conditions 6, 7, and 8. Taken together, these conditions arrange an A-B-A evaluation of the border. In the last session of Condition 6 without the border, off-key pecks were common and their locations formed patterns that were idiosyncratic across pigeons. In Condition 7 with the border, off-key pecks were rare. Removing the border in Condition 8 restored the idiosyncratic patterns of off-key pecks observed in Condition 6.

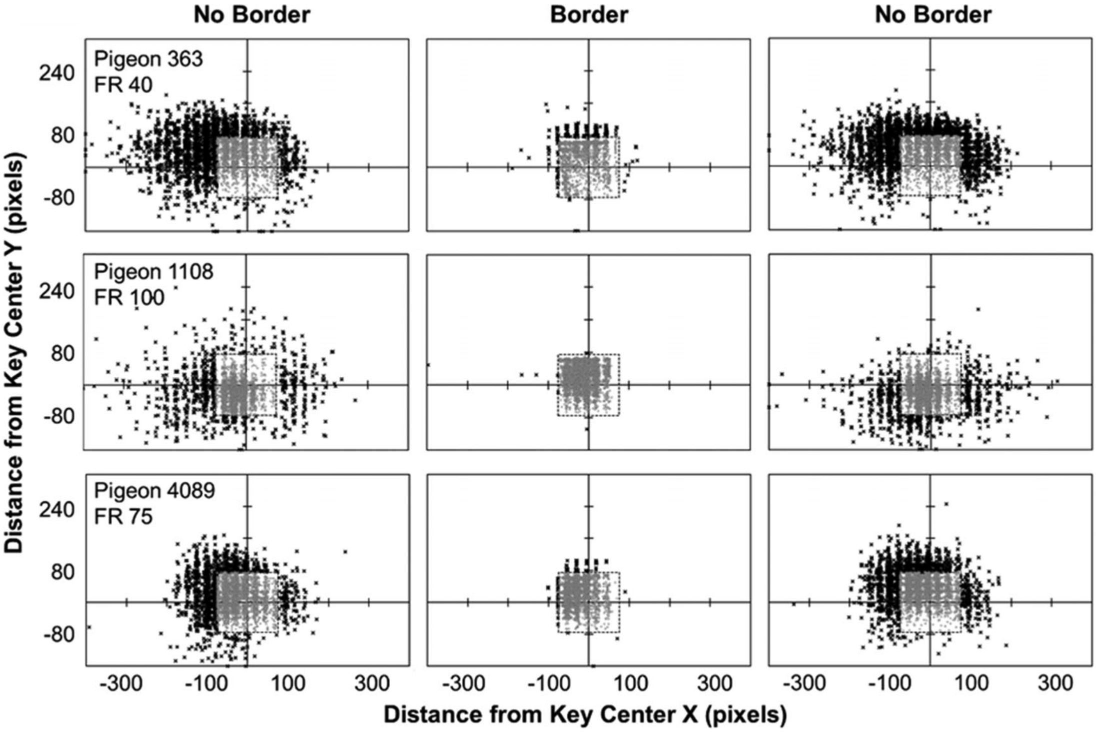
Summary of Test B. In summary, we were able to establish moderate to high levels of response accuracy by punishing off-key responding, but because the addition of a punishment procedure might complicate the study of operant behavior in many cases, we sought methods in which inaccurate responding produced no consequences. Adding a target to the center of the key and providing visual feedback did not affect response accuracy or response rates systematically. Raising the FR requirement increased response accuracy and response rates for one pigeon but did not affect accuracy or rates of responding for the other two pigeons. The most effective manipulation was adding a physical border around the key in Condition 7, which increased response accuracy and response rates for all three pigeons.

Test C: Response Accuracy in a Conventional Chamber

Although adding a physical border to the virtual key greatly increased response accuracy, it was less than perfect. Response accuracy also is less than perfect in conventional chambers. A well-used pigeon chamber almost certainly will show evidence of pecks that have

Figure 3

Response Locations per Pigeon in the Final Session of the Last Three Conditions of Test B



Note. Corrdinates (X and Y) relative to the center of the key, in pixels, for all responses during the last No-Border, Border, and No-Border session at each pigeon's terminal FR. The square centered in each panel represents the key. Gray circles represent on-key pecks; black X's represent off-key pecks.

struck the metal panel surrounding the chamber. Bachrach (1966) had enough of an interest in off-key pecks to develop a method to record them using carbon paper. Here we describe the accuracy of our pigeons as they responded on a conventional key.

