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THE SKINNER BOX EVOLVING TO DETECT MOVEMENT AND VOCALIZATION

LA EVOLUCIÓN DE LA CAJA DE SKINNER PARA DETECTAR MOVIMIENTO Y VOCALIZACIÓN

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Abstract

A typical Skinner box has three essential features: discriminanda, an operandum, and a device for delivering reinforcers, usually a feeder. These features correspond to Skinner's three-term contingency consisting of a stimulus, a response, and a consequence. In a typical operant experiment, the operandum is used to measure a response topography that the animal emits easily and the baseline level of which is high enough to be conditioned as operant response, for example, lever pressing for rats and key pecking for pigeons. Because those responses can be detected using a microswitch, a human observer is not required to detect the response. However, the natural response repertoire of animals is not limited to such contact responses with the operandum. Many researchers have developed various automated experimental systems designed to detect responses other than contact responses with the operanda, for example, locomotion, turning responses, and vocalization. Recent technologies make it possible to detect responses such as these latter ones in

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real time without a human observer. The present paper provides a developmental history of how the components of the Skinner box have been modified to detect response topographies other than contact responding to a particular operandum.

Keywords: Skinner box, video-tracking system, vocal-recognition system, automated system

Resumen

Una caja de Skinner típica tiene tres características esenciales: discriminanda, un operandum y un dispositivo para entregar reforzadores, normalmente un comedero. Estas características corresponden a la contingencia de tres términos de Skinner que consiste en un estímulo, una respuesta y una consecuencia. En un experimento operante típico, el operandum se usa para medir una topografía de la respuesta que el animal emite fácilmente y la línea base de ésta que es lo suficientemente alta para condicionarse como respuesta operante, por ejemplo, presión a la palanca para ratas y picoteo a una tecla para palomas. Debido a que estas respuestas pueden detectarse usando un microinterruptor, no se necesita un observador humano para detectar la respuesta. Sin embargo, el repertorio natural de respuestas de los animales no se limita a tal contacto de las respuestas con el operandum. Muchos investigadores han desarrollado una variedad de sistemas automáticos experimentales diseñados para detectar respuestas diferentes de las respuestas de contacto con el operando, por ejemplo, locomoción, respuestas de voltear y vocalizaciones. Las tecnologías recientes han hecho posible detectar respuestas como las anteriores en tiempo real y sin un observador humano. El presente trabajo describe el desarrollo histórico de cómo los componentes de una caja de Skinner se han modificado para detectar topografías de las respuestas diferentes de las respuestas de contacto en un operandum particular.

Palabras clave: Caja de Skinner, sistemas de seguimiento en video, sistema de reconocimiento vocal, sistema automatizado

After B. F. Skinner's development of the operant chamber in the early twentieth century, the chamber (more colloquially called the Skinner box) has been used to investigate the behavioral effects of myriad three-term contingencies, allowing Skinner and his co-workers to discover general behavioral laws. A typical Skinner box has three components: a discriminandum, an operandum, and a feeder, defining the three-term contingency. Depending on the experimental purpose, those three components can be specialized or modified. The usual operant experiments contains an operandum to detect a response topography that the animal emits. This topography is easily emitted and the operant level is sufficiently high to allow the response to be conditioned as operant response. Examples are lever pressing for rats and key pecking for pigeons. Because those responses can be detected using a microswitch, they do not require a human observer to detect the response. In such experiments, the responses are arbitrary and the specific response topography is not so essential to the exploration of general laws of behavior. However, the natural response repertoire of animals in Skinner boxes is not limited to such contact responses to the operandum (for example, Falk, 1971; Manabe, Kuwata, Kurashige, Chino, & Ogawa, 1992; Reid, Vazquez, & Rico, 1985; Staddon & Simmelhag, 1971; Staddon, 1977; Wallace & Singer, 1976). Although many of those responses cannot be detected by using a conventional microswitch, the analysis of responses other than contact responses to the operandum is essential for fully understanding of many behavioral phenomena, such as the rate and temporal location of adjunctive and interim behavior in relation to the terminal response, as may be the case in behavioral contrast, superstitious behavior and schedule-induced behavior (Staddon, 1977).

