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Recent advances in operant conditioning technology: A versatile and affordable computerized touchscreen system

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We report the construction of a new operant chamber that incorporates modern computer, touchscreen, and display technologies. An LCD display was housed in the front wall of a lightweight Plexiglas chamber. An Apple eMac computer was used to present visual stimuli on the monitor and to control other chamber events. Responses to the stimuli were recorded using a transparent resistive-type touchscreen that overlaid the monitor. The resulting system is simple and inexpensive to construct but powerful and flexible enough to explore a broad range of issues in animal learning and behavior.

Researchers investigating instrumental or operant conditioning in animals have constructed a wide variety of experimental equipment to arrange consequences for responding in controlled laboratory environments. Operant conditioning chambers, or "Skinner boxes," were devised so that experimenters could repeatedly deliver reinforcers following behavior without having to handle the animal trial after trial. An animal can activate one or more response devices inside the chamber, and the researcher can present reinforcement (e.g., food) or punishment (e.g., shock) to the animal inside the box, contingent on the response being made. The operant chamber has also been used to explore a broad range of issues in the stimulus control of behavior with what are called *discriminated operants*. Here, different discriminative stimuli, such as two differently colored pecking keys displaying white lines of two different orientations, are presented, and the animal is required to respond differently depending on the stimuli. These kinds of visual stimuli have been effectively used to examine such issues as associative competition (Reynolds, 1961), peak shift (Purtle, 1973), and memory (Blough, 1959) in animals.

Although researchers investigating instrumental learning continue to rely heavily on the "traditional" Skinner box for experimentation, improvements in a number of technologies have considerably broadened the types of studies that can be conducted with the operant chamber. As well, over the past 3 decades, the nature of the stimulus information that experimenters have presented to animals in the operant chamber has become increasingly complex, due to advances in technology and to the expanding of researchers' interests to include issues related to animal perception and cognition (Fetterman, 1996; Wasserman, 1993).

So, although traditional operant chambers continue to be useful, the stimulus information that is presented and the responses that are required of animals are becoming increasingly complex. Researchers of today and tomorrow will need a tool that is (1) powerful enough to probe sensitively into the perceptual and cognitive processes of animals, (2) inexpensive, so that many scientists can use the device, (3) flexible, so that it can be used to investigate a large variety of perceptual and cognitive issues, and (4) easy to construct and to use. Here, we report recent work whose aim was to develop an operant chamber that meets these criteria and that incorporates recent advances in computer technology. We hope that this report might be helpful both to beginning researchers in animal learning and behavior, who may be establishing an operant laboratory, and to more established researchers contemplating an update of their current operant technology.

Overview

The operant system consisted of five Apple eMac computers and four operant chambers, along with supporting hardware and software. Four of the eMac computers independently controlled the experimental sessions in each of the four operant chambers (Figure 1). The fifth eMac served as the hub of communication among the four eMac computers and their corresponding operant chambers (see the Base Computer section below).

Chamber Hardware

The operant chambers were constructed in the machine shop in the Department of Psychology at the University of

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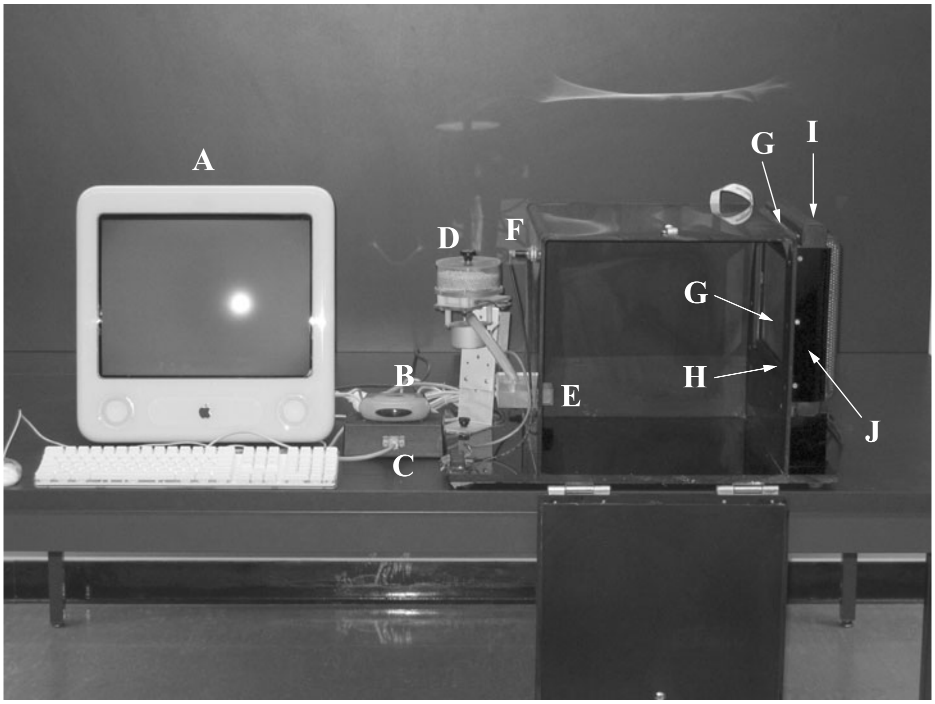