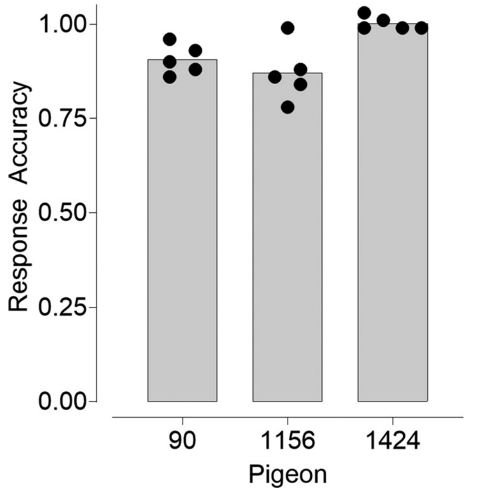
Three pigeons (Pigeons 90, 1156, and 1424) were studied in an operant chamber with three plastic keys. Only the center key was used; it was about the same size as the virtual key on our touchscreen (circle with a diameter of 2.7 cm vs. a square with sides of 2.7 cm), lit red, and located in the same position on the pigeon work panel. We replaced the door to the chamber with a clear acrylic panel, which allowed us to record the sessions with a video camera (Sony Handycam Model: HDR-CX405) on a tripod outside the chamber. Key pecks were reinforced with 4-s access to food according to an FR 50 schedule and recorded for five successive sessions that lasted until 40 ratios were completed or 4 hr elapsed, whichever came first.

Two undergraduate research assistants independently observed the first 5 min of each video in slow motion (0.25x speed) and advanced a mechanical counter when they saw a peck toward the key. A peck was defined as movement of the pigeon's beak toward the key that made contact with any part of the chamber. The beak had to break contact with the chamber before another peck could be counted. If a ratio was in progress when 5 min had elapsed, the observer continued counting until the end of the ratio. The observers were free to watch parts of the video as many times as necessary until they felt confident about their counts. The primary observer watched all of the videos; the secondary observer watched two randomly selected videos for each pigeon. Interobserver agreement was calculated on a ratio-by-ratio basis by dividing lower count by the higher count and multiplying by 100. The mean agreement was 96%, 91%, and 93% for Pigeons 90, 1156, and 1424, respectively.

Pecking accuracy was calculated by dividing the number of pecks recorded by the computer (necessarily 50 pecks for each instance of the FR schedule) by the number of pecks recorded by the primary observer. Figure 4 shows each pigeon's accuracy in each of the five sessions, as well as the mean. Accuracy averaged .86 and .90 for Pigeons 1156 and 90, respectively. Accuracy for Pigeon 1424 exceeded the theoretical maximum of 1.0 in some cases, indicating that the equipment recorded more pecks than the observers. Pigeon 1424's responding had a topography commonly called "trilling" or "high-rate fluttering" (Barrera, 1974): The pigeon rapidly opened and closed its beak, repeatedly operating the key's switching circuit while maintaining contact with the key. As a result, the equipment detected multiple responses when the observers could not. This issue aside, the results are similar to those obtained with the touchscreen key surrounded by a border, in which case accuracy ranged from .86 to 1.00. When the key on the touchscreen is recessed behind a physical border, accuracy of touchscreen key pecking is comparable to conventional key pecking.

Figure 4

Response Accuracy per Pigeon Across Sessions of Test C



Note. Response accuracy was measured as the proportion of pecks recorded by observers that were also recorded by the experimental equipment, for each pigeon during the five videotaped sessions. Dots show the accuracy in each session; bars show the mean across sessions.