Many researchers have developed various automated measurement systems in attempts to detect responses other than simple contact responses to the operandum, for example, locomotion, turning responses and vocalization. Recent technologies make it possible to detect such responses in real time in the absence of a human observer. The present review is of ways to detect, shape and reinforce in real time response topographies other than contact responding to an operandum. The first part is a review of studies that have developed alternative systems to a human observer's visual observation for measuring operant responses. This review is followed by a discussion of alternative systems for measuring responses topographies other than those associated with direct operandum contact.

Measuring Movements of Animals

Methods to Detect Position, Locomotion and Movement of Subjects

Several methods have been developed for the detection of position, locomotion and movement of subjects. Numerous types of detectors or sensors have been used, ranging from force sensors to Charge Coupled Devices (CCD). This section reviews various experimental systems that can be used to measure and reinforce locomotion and certain other movements of subjects in Skinner boxes.

Infrared devices.

The typical infrared (IR) beam system has a dense array of IR LEDs on one side and phototransistors on the other (Clarke, Smith, & Justesen, 1985; McLelland, Winkler, & Martin-Iverson, 2015). When an animal crosses one of the photo beams, its location can be identified by the phototransistors that are activated by the movement. If an additional array of pairs of IR LED and phototransistor is mounted at the animal's head level, rearing also can be detected as these phototransistors are activated by the rearing movement. This system can measure the staying time and distance traveled as well as the detection of the location and rearing of animals (Dietz, Wang, & Kabbaj, 2007; Gresack et al., 2010; Tang, Orchard, & Sanford, 2002; Zakharova, Leoni, Kichko, & Izenwasser, 2009). The system furthermore can be used to reinforce these movements.

Mechanical force sensors.

Force sensors have been used to detect both position and movement of animals in experimental chambers. Fowler et al. (2001) used a force plate actometer that had a force transducer at each of the four corners of the plate. The experimental cage was balanced on the four transducers. When an animal was at the center of the cage, the four forces detected by the four transducers was the same value. If an animal moved to the rear position, the force to the rear transducers increased and that to the front transducers fell proportionally to the distance involved. The location of the center of applied force, defining the animal's location, can be estimated based on the four forces at the support points. Fowler et al. (2001) demonstrated that the force-plate actometer can measure locomotion, spatial pattern of movements, whole-body tremor, and rotational behavior in rats.

When subjects engage in a certain activity, the activity makes a distinct vibration that can be detected by force transducers. Quinn et al. (2003) demonstrated the reliability of the LABORASTM system (Metris b.v., Hoofddorp, The Netherlands), which automatically classifies the vibration signals, created by the movement of rats, into several behavioral categories, such as feeding, drinking, rearing, climbing (see also Van de Weerd et al., 2001). The system consists of a triangular-shaped plate, two force transducers positioned orthogonally to one another, and a third, fixed, point attached to the bottom plate. This system thus can be used to reinforce several topographically different responses concurrently.

An alternative to the above detection system is to use low-cost vibration detectors using loudspeakers instead of high-cost transducers (Parreño, Sarazá, & Subero, 1985). Vibrations move a magnet in a coil of loudspeaker, so that the loudspeaker acts as a sensitive microphone.

Radio-frequency identifier (RFID) microchips.

Another tracking method for individual subjects involves the use of radio- frequency identifier (RFID) microchips (Dell'Omo, Shore, & Lipp, 1998; Le Calvez, Perron-Lepage, & Burnett, 2006; Rao & Edmondson, 1990). An RFID system consists of an RFID transponder and an RFID antenna. When the microchip is within the electromagnetic field produced by the antenna, the microchip produces the ID and the antenna detector reads the ID. Bains et al. (2016) placed a home-cage on an inconspicuous plate to which 18 RFID antennae were attached. The device then was used to tracked individual microchip-implanted mice. Bains et al. demonstrated that the system was adequate for measuring the circadian rhythms of individual mice in a small social group. In addition, they found that the inter-mouse space was larger during the active, dark, phase than during the light phase of the 24-hr cycle. Although the spatial resolution of the system is not high, the system might be used to automatically reinforce social interactions.