Figure 1. Photograph showing the eMac computer that controls each box, the corresponding operant chamber, and supporting peripheral devices. (A) Apple eMac computer, mouse, and keyboard, (B) Belkin serial to USB adapter, (C) interface, (D) feeder, (E) food cup, (F) chamber light, (G) touchscreen, (H) frame, (I) monitor, and (J) track for monitor. Note that the stainless steel floor pan has been removed in this picture.

Iowa (Judson S. Brown Psychology Instrumentation Shop). Each chamber was 36 (h) × 36 (l) × 41 (w) cm in size and was built from 0.25-in. black opaque Plexiglas. Plexiglas has decided advantages over other construction materials: (1) It can be easily heated, bent, and tapped for screws, (2) it is durable and easy to clean, and (3) it is inexpensive. Another advantage of Plexiglas is that the resulting chamber is very light; even with the monitor in place (see below), the apparatus can be carried by a single person.

The roof, front, and rear wall of the operant chamber (Figure 1) were constructed from a single piece of Plexiglas that was heated and then bent in two locations. This piece then was attached to the base (a single piece of 1-in. black opaque Plexiglas). The two sidewalls of the chamber, one of which was a door, were constructed from two separate pieces of Plexiglas. The bottom of the door was hinged to the base of the apparatus, and the top of the door opened outward. All of the interior surfaces of the chamber were lightly sanded to reduce glare from the lighting inside the chamber. A square stainless steel pan with a removable stainless steel mesh top served as the floor of the chamber. The stainless steel mesh is strong enough to support an animal during the experiment, and any droppings fall though the wire mesh panel and into the pan.

Feeding System

A Plexiglas food cup was located near the base of the rear wall of the chamber (Figure 1). We attached a 45-mg pellet feeder (MedAssociates, Georgia, VT, Model ENV-203IR) to the box for the delivery of food into the cup. The model of feeder we purchased had an infrared detector that senses whether a pellet has blocked the feeder from rotating (i.e., feeder jam) and cycles up to eight times in search of a free slot at which a pellet can be delivered; this infrared technology added less than $50 to the price of each pellet feeder. A 5-V houselight was also attached to the rear wall of the chamber to provide ambient illumination of the interior of the chamber.

Chamber Monitor and Display Hardware

A 28.5 × 18.5 cm opening (Figure 1) was cut in the front wall of the chamber and was suitable for viewing most of the display area of a 15-in. LCD flat screen monitor (NEC, Melville, NY, Model 1550V). This monitor offered good resolution (1,024 × 768 pixels), viewing angle (45º top–bottom, 60º left–right), and contrast (to the human eye) for a model of its modest price. Three pairs of vertical nylon *tracks* were mounted on the exterior of the front wall of the chamber on either side of the opening. The tracks held the monitor and corresponding hardware firmly in place. Each U-shaped track had a central groove in which the monitor (or other hardware) could be placed; each side of the track prevented the monitor from moving horizontally. The original base (stand) of the monitor was removed, and the sides of the monitor (see below) were positioned into the top of the track located farthest from the front wall of the chamber. The monitor then slid down the groove into its final resting spot, so that the bottom of the screen of the monitor corresponded with the bottom edge of the opening in the front wall. The track system allowed the screen to be precisely and securely positioned with respect to the touchscreen recording device (see below). The track also allowed the monitor to slide in and out from the top of the chamber for routine cleaning and maintenance.