Test D: Stimulus Generalization across Simulated Wavelengths

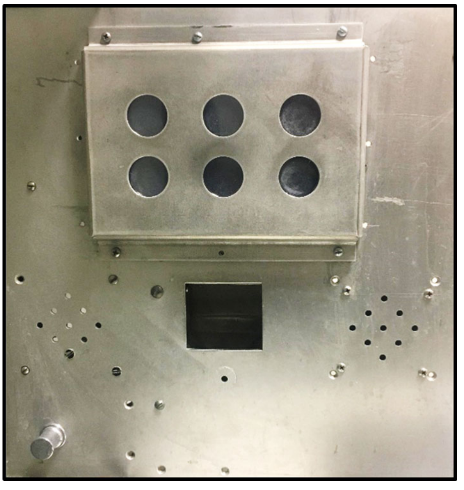
As we have noted, our touchscreen mixes red, green, and blue elements of pixels to produce stimuli that mimic colors produced by specific wavelengths of light. We wondered whether these colors are functionally similar to pure wavelengths of light produced by passing white light through a filter. To find out, we replicated a portion of Guttman and Kalish's (1956) study of stimulus generalization, replacing their pure wavelengths of light with our simulated wavelengths. Guttman and Kalish reinforced pigeons' pecks on a translucent key lit from behind with a 550-nm light. Then they conducted a generalization test under extinction. Over the course of the test session, each pigeon was exposed to 11 wavelengths ranging from 490 nm to 610 nm, with the 550-nm training stimulus at the midpoint of the range. Test responding was highest at 550 nm and decreased as the wavelength of the test stimuli differed, in either direction, from 550 nm. When responding was graphed as a function of wavelength, the result was a "generalization gradient" with an inverted-V shape. Here we report our test to see if a similar gradient would be obtained with simulated wavelengths.

Because of the importance of physical borders, we modified the apparatus by covering the touchscreen with a stainless-steel faceplate that divided the screen into keys with distinct borders. As shown in Figure 5, the faceplate had six circular openings, 2.8 cm in diameter, arranged in two rows of three spaced evenly 4.2 cm apart from center to center. The openings became response keys when a color was displayed through the opening. The centers of the bottom and top rows of keys were located 23 and 27 cm above the floor of the chamber, respectively.

Pigeons 88, 90, 363, 1108, 1156, 1424, and 4089 were studied in the newly modified chambers. Although the faceplate permitted six possible key locations, only the center key on the bottom row was used for the present test. Pecks that occurred on the five inactive locations were recorded but had no programmed consequences. Visual feedback was provided after each key peck by showing a white square (15 x 15 pixels) in the center of the key for 100 ms. Although our previous tests indicated that the feedback was unnecessary, it was useful to us as

Figure 5

The Pigeon Work Panel with the Metal Faceplate Attached



Note. This faceplate was used in Tests D, E, F, and G.

we watched a duplicate of the touchscreen display on the monitor in the control room: The appearance of the feedback let us see that the key had been pecked.

Training sessions consisted of 30 components, each lasting 60 s, during which the key light was 550 nm and pecks were reinforced with 3.5-s access to food on a variable-interval (VI) 60-s schedule. The components were separated by 10-s intervals during which the houselight was turned off, the key darkened, and the VI schedule suspended. Training continued for a minimum of 10 sessions and until response rates in the most recent six sessions were judged stable by visual inspection. All of the pigeons completed training in 10 to 14 sessions.

The test session consisted of 138 components, each lasting 30 s. For the first six components, the key light was 550 nm and key pecks were reinforced on a VI 60-s schedule. For the remaining 132 components, the VI schedule was suspended and the color of the key changed from component to component. These test components were divided into 12 sets. Within each set of components, 11 simulated wavelengths (490, 510, 520, 530, 540, 550, 560, 570, 580, 590, and 610 nm) were used to light the key, one per component, selected randomly without replacement.

Each pigeon was exposed to the training and testing procedure twice. In the first instance, the touchscreen was covered with the transparent Mylar screen protector used previously. In the second instance, the screen was covered with a translucent protector ("Etched Glass" window film; www.artscapeinc.com) that we thought might diffuse and blend the light coming from the red, green, and blue pixels.

Figure 6 shows the percentage of key pecks in the presence of each simulated wavelength during the test sessions using transparent and translucent screen protectors. Our manipulation of simulated wavelengths failed to produce the orderly, symmetrical generalization gradient described by Guttman and Kalish (1956; except perhaps in the case of Pigeon 90's test with the translucent screen protector). Simulating wavelengths of light by mixing red, green, and blue pixels did not produce stimuli that match stimuli produced with true wavelengths of light. It is possible that the presentation of visual feedback following each peck during training may have affected responding during test sessions. This possibility was not evaluated in the present study, but may be explored in future research.