Electromagnetic-field analyzing systems.

Moving a magnet into a coil of wire produces an electric current that can be measured in volts. Niikura, Takahashi, Iino, Funatsu, and Matsuda (2017) implanted a strong and a weak magnet in either hind limb of individual rats. The rats were placed in a chamber surrounded by a 7000-turn circular wire coil. Because movements of a limb implanted with a strong magnet produces a large amplitude of voltage while the other side limb implanted with a weak magnet produces a small amplitude of voltage, the movements in each limb can be detected separately according to their amplitude. Niikura et al. could detect asymmetrical movements of uninjured and injured limbs that can provide an index of spontaneous pain-related behavior of animals. Although surgery to implant the magnet into the limb is an invasive procedure, this method could allow the reinforcement of a specific limb movement.

Microwave radar systems.

Vanuytven, Vermeire, and Niemegeers (1979) demonstrated that a microwave radar system developed by the Janssen Scientific Instruments (J.S.I.) Division could be used to detect motility changes as a function of drug dose (see also Marsden & King, 1979; Rose, Dell, & Love, 1985). Pasquali, Scannapieco, and Renzi (2006) also developed a microwave radar system for the monitoring of general locomotor activity in mice. An animal cage was positioned above an aluminum bulkhead on which a radar was positioned. A radar system produced a certain frequency of microwave to an experimental cage and the detector detected a Doppler signal from animal. The radar system was sensitive to a locomotion, but not to movement of only a part of the body. The system has the additional advantage of being able to detect movements of animals in the dark.

Motion detectors using capacity condensers.

Capacitance is changed when an animal passes between an antenna and a contact plate. Several studies used this antenna effect to detect animal locomotion and position using a series of metal plates (Clarke, Smith, & Justesen, 1992; Moraes, Ferrarezi, Mont'Alverne, & Garcia-Cairasco, 1997; Tarpy & Murcek, 1984). Moraes et al. (1997) measured locomotor activity of rats throughout a 6-day period using this detection system, which also could detect their circadian rhythms. One potential limitation of the system was noted by Clarke et al. (1992): short-circuiting occurred from urine and fecal contamination if the gap between the plates is not large enough.

Ultrasonic sensors.

Akaka and Houck (1980) developed an ultrasonic monitoring system that they used to monitor circadian rhythms of the octopus. This system produces an ultrasonic wave in a closed experimental chamber, and detects the reflection of the generated wave. If the animal does not move, the amplitude of reflection does not change. When the animal moves, the amplitude varies in proportion to the size of the animal, the movement velocity, and the direction of the movement. This system is useful for detecting the movement of animals in dark environments and also aquatic environments. Some animals, however, such as rodents and bats, can hear the ultrasonic sound, and this may disrupt their activity. In addition, comparisons of activity based on amplitude caused by the movement between different animals in body size are difficult (see Young, Young, Li, & Lin, 1996 as the later development)

Video tracking systems.

Since the 1970s, many real-time video tracking systems have been developed. These systems detect the locations and movements of objects based on an incoming video image. In the initial stage, specialized hardware was developed to track objects (Black, Whitney, & Gilbert, 1976). The most recent system, however, consists of only a personal computer and a web camera (Togasaki et al., 2005; Tort et al., 2006).

Many algorithms of tracking also have been developed (Yilmaz, Javed, & Shah, 2006). In a recent one, Barnard et al. (2016) developed a 3D-video recognition system that automatically categorize frequently observed temporal patterns of movement without any preset list of responses. One of the problems with video-tracking systems was their high cost; however, the cost recently has dropped dramatically because of the general availability of low-cost personal computers, such as Raspberry pi, and open-source software for visual recognition, such as Open Source Computer Vision Library (OpenCV).