Some advantages of the LCD monitor are that the screen emitted less heat into the operant chamber than do traditional CRT monitors and occupied far less space. In addition, the use of an LCD display may reduce concerns regarding flicker–fusion frequencies with some animals. Standard CRT displays present continually alternating interlaced lines of brightness information on a screen; odd lines are presented first, followed by even lines. Humans generally see the screen as "flickering" if the refresh rate of the lines is 30 Hz or less, but as being continuous if the cycling of the lines is above this threshold. The flicker–fusion frequencies of some species are notably higher than that of humans (Delius, Emmerton, Horster, Jager, & Ostheim, 2000), possibly leading to problems with animals' discriminating some types of images presented on video screens (see Lea & Dittrich, 2000, for a review). The refresh rates of LCD displays, in contrast, are normally twice as high as those of CRT displays (true for the current model), thereby reducing problems associated with the flicker–fusion thresholds of some species.

Although LCD displays have a number of advantages, they may have some disadvantages for some applications. The viewing angle of the monitor used in the present report was modest (45º top–bottom, 60º left–right). As the human eye moves outside of the viewing angle, the image becomes more distorted in terms of brightness, color, and contrast. Although the viewing angle reported for the monitor used here should be sufficient for most applications, other, more expensive monitors (a 30%–50% increase in cost) have better viewing angles (e.g., NEC Model LCD1550M-BK: 85º top–bottom, 85º left–right). In addition, the persistence of visual stimuli on some LCD displays with longer refresh rates could cause problems with the control of stimulus durations for some preparations. Clearly, all of these factors must be considered, and the choice of a screen may vary depending on the species and the application.

Touchscreen

We used a clear 15-in. AccuTouch resistive touchscreen (Figure 1) produced by EloTouch Systems (EloTouch Systems, Fremont, CA, Model 452981-000) to record responding (in our case, a pigeon's peck) of the animal inside the box. The touchscreen was placed in the middle of the three previously mentioned vertical tracks; this middle track held the touchscreen firmly between the face of the monitor and the opening in the chamber. Like the monitor, the touchscreen was inserted into and removed for cleaning and maintenance from the vertical track at the top of the box. The spacing between the screen of the monitor and the touchscreen was set at just 2 mm, to reduce the influence of image parallax from inside the chamber. A rectangular frame of black Plexiglas was placed in the third track and served to border the viewable area of the monitor and touchscreen. A sheet of mylar transparency material (Dick Blick Art Supply, Galesburg, IL, Model 55506-1305) was placed between the touchscreen and this frame to reduce the abrasive impact of pigeons' repeated pecking at the touchscreen; this sheet was replaced as necessary.

The resistive touchscreen reported here allows spatial resolutions of up to 0.62 mm (J. E. Ford, EloTouch technician, personal communication, July 1, 2003). EloTouch Systems provides software that allows the user to calibrate the coordinates of the touchscreen with the coordinates of the monitor. The calibration in the system reported here was conducted on the screen inside the operant chamber. Circular "targets" were displayed on the monitor, and the user was required to "touch" the center of each of the targets. Localization of the targets can be difficult in space-limited chambers and can lead to inaccuracies in calibration. So we constructed a template or panel that overlaid the face of the touchscreen after it was placed into the third track (the frame was removed during this calibration procedure). Small holes in the panel were precisely positioned with the center of each of the calibration targets presented on the monitor. The user then inserted a small stylus into the hole over each target, thus activating the screen. The calibrating program matched the screen coordinates with the touchscreen coordinates, producing nearly perfect (within 1–2 pixels) and reproducible calibration.

The Accutouch touchscreen is composed of a pane of glass with "5-wire" resistive touch-sensitive technology imbedded into the pane. When a response (e.g., a touch or a peck) is made to the screen, it pushes an exterior touch membrane against a resistive coating on the glass panel, making electrical contact. Only 3–4 oz of force is required for the outer membrane to make contact with the inner membrane of the screen (J. E. Ford, EloTouch technician, personal communication, July 1, 2003). One advantage of the 5-wire technology is that the x and y location of the resistance (e.g., response location) is recorded only when the outer and the inner membranes make contact. With other touchscreen technologies, the x- and y-coordinates are recorded separately as electrical gradients in the inner and the outer membranes of the screen, respectively. Partial depressions or wear to the outer layer of these systems can lead to irregularities in the electrical gradients used to establish the response location.