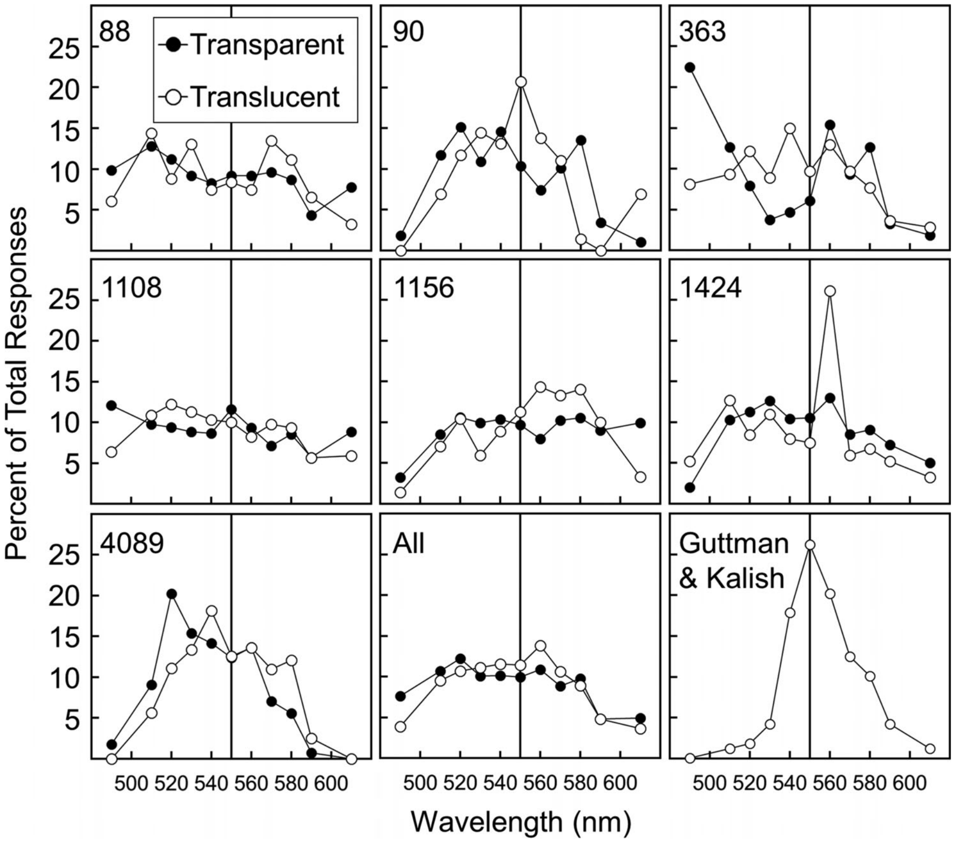
Test E: Discriminative Control with Simulated Wavelengths

Although the simulated wavelengths in our test were not functionally equivalent to physical wavelengths, they still may be able to produce serviceable discriminative stimuli. Although obtaining stimulus control is often necessary in operant research, stimuli commonly are specified imprecisely by color names (e.g., "red," yellow"), and the stimuli themselves may be produced by putting a plastic cap over a 28-V bulb. These caps vary widely, and the "green" key in one chamber may differ in wavelength from the "green" key in another chamber, even in the same laboratory. Here we demonstrate that stimuli defined in terms of simulated wavelength, whatever their limitations, are still serviceable for discriminative control.

Pigeons 363, 1108, 1156, and 4089 were studied in the touchscreen chambers outfitted as described in the previous test. Key pecking was maintained on a multiple schedule with a VI 30-s schedule of food reinforcement

Figure 6

Stimulus Generalization Gradients Produced by Simulated Wavelengths in Test D



Note. Percent of the total responses recorded in the presence of each tested stimulus (wavelength or simulated wavelength, in nm) in the generalization test using a transparent (filled symbols) or translucent (unfilled symbols) screen protector. The bottom center panel shows the mean percent averaged across pigeons in Test D, and the bottom-right panel shows results from Guttman & Kalish (1956). The vertical line marks the position of the training stimulus, 550 nm.