Pear (1985) tracked White Carneau pigeons' spatiotemporal movements when key-peck responses were reinforced under variable-interval schedules. The pigeons' heads and necks were darkened with black shoe polish as a distinctive marker for detecting the centroid by the video tracking system (see also Pear & Eldridge, 1984). Pear found a regular spatiotemporal pattern between reinforcements that might develop into superstitious behavior. Pear, Silva, and Kincaid (1989) thereafter extended the tracking method from 2D to 3D analysis.

Methods for shaping and reinforcing specific locomotion or motion

Almost attempts to shape or reinforce a specific locomotion or motion of animals have been through using video systems. One of the first such attempts was a study that differentially reinforced pecking location of pigeons using a video tracking system (Hori & Watanabe, 1987). Pear and Legris (1987) shaped a response defined as lowering the head position to a virtual target 3-cm diameter sphere using an automated video tracking system (Pear, 1985; Pear & Eldridge, 1984).

Manabe (1992) automatically reinforced a key-pecking response and a turning response of pigeons concurrently using a vide tracking system. Pigeons wore a harness with two Ping-Pong balls on the top. One Ping-Pong ball was set at the pigeon's neck and the other was set at its tail (see Figure 1). A video camera connected to a video tracking system was located above the experimental chamber. The video tracking system calculated the pigeon's orientation based on two centroids made of the two Ping-Pong balls. When the angle of a subject's orientation changed from the area (0° through +45°) to the area (0° through -45°) through ±180°, or vice versa, the movement was counted as a turning. In Manabe's study, negative behavioral contrast was found with both key-pecking and turning responses. In addition, an avoidance response from a negative discriminative stimulus also was investigated. Pigeons turned away from the response key just after presentation of the negative discriminative stimulus on the key. The detection of such movement is difficult using detectors other than a video tacking system.

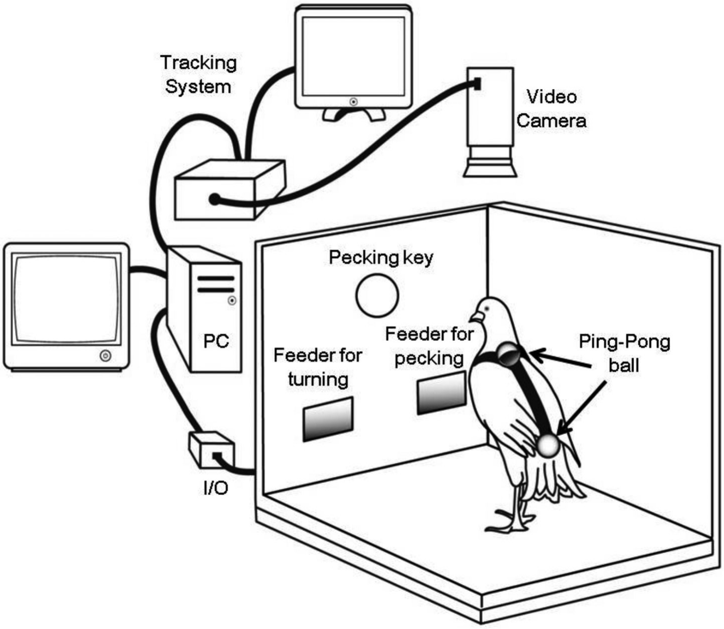

Figure 1. The behavioral tracking system. A video camera is connected to a video tracking system that calculate centroids (x, y coordinates) of two Ping-Pong balls on a neck and a tail. The values are sent to personal computer via RS-232C cable. The orientation of pigeon is calculated based on the coordinate values. (Adapted from Manabe, 1992)

Without a marker, Publicover, Hayes, Guerrero, and Hunter (2009) shaped a certain locomotion pattern of mice using a video tracking system. In fish experiments, especial when zebrafish have been used within the last decade, video tracking systems have become quite popular. Using such a system, correct choice responses of zebrafish were automatically reinforced in an appetitive conditioning procedure (Mueller & Neuhauss, 2012; Parker et al., 2013; Parker, Millington, Combe, & Brennan, 2012) and in an avoidance learning procedure (Aoki, Tsuboi, & Okamoto, 2015). With a similar system, crayfish also have been trained to avoid electric shock (Bhimani & Huber, 2016).