Although older versions of the 5-wire touchscreens have provided accurate coordinate data over 8 years of operation in our laboratory, we conducted two sets of tests to determine the accuracy of the coordinate data obtained for the newer touchscreens described here. For the first set of these tests, a human experimenter delivered 600 responses with a stylus (7-mm diameter) to a single blue circular target (5-mm diameter) that appeared on the computer monitor. The experimenter was trained to make responses to the target that were (1) too light to register by the touchscreen, (2) light, but with enough force to be registered by the touchscreen, and (3) hard, in which the impact of the stylus with the screen made a loud noise. The experimenter made 200 responses of each magnitude. Not surprisingly, 0 out of the 200 subthreshold responses were detected by the touchscreen, and no coordinate information was indicated by the system for these responses. Likewise, 100% of the light responses and 100% of the hard responses were reported as falling within 0.5 cm of the focal point of the target on the screen.

Five adult pigeons, which had previously participated in a variety of experiments requiring responses to stimuli that appeared on the computer screen, were also used for a second series of similar touchscreen tests. The pigeons were maintained at 85% of their free-feeding weights, using controlled feedings of mixed grain. Prior to the start of a session, a pigeon was placed into the operant chamber. A black Plexiglas panel that had a square opening (length = 1.5 cm) cut out in the center was positioned in front of the touchscreen and monitor by sliding the panel into the third of the three vertical tracks (thereby replacing the frame; see above). During each trial of the session, a blue square (length = 1.5 cm) appeared in the center of the LCD monitor, which could be seen through the hole in the Plexiglas panel. A single peck to the blue square by the pigeon (over any portion of its area) resulted in the stimulus's being cleared from the screen and the delivery of a food pellet into the cup located in the rear of the chamber. The stimulus then reappeared on the screen in the same location for the start of the next trial. Each session comprised 150 trials, and each pigeon encountered three such sessions (for a total of 450 trials). The Plexiglas panel ensured that the birds' responses to the blue stimulus fell within the perimeter of a 1.5-cm square around the center of the touchscreen. The resulting Cartesian data provided by the touchscreen for each peck (450 for each bird) were then examined to see whether the *x–y* values were aligned with the coordinates that defined the position of the stimulus on the LCD display—that is, whether the *x–y* values provided by the touchscreen for each peck fell within the coordinates that defined the perimeter of the opening in the panel and the stimulus on the monitor. Notably, 2,250 out of 2,250 responses recorded by the touchscreen fell within the perimeter of the coordinates that defined the blue square being displayed on the monitor. Combined, our past experience with the 5-wire touchscreens and the results from the touchscreen tests with humans and pigeons reported here indicate that the 5-wire resistive touchscreens provide accurate and reliable response coordinate data under a variety of testing conditions.

Chamber Computers

The houselight, feeder, touchscreen, monitor, and trial events for each chamber were controlled by a single eMac computer (Figure 1). The eMac (Model Z083) that we purchased on line from the AppleStore (www.apple.com) was outfitted with a 700-MHz G4 processor, 128 MB of RAM, a CD-RW drive, a 17-in. display, a keyboard, a mouse, and a 40-GB hard drive as standard equipment. We added 256 MB of memory, so that each unit contained a total of 384 MB of RAM. The purchase price of each computer with the modifications was $928 (Apple educational price). In general, we have found the new eMacs to be extremely powerful computers, and they have been able to handle all of our computational and programming needs.

One advantage of the operant system described here is that the stimuli presented to the animal in the chamber can be simultaneously viewed by the experimenter on the screen of the controlling eMac, using dual-screen technology. Hence, the experimenter can monitor "on line" the animal's interaction with the actual stimuli. The sharing of stimulus information does not necessarily occur both ways, however, since the experimenter can also view trial and session data on the screen of the eMac that are not presented to the animal in the chamber because of the panel in front of the pigeon's screen. In addition to observing the trials as they occur on the screen of the eMac, the experimenter can also use the mouse to respond to stimuli that the animal observes in the chamber; that is, the experimenter can make responses to the stimuli that the pigeon sees in the box. This feature of the operant system is particularly helpful during shaping and preliminary training when the animals are not responding reliably.

Chamber Interface and Peripheral Devices

Each eMac chamber computer has five USB, two Firewire 400, and one auxiliary monitor port, which allow for several connections with peripheral devices. The LCD monitor in the chamber was connected to the auxiliary monitor port on the eMac, using a special VGA to USB adapter made by Apple (Model M8639G/A). The touchscreen and computer communicated with each other through a touchscreen controller card (EloTouch Systems, Model 608244-000) manufactured by EloTouch Systems. We attached the touchscreen controller card externally to the wall that was opposite the door of the operant chamber. The touchscreen was connected to the touchscreen controller card, using a special cable attached (during manufacturing) to the touchscreen. The touchscreen controller card was connected to the first of the five USB ports on the chamber computer with a separate USB cable. The software driver that supported the controller card and the touchscreen was supplied by EloTouch and was installed on the hard drive of the computer controlling each chamber.