(4-s access) in one component and extinction (EXT) in the other. In each session, the components alternated every 5 min until each was presented five times. As shown in Table 2, different simulated wavelengths accompanied the VI and EXT components; the wavelengths were selected from the range used in the previous test of stimulus generalization. Sessions continued until there was clear discriminative control by the stimuli correlated with the VI component (S+ stimulus) and EXT component (S-). Discrimination ratios were calculated for each session by dividing the response rate in the presence of S+ by the sum of the response rates in S+ and S-, and multiplying by 100. Each pigeon's training ended when the discrimination ratio was 90 or higher for five consecutive sessions. As shown in Table 2, this outcome was achieved in nine to 23 sessions, depending on the pigeon. This finding addressed another potential complication related to the color stimuli presented by the touchscreen: It is possible that changes to the viewing angle may change perception of the colors presented by the touchscreen. Although we could not control the pigeons' viewing angle, we were successful in training the pigeons to distinguish between two colors on the touchscreen. Future research may seek to investigate the boundaries of the stimulus discrimination, but clearly, responding can be brought under stimulus control by simulated wavelengths on the touchscreen.

Table 2

Simulated Wavelengths Used for S+ and S- for Each Pigeon in Test E

Pigeon	S+	S-	Sessions	Rate in S+	Rate in S-	Discrimination Ratio
363	490	610	12	34	0.2	100
1108	550	610	23	133	9.0	94
1156	550	490	21	84	1.2	99
4089	490	550	9	52	2.8	95

Note. Wavelengths are shown in nm. Also shown are the number of sessions required to complete discrimination training, response rates (pecks per minute) in the presence of S+ and S-, and discrimination ratios in the final session for each pigeon.

Test F: Discriminative Control with Geometric Stimuli

An obvious advantage of touchscreen keys over conventional keys is the virtually unlimited variety of stimuli that may be displayed on touchscreen keys. Here we report evidence of discriminative control by geometric stimuli.

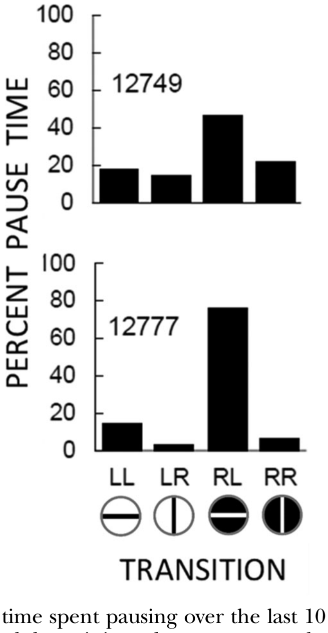
The subjects were two pigeons, 12749 and 12777, that had acquired key pecking through the training described below in Test G. They were studied in touchscreen chambers outfitted as described in Tests D and E as they responded on a multiple schedule in which completing an FR was reinforced with either brief access to food pellets (1.5 s in the "lean" component) or longer access (5.5 s in the "rich" component). The lower center key was used, and the FR requirement was the same in both components. The rich and lean components alternated in an irregular order to create 40 transitions between components, 10 of each possible type: lean–lean, lean–rich, rich–lean, and rich–rich. In this arrangement, a pause in responding is generated in the transitions, with relatively long pauses in the rich–lean transition and relatively brief pauses in the others (e.g., Perone & Courtney, 1992). During a series of preliminary sessions, the lean and rich components were correlated with key colors and two parameters were manipulated until extended pauses were observed reliably in the rich–lean transition: (a) the FR in both components was raised in steps of five or 10 responses and (b) the reinforcer durations for the rich and lean components were raised or lowered.

When the terminal parameters were reached, each of the four types of transition was accompanied by a unique geometric stimulus, as follows: lean–lean: a black horizontal line on a white key; lean–rich: a black vertical line on a white key; rich–lean: a white horizontal line on a black key; and rich–rich: a white vertical line on a black key (cf. Retzlaff et al., 2017). Training was continued for a minimum of 20 sessions and until pausing in each of the four transitions was judged stable by visual inspection over 10 consecutive sessions.