Measuring Vocal Responses of Animals

Methods for Detecting Animal Vocalizations

Skinner (1957) implied that animal vocalizations are instinctive, innate, and emotional responses, and so are not under control of the operant contingency. Ever since Skinner published *Verbal Behavior* in 1957, many researchers have been interested in whether animal vocalizations are sensitive to operant contingencies or not.

In the 1960s and 1970s, many studies examined the sensitivity of vocalizations to operant contingencies using various species, such as Budgerigars (Ginsburg, 1960), chicks (Lane & Shinkman, 1963), dogs (Salzinger & Waller, 1962), mynah birds (Hake & Mabry, 1979), cats (Molliver, 1963), monkeys (Aitken & Wilson Jr, 1979), dolphins (Lilly, 1965), and sea lions (Schusterman & Balliet, 1970).

Detection of vocalizations based on amplitude.

The first device used to reinforce animal vocalizations in an automated way was a voice-operated relay or a voice-activated switch that activates a relay when the amplitude of an auditory signal exceeds the predetermined threshold voltage. Because these devices have no vocal recognition function, noises made by animals could activate the switch. To reduce such false alarms, audio filters that eliminated low- and high-frequency noises were used. In addition, materials such as tough-skinned foam rubber and room-temperature vulcanizing rubber were used to reduce the noise generated by the animals (Hake & Mabry, 1979). However, it was impossible to completely eliminate all such noises (Myers, Horel, & Pennypacker, 1965).

Detection based on frequency.

Sound has three properties: amplitude, duration, and frequency. The ideal recognition system is a device that analyzes all three properties simultaneously in real time. On the one hand, amplitude and duration are easy to measure in real time. On the other, it is difficult to analyze the frequency of incoming auditory signals in real time. An established frequency analysis method is spectral analysis based on the Fast Fourier Transform (FFT). However, an analysis based on FFT requires extensive calculation. It was impossible to complete the calculation in real time until the late1980s, when digital signal processors (DSP), which are microprocessors specialized for digital signal processing, became available to general users. Before this time, an alternate fast- frequency analysis method for animal vocalizations was the zero-crossing method developed by Staddon, McGeorge, Bruce, and Klein (1978). A digital version of zero-crossing measures in each interval the time between successive two zero-crossing points from positive to negative in voltage waveform. The instantaneous frequency is converted from the reciprocal of the interval (Manabe, Staddon, & Cleaveland, 1997). Although the calculation is simple and quick to accomplish, it is impossible to detect high frequency with small amplitude components of sounds without a low-cut audio filter.

After A/D boards with the DSP chip were available to general users, it was possible to reinforce vocalizations of animals using real-time recognition algorithms based on FFT. The latest advancements in the processing speed of CPUs makes it possible to recognize animal vocalization without the DSP chip.

Methods to Shape and Reinforce Animal Vocalizations

The Budgerigar is the most studied species in automated vocal operant conditioning experiments. Manabe, Kawashima, and Staddon (1995) trained budgerigars to produce two different vocalizations, high-pitch- and low-pitch-calls, using a DSP board for vocalization recognition in real time. During shaping, the bird's call was induced by a play-back procedure in which a flock sound was played. When the subject called back in response to the sound, the call initially was manually reinforced by the experimenter and, later, automatically reinforced. After the birds produced the call in the absence of the play-back sound, the call was shaped into two distinct vocalizations, high- and low-pitch calls, using a changing-criterion procedure. In the changing-criterion procedure, peak-energy spectra with a Hamming window was calculated every 12.8 ms. When all six 12.8-ms initial peak-energy spectra fell within one of two target bandwidths, the sound was recognized as a "correct" call (see Figure 2). The high-pitch and low-pitch trials were conducted in a quasi-random sequence. In the initial phase, the two bandwidths were overlapped. Depending on subjects' performance, the overlap area was narrowed and the two target bandwidths were separated into two distinct ones in the last phase.