The chamber computer controlled the feeder and chamber light, using a separate interface (Figures 1 and 2). The output from the computer to the interface made use of a 9-pin serial cable. Because the eMacs do not have serial ports, a Belkin serial-to-USB converter (Belkin, Compton, CA, Model F5U103) served as an adapter between the interface and the chamber computer. The line from the USB adapter was connected using a USB cable to the second USB port on the eMac. The interface (Figure 2) first converted serial binary information sent from the computer to TTL logic, using a common microchip (MAX232). The TTL logic commands were then interpreted by a second programmable microchip (AT89C205I) and were used to drive either the chamber light alone (Bit 1), the feeder alone (Bit 2), or the chamber light and the feeder simultaneously (Bits 1 and 2). These binary commands are then sent to a third chip (ULN2003) that served as an additional buffer between the computer and the peripheral devices. The 5 V needed to drive the interface was regulated by a separate microchip (7805). The output lines from the interface were hardwired to the operant chamber components (light and feeder).

Base Computer

The components of the system described thus far constitute a complete operant chamber system. We also purchased a fifth eMac which served as the *base* for the other four computers; this fifth computer is the center of the wireless file sharing network for the four chambers. Each of the chamber computers is connected to a switch (EtherFast 10/100 5-Port Workgroup Switch, Model EZXS55W Version 3.0); the switch and the base computer were then connected to a Linksys 2.4-GHz wireless Ethernet bridge (Model Wet11). We used the combination of the switch and the bridge (rather than a completely wired connection) for this local network, since our base computer was located somewhat farther away from the four chamber computers. Other types of wired or wireless connections may be more desirable depending on specific work environments. During the course of a day, the four computers that control the operant boxes are constantly being used for "running" the experimental sessions in our laboratory. Hence, modifying programs, organizing the information on each of the individual computers, or transferring data