Figure 7 shows how the time spent pausing was distributed across the four transitions during the 10 stable sessions. Pausing was disproportionately high in the rich–lean transition, a

Figure 7

Pausing in Transitions between Multiple-Schedule Components in Test F



Note. Of the time spent pausing over the last 10 sessions of multiple-schedule training, the percentage that occurred in the lean–lean (LL), lean–rich (LR), rich–lean (RL), and rich–rich (RR) transitions between components. Also shown are the four stimuli that accompanied the transitions.

result that is possible only if the pigeons discriminate the worsening conditions represented by this transition. As Perone and Courtney (1992) demonstrated, if discriminative stimuli are removed from the procedure—the key is white in every transition—the extended pausing in the rich–lean transition disappears. Unsurprisingly, geometric stimuli produced by the touchscreen can function as discriminative stimuli.

Test G: Autoshaping when the Key has a Physical Border

We began our evaluation of the touchscreen with an autoshaping procedure that yielded disappointing results in terms of both the acquisition and accuracy of key pecking. We later learned that adding a physical border to the key increases accuracy to a level comparable to that obtained in chambers with conventional plastic keys. Here we report the results of a second autoshaping test, conducted this time with the faceplate on the touchscreen to create borders for the keys.

Eight experimentally naive pigeons (Pigeons 9202, 12749, 12777, 12890, 12894, 12903, 15327, and 15390) served as subjects. The procedure was identical to our initial autoshaping study (Test A), except that the key was yellow and sessions ended after 80 food deliveries. The pigeons were exposed to up to two sessions of autoshaping, followed by one session in which 40 reinforcers could be earned on an FR 1 schedule.

As before, autoshaping was considered complete when the pigeon pecked the key on 10 consecutive trials. This criterion was met during the first session in 32, 64, 65, 71, and 75 trials by Pigeons 9202, 12749, 12894, 15327, and 12890, respectively. After the other three pigeons failed to meet the criterion by the end of the second session, they were exposed to the FR 1 schedule. The 40 ratios were completed in 9 min, 3 min, and 17 min by Pigeons 12777, 12903, and 15390, respectively.

At first blush, it may appear that our apparatus produces unreliable outcomes with an autoshaping procedures: In our two evaluations (Test A and Test G), only 6 of 11 pigeons met the acquisition criterion—a success rate of 55%. Using the same procedure with a conventional chamber, Brown and Jenkins (1968) reported the acquisition of key pecking with 100% of their 36 pigeons. The difference in success rates may come not from using different kinds of response technology, but rather from differences in the definition of success. Our criterion was a key peck on 10 consecutive autoshaping trials. Brown and Jenkins's criterion was a single key peck within 160 trials. They reported that the first peck occurred, on average, in the 45^{th} trial, with a range across pigeons from 6 to 119. Applying Brown and Jenkins's criterion to our 11 pigeons in Tests A and G, we find that nine pigeons pecked the key within 160 trials (82%). Among these nine pigeons, the first peck occurred, on average, in the 47^{th} trial, with a range of 11 to 89 trials. We judge the outcomes in our touchscreen chambers to be acceptably similar to Brown and Jenkins's results. And it should be noted that, autoshaping aside, all of our pigeons acquired key pecking when exposed to an FR 1 schedule.

Conclusions

We tested a touchscreen apparatus for pigeons with autoshaping and stimulus generalization procedures as well as FR, VI, and multiple schedules (VI-EXT and FR-FR). Until we placed a physical border around each virtual key, a substantial proportion of pecks missed the key. With a border in place, the relative rate of off-key pecks was comparable to that obtained with conventional electromechanical response keys. Although we found that the touchscreen's pixels did not duplicate pure wavelengths of light, the pixels still can provide colors and geometric shapes that serve as effective discriminative stimuli.

In free-operant research with pigeons, touchscreen technology is a practical alternative to conventional pigeon keys for both presenting stimuli and recording responses. The primary benefit is the flexibility afforded by the touchscreen itself: Because it is driven by software, it allows the experimenter to present an almost unlimited variety of stimuli (geometric shapes and photographic images in addition to colors) as well as to change the number of keys and their spatial location. These benefits broaden the scope of research that can be accomplished without modifying the chamber's hardware.