Another differentiation procedure, the N-back procedure, was used to shape different calls by an automated system (Manabe et al., 1997). This system reinforced calls only when 90% of all frequency distributions during a 213.3-ms period were between 1 and 6 kHz. In the next phase, calls different from the last reinforced call were reinforced (one-back condition). The difference was calculated in terms of the sum of the overlapping areas of frequency distributions of the two calls. When the sum was small enough, the two calls were recognized as different. The criterion for "different" was made progressively more stringent depending on the subject' performance. In the second and the third phases, calls different from the previous two or three calls were reinforced (two- and three-back conditions). With this automated vocal recognition system using N-back procedure, several different calls could be differentiated.

Once calls are under the control of food reinforcement, the calls can be controlled by visual and auditory stimuli (Cleaveland & Manabe, 2010; Manabe, 1997; Manabe & Dooling, 1997; Manabe, Dooling, & Brittan-Powell, 2008; Manabe et

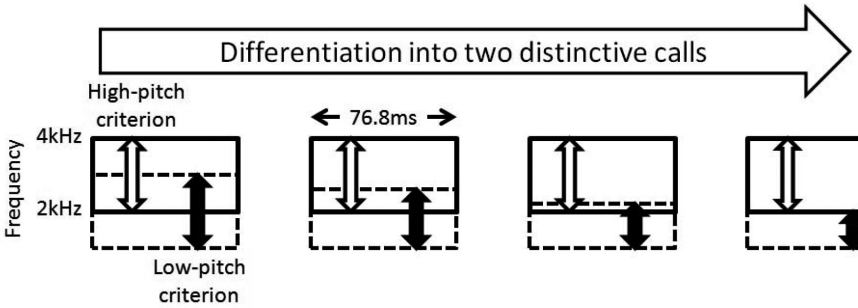

Figure 2. Changing criterion procedure that differentiates a call into two different calls. When all six 12.8-ms initial peak-energy spectra fell within one of two target bandwidth, the sound was recognized as a "correct" call. In the initial phase, the two bandwidths were overlapped. Depending on subjects' performance, the overlap area was narrowed and the two target bandwidths were separated into two distinctive ones in the last phase. (Adapted from Manabe, Kawashima, & Staddon, 1995)

al., 1995; Osmanski & Dooling, 2009; Seki & Dooling, 2016). Such automated systems make it possible to use vocalizations even as sample responses in matching-to-sample tasks (Manabe et al., 1995). In addition, effects of hearing deficits on vocalization can be assessed using this system (Dooling, Ryals, & Manabe, 1997; Osmanski & Dooling, 2009).

Vocal intensity also can be differentially reinforced using the automated system (Manabe, Sadr, & Dooling, 1998). Because the measure of call intensity is affected by the distance between the bird's beak and the microphone, a small audio FM transmitter with a microphone was attached to the bird's head with super glue, so that the bird could move freely in the test apparatus. The FM transmissions were monitored with a small FM radio, the output of which was sent directly to the DSP board in a personal computer (see Figure 3). In these experiments, budgerigars adjusted call intensity in a voluntary way and also increased call intensity when the environment was noisy, an example of the Lombard effect.

Conclusion

The very first box that Skinner developed was a narrow corridor supported in the middle on a fulcrum, much like a child's see-saw (Skinner, 1956). There was no obvious operandum, such as a lever or response key. The Skinner box detected the rat's movement around the corridor automatically as the ends of the corridor moved up and down based on the see-saw mechanism. Since the starting position