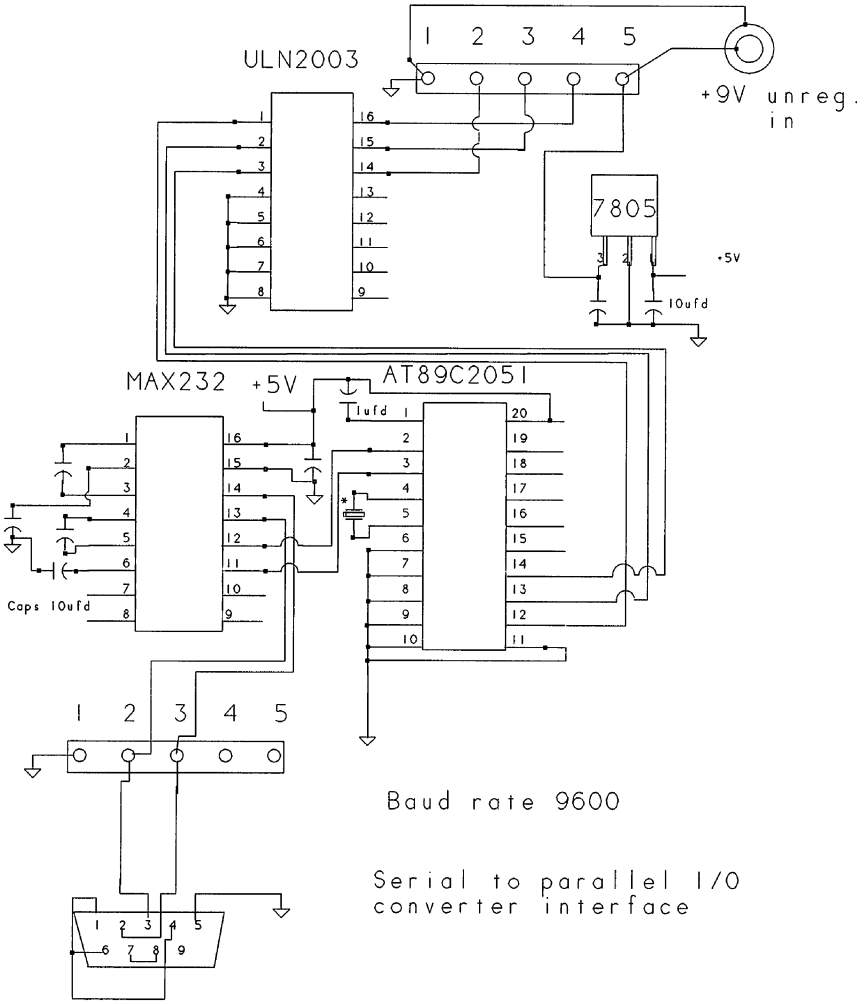

Figure 2. A schematic of the components in the interface (serial to parallel I/O converter) between the chamber computer and the feeder and chamber light. The name of each chip is located above each chip in the diagram. Each of the pins on the chip is numbered. The input lines from the serial port (9-pin port) on the Belkin USB to serial adapter are shown at the bottom of the diagram, whereas the three lines leaving the interface are shown at the top of the diagram (5-pin strip, Pins 2 to 4). Abbreviations and symbols: cap = capacitor = ⊥, GRD = ground = ⏚, μfd = micro farad, V = volts, and unreg = unregulated voltage.

to a storage device would be difficult without the fifth computer. The addition of the fifth computer was especially useful, because it can communicate and file share with the other four chamber computers across a local network while the chamber computers are running experimental programs.

One concern is that file sharing across the wireless network between the base computer and chamber computers could tax the network and delay events in the experimental chambers (e.g., time to reinforcement and duration of stimuli). To examine this possibility, we conducted a test of the operant system in which we measured the time it took the chamber computer to (1) present a 32K JPEG image on the computer screen from the hard drive of the computer and (2) flash the chamber light and deliver a food pellet (this measure included the latency for *both* events to occur) while a variety of different file sharing loads and other tasks were being conducted. Both of these measures were recorded by having the computer calculate how long it took it to pass through the part of the program code used to generate these events. A 32K JPEG image appeared on the LCD monitor in the chamber at the beginning of each trial of the test session. The experimenter then immediately touched the image, clearing it from the screen, resulting in the flashing of the chamber light and the delivery of a food pellet. After a 2-sec intertrial interval (ITI), the image then reappeared on the screen for the next trial. During each trial, the chamber computer recorded the time it took to display the image on the screen following the conclusion of the 2-sec ITI (stimulus onset interval), as well as the interval between the disappearance of the image and the appearance of the food pellets (pellet onset interval). Furthermore, these two measurements were recorded under seven different conditions in which: (1) file sharing was functioning between the base and the chamber computers but no additional demands were placed on the network (baseline condition), (2) file sharing between the base computer and the chamber computer was turned off, (3) a 1-MB file was being copied from the hard drive of the chamber computer to the hard drive of the base computer across the local file-sharing network by an assistant, (4) a 100-MB file was being copied over the network, (5) a 1-MB file was being copied from the hard drive of the chamber computer to an external hard drive (LaCie firewire 400 external hard drive, 20-GB drive: Model 300135) attached to the base computer, (6) a 100-MB file was being copied from the chamber computer to the same storage device, and finally, (7) an assistant was typing code into an unrelated Hypercard program located on the hard drive of the chamber computer, using the base computer and the file-sharing connection. Each condition entailed 20 tests (trials).

The time it took the computer to present the image and to deliver the food pellet for each of the seven conditions is displayed in Figure 3. In general, the pellet/light onset intervals (Figure 3, top) were longer than the stimulus onset intervals (Figure 3, bottom). The difference in time between these measures is likely due to the fact that turning on lights and delivering the food pellet required several lines of programming and communication with remote devices, whereas the image that was presented during each trial was stored on the hard drive of the chamber computer and could be displayed with a single line of code.

Transferring files from the hard drive of the chamber computer to the hard drive of the base computer or to an external hard drive (for either a 1- or a 100-MB file) tended to increase the stimulus onset interval (Figure 3, top: from 214 to 298 msec), as compared with when file sharing was on but no other demands were placed on the network (baseline condition = 95 msec). File transfer for any of the 1-MB, 100-MB, hard drive, or LaCie combinations (Figure 3, bottom: from 1,340 to 1,370 msec) did not appreciably delay the appearance of the food pellet, as compared with baseline (1,331 msec), however. Thus, although it took the computer longer to flash the lights and present the food pellet (a series of relatively nondemanding tasks), file transfer did appear to have a more dramatic effect on the time it took the computer to present the JEPG image. Notably, the image onset interval became longer as the size of the file being transferred increased: 214 msec for a 1-MB file being copied, as compared with 246 msec for a 100-MB file being copied under the same conditions (Figure 3, top). Likewise, it appeared that copying files from the chamber computer to an external hard drive (1 MB, 259 msec and 100 MB, 298 msec) extended the stimulus onset interval, as compared with when these same files were copied from the hard drive of the chamber computer to the hard drive of the base computer (1 MB, 214 msec and 100 MB, 246 msec, respectively).