Barriers to the adoption of touchscreen technology should be noted. First, because we are aware of no commercially available touchscreen apparatuses for pigeons, experimenters must build their own. This requires some competence in basic electronics, configuring computer hardware, and writing software for real-time process control. Unless existing electromechanical chambers are available for modification, the project requires either the money to buy the chambers and essential components (notably, the feeder), or the construction and design skills to build the chambers from scratch. We were fortunate to have basic electronic, hardware, and software skills and old chambers available for modification. As a consequence, we were able to build our chambers for about $500 each.

Our project was concerned with developing and assessing touchscreens for use with pigeons. We should note that touchscreen technology for use with rats and mice is growing in popularity (Dumont et al., 2021), to the extent that commercial versions are sold by Campden Instruments (https://campdeninstruments.com), Lafayette Instruments (https://lafayetteneuroscience.com), and Med Associates (https://www.med-associates.com). The technology is used primarily in assays of rodent cognition by neuroscientists, although some free-operant work can be found in the literature (e.g., an experiment involving progressive-ratio schedules by Hailwood et al., 2018). Our system could be readily adapted for use with rats; the principal changes would be lowering the placement of the touchscreen and changing the type of feeder. Although the variety of visual stimuli afforded by the touchscreen may be less important with rats than with pigeons, there are advantages of our system with regard to auditory stimuli, which are used often with rats. Because each chamber has a dedicated computer, an unlimited number of auditory stimuli can be produced using the computer's built-in audio circuits in conjunction with the media software resources provided by the Windows operating system. These resources can be tapped by programs written in Visual Basic and other high-level computer languages. Development of a rodent version of our system would be a logical extension of the present project.

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Appendix

List of components, functions, and prices (in USD as of 2017) of components used in the design.

Component	Function	Price per unit in 2017 (USD)
Single-Board Computer[a]	Computer to control equipment and record experimental events	150
Denkovi USB 4-Relay Output Module (JQC-3FC/3FC/T73 DC5V)	Interface between computer and Houselight, Clicker, and Feeder and Feederlight	19
ELO 7-in Resistive Touchscreen (0700 L)[b]	Touchscreen in chamber	250
28-v Feedback Relay	Clicker in chamber	15
8-ohm Speaker[c]	Speaker used for white noise in the chamber	7
Amplifier[c]	Amplifier used to amplify the sound delivered through the computer's audio port	
Miscellaneous Equipment		
Grafix Clear .005 Dura-Lar Film (P05DC0912)[d]	Transparent screen protector for touchscreen	7
Etched Glass window film (SKU: 010121)[d]	Translucent screen protector for touchscreen	21
General Purpose Adhesive Rubber 2 in x 36 in, 0.125 in thick, 50A Durometer (33-P005-125-002-036)[d]	Rubber key border for touchscreen	12
12-gang Screw Terminal	Screw terminal in chamber	8
Trendnet USB VGA male–male 15 ft cable	Cable to connect computer to switchboard	18
Ankler 4-Port USB 3.0 Hub[e]	USB Hub to connect switchboard to mouse and keyboard in control room	10
Trendnet KVM Switchboard (TK-803R)[f]	Switchboard in control room to switch focus of monitor, mouse, and keyboard	120
Total for four-chamber setup:		**2038**

Note. [a]We used two kinds of single-board computers during our evaluation. In the initial setup, we used a Tronsmart computer (Model: Ara X5). When we assembled our set of four chambers, we used Minis Forum computers (Model: Z83-F). Although we used single-board computers, the present setup could be operated by any computer operating Windows 10. [b]ELO now makes a new version of the monitor used in the present study (0700 L). At the time this was written ELO vendors still carry the 0700 L; however it is possible that this model will be unavailable in the future. Although we used the 0700 L, any resistive touchscreen monitor or infrared touchframe could be used to detect pigeon responses in its place. [c]We used computer speakers that had been donated to the laboratory or purchased inexpensively. The 8-ohm speaker and amplifier built into the computer speaker were removed from the casing and added to the chamber. [d]These items were purchased once and provided enough materials to outfit four chambers. [e]In our initial configuration, this hub was needed in on top of each chamber in combination with the Tronsmart computer to provide the USB ports required to operate a mouse and keyboard in the control room. When the KVM switchboard was used in combination with the Minis Forum computers, only one hub was needed in the control room for the mouse and keyboard. [f]The KVM switch was used for connecting several chambers to one computer monitor, mouse, and keyboard in the control room. This model could connect up to eight chambers.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website.