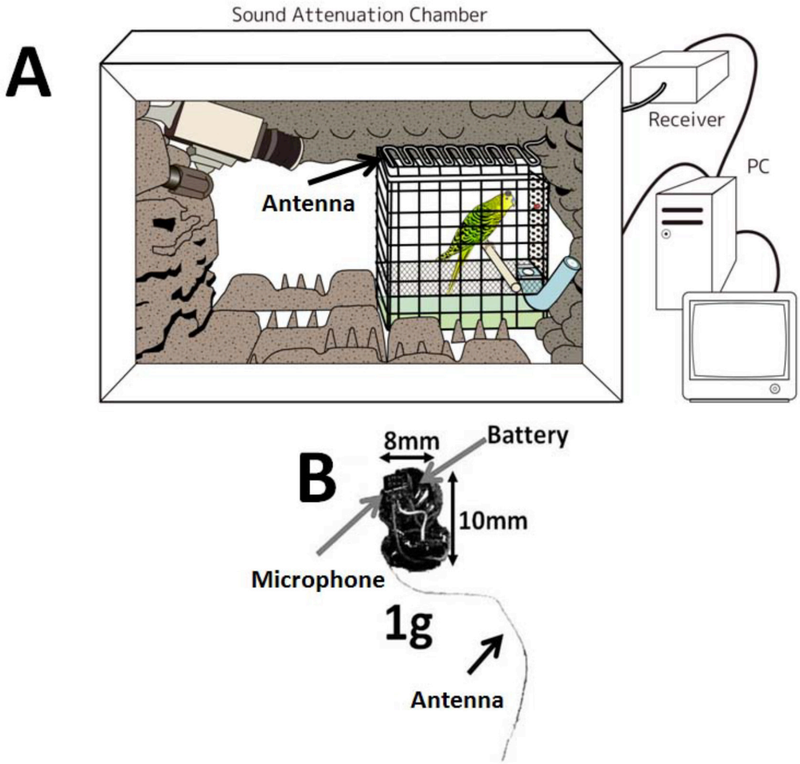

Figure 3. Vocal recognition system and a head-set for budgerigars A: Experimental chamber. A coil antenna is mounted just under the ceiling of the test cage. A DSP board is in the personal computer. B: FM Transmitter. The transmitter is consisted by a small microphone for hearing aide, a battery, a circuit and an antenna. The weight of the transmitter is about 1g. The transmitter was attached on bird's head by super glue. (Adapted from Manabe, Sadr, & Dooling, 1998)

and the goal position was the same, subject could start the response voluntary. The innovation made possible studies based on free operant. The next innovation in the evolution of the Skinner box was to introduce an operandum that defined the target of response. With this device, the response cost is much lower (as compared to ambulating back and forth across the corridor in the first version of the Skinner box) and counting of such discrete responses was easy, using a microswitch. In the contemporary innovations reviewed in this article, modern technology has been harnessed to allow the detection of animal activities without operanda, thus taking the evolution of the Skinner box to another level.

Many biomedical researchers who are interested in psychopharmacology or circadian rhythms seek valid and reliable ways to detect activity other than contact responses to operanda. In such studies, the technologies used range from microwave radar systems to video tracking systems. In operant studies, the important role of adjunctive and interim behaviors on terminal responses to operanda has become recognized. Video-tracking systems have been used that allow such adjunctive and interim behaviors to be inferred based on the measurement of the position of a body part or a certain movement. The low cost of and growing interest in fish as experimental subjects also have contributed to the popularity of using video tracking systems as a way of measuring operant behavior.

In early investigations of vocalizations of nonhuman animals, the interest was in whether or not such vocalizations could be controlled by their consequences, specifically reinforcement. In these early demonstrations, the voice-activated switch was used to detect animal vocalizations. Animals' vocalizations indeed were shown to be sensitive to operant contingencies. However, these switches could be activated by noise other than the animal's vocalization. Subsequently, the method for detecting animal vocalizations has shifted to digital signal processing based on FFT. Studies using real-time vocal recognition system have revealed both animals' capabilities of vocal modulation and the effects of hearing on animals' vocalizations.

The Skinner box continues to evolve using the latest technologies to allow investigation of many different types of three-term contingencies. Soon, even low-cost systems will have capabilities of detecting activities of animals in even greater detail. These technological advances will further advance the science of behavior that began with Skinner's first box, but which could not have been anticipated when that box consisted of only a single contact operandum, a feeder, and a stimulus generator.

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