Two final observations were that turning on file sharing alone (the baseline condition) had little effect on either the stimulus onset interval (95 msec) or the pellet onset interval (1,333 msec), as compared with when file sharing was turned off (88 and 1,318 msec, respectively). File sharing also had little effect on the chamber events when a user was modifying Hypercard programs on the chamber computer over the network.

The results of these tests suggest that enabling file sharing and transferring files can delay some events that occur in the operant chambers in our application. Although delays of a few hundred milliseconds are not large enough to cause concern for most applications (e.g., presenting an individual stimulus at the start of a trial), they could have an effect on behavior under other circumstances (e.g., stimulus–stimulus pairings). So the effects of file sharing should be evaluated for each application. Users concerned with this issue can also turn off file sharing during experimentation and turn it back on following the conclusion of testing.

Software

The programs used to control experimental sessions were stored on the hard drive of each eMac chamber computer. All of the programs and libraries used to generate the programs that run the experimental sessions are constructed using HyperCard, a programming language de-

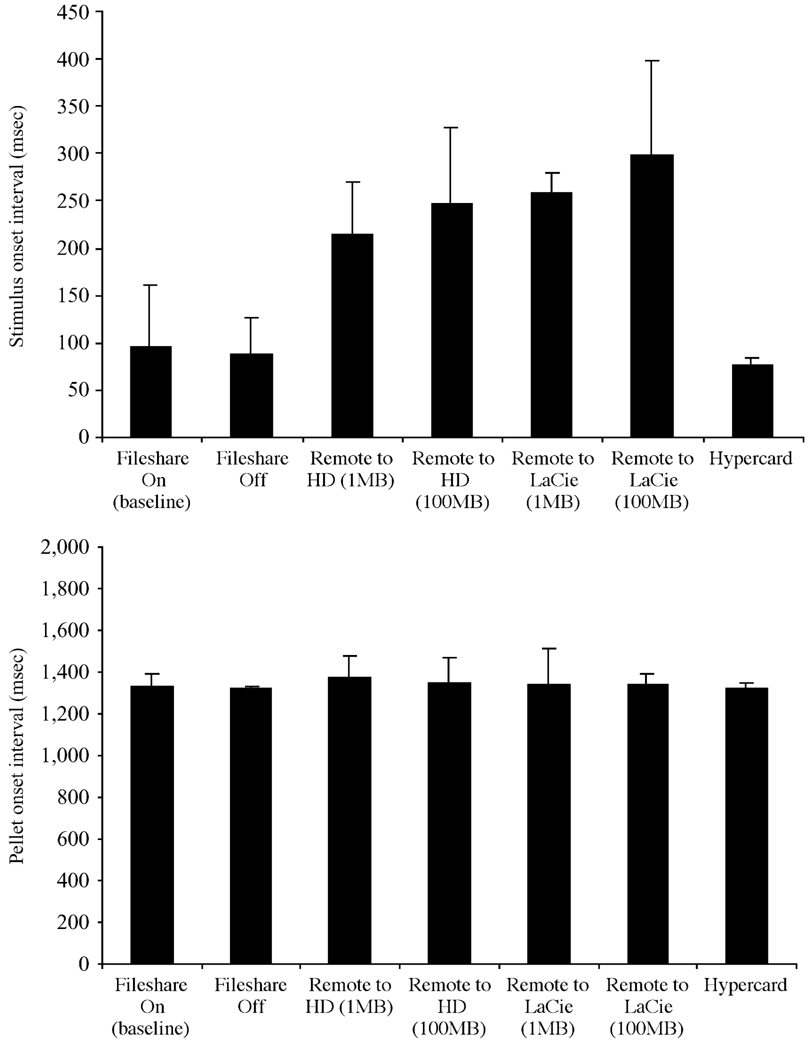

Figure 3. Stimulus onset intervals (top) and pellet/feeder light onset intervals (bottom) for each of the seven conditions (from left to right): file sharing on (baseline), file sharing off, transfer of a 1-MB file from the chamber computer to the base computer, transfer of a 100-MB file from the chamber computer to the base computer, transfer of a 1-MB file from the chamber computer to an external hard drive attached to the base computer, transfer of a 100-MB file from the chamber computer to an external hard drive attached to the base computer, and file sharing on and an assistant working with a Hypercard program on the chamber computer over the file sharing network. The label "Remote" in the figure refers to the chamber computer for these conditions.

veloped by Apple. A freeware copy of a HyperCard program called "Pigeon Tools," which is used to test the functions of the operant chamber (e.g., touchscreen, feeder) prior to each experimental session, is available on our laboratory Web site (http://www.psychology.uiowa.edu/Faculty/Wasserman/).

Each of the eMac computers is equipped with both OS 9.2 and OS X as operating systems. We use OS 9.2 as our operating system because it is most compatible with many of the older operant systems and programs that we use for experimentation. Although Apple will likely need to support OS 9.2 for educational purposes in the foreseeable future, we plan to shift to OS X, the newest Apple operating system. The fact that the eMac (or alternatively, the iBook, for researchers who would prefer a laptop-based system) is bootable in both operating systems should make this transition a relatively simple one. Because the computer and interface are currently compatible with OS X, this change should require an adjustment in the programming language that we use for program development (our Hypercard programs do not function in OS X or in the "Classic Mode" 9.X emulation mode while in OS X). One candidate may be Supercard (http://www.SuperCard.us/HyperCard/index.html), a programming

Table 1
List of the Components Used to Build Each Operant Chamber and the Corresponding Manufacturer (With Contact Information in the Final Column), Model Number, and Cost

Item	Company	Model	Price	Contact Information
Chamber computer	Apple	eMac (Z083)	$839.00	www.apple.com
Chamber LCD monitor	NEC	LCD 1550V	$269.00	www.nec.com
Monitor VGA adapter	Apple	M8639G/A	$17.10	www.apple.com
Chamber touchscreen	EloTouch	452981-000	$138.00	www.elotouch.com
Touchscreen controller card	EloTouch	608244-000	$138.00	www.elotouch.com
USB-serial adapter	Belkin	F5U103	$59.95	www.belkin.com
Pellet feeder	Med associates	ENV-203IR	$400.00	www.med-associates.com
Construction Costs			$300.00	
Total			$2,161.05	

Note— Construction costs include the Plexiglas, minor hardware (e.g., hinges), and labor required to make the chamber.

tool similar to HyperCard that is designed for OS X systems and that apparently can run older Hypercard programs. Future versions of our “Pigeons Tools” program that are based on Supercard will be placed on our Web site for common use.

System Price

As can be seen in Table 1, the hardware used for each individual operant chamber costs approximately $2,160. We believe that this represents a very modest price for this conditioning system. As an exercise, we did some “comparison shopping” with other prepackaged operant systems. Although these systems have the convenience of being put together and shipped to the researcher with relatively little assembly (some companies offer on-site installation and training), these system are at least two to three times more expensive than the system we developed, and they are generally less flexible and have fewer features (e.g., displaying stimulus information).

Conclusion

As we mentioned in the introduction, the operant chambers reported here were designed to meet a number of research needs: We wanted the new chambers (1) to be inexpensive, (2) to process information faster, (3) to be capable of presenting more complex stimulus information and to present stimulus information over a great area of a computer screen, and (4) to use LCD displays to reduce some possible problems with the CRT type displays. We believe that the operant system we have developed has met or exceeded each of these criteria. Each chamber can be constructed for approximately $2,000. This price is a considerable value, as compared with other prepackaged systems we investigated that are commercially available. The eMac computers we have used to control the events in the chambers are able to present complex stimulus information and to process large amounts of information very quickly. Indeed, we are currently displaying video clips in the chambers as stimulus information. Furthermore, although computer technology will advance over the next decade, we anticipate that these computers will remain powerful enough to answer interesting questions in behavioral research for many years to come. The use of large LCD displays also enables us to present and to record information across a large area in the chamber. In addition, the technology used to produce images on the LCD display may reduce concerns with flicker–fusion frequencies and may present stimuli that are more comparable to what an animal may see in its natural environment.

Finally, for a variety of historical and practical reasons, we have used the Apple platform for our operant chambers. Although much of the equipment we have described here has been based on the Apple platform, the operant chamber and its accompanying hardware could easily be made to work with a non-Apple–based system. For example, the touchscreen, operant chamber, LCD monitor, and feeder can all be used in conjunction with a PC. The use of a PC-based system might also reduce the total price of each chamber somewhat, because PC hardware is slightly less expensive in initial cost than Apple hardware.

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