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AN INEXPENSIVE METHOD TO STUDY RESPONSE VARIABILITY IN ACQUISITION AND EXTINCTION OF OPERANT BEHAVIOR

UN MÉTODO ECONÓMICO PARA ESTUDIAR VARIABILIDAD EN LA ADQUISICIÓN Y EXTINCIÓN DE LA CONDUCTA OPERANTE

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Abstract

To examine operant response variability in detail, a lever was attached to the Thumbstick of a videogame controller, which functions as a joystick. The controller was mounted outside of a standard rodent operant chamber with the lever extending into the chamber. Movement of the lever was restricted to a vertical downward distance of 2 cm. Food pellet delivery was used as reinforcement of lever movement. Criteria for reinforcement were that the lever should be held between two criteria distances, one from the top resting position of the lever and one from the end position of full movement, and the holding response should last a certain duration. Apparatus construction and development of algorithms for response detection and display in graph format as actograms are described in detail. The use of the equipment is illustrated with two demonstration experiments that examined response variability in extinction and during acquisition. The recording method allows for

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display of considerable detail regarding variability in real time with a resolution of 100 ms. For example, for Experiment 1, extinction of a relatively “simple” operant generated considerably new response forms with very little repetition of the form of the previously reinforced operant.

Keywords: Response variability, operant, joystick, acquisition, extinction, variation and selection, rats

Resumen

Para examinar en detalle la variabilidad de la respuesta operante, se añadió una palanca al Thumbstick de un control de videojuegos que funciona como un joystick. El control se montó fuera de una cámara operante estándar para roedores con la palanca extendida dentro de la cámara. El movimiento de la palanca se restringió a una distancia vertical hacia abajo de 2 cm. La entrega de pellets se usó como reforzador del movimiento de la palanca. Los criterios para el reforzamiento fueron que la palanca debía mantenerse entre dos distancias criterio, una desde la posición de reposo superior de la palanca y una desde la posición final del movimiento completo y la respuesta debía tener una cierta duración. Se describe en detalle la construcción del aparato, el desarrollo de algoritmos para la detección de respuestas y el análisis gráfico por medio de actogramas. El uso del equipo se ilustra con dos demostraciones de experimentos que examinan la variabilidad de la respuesta en extinción y durante la adquisición. El método de registro permite mostrar en tiempo real con una resolución de 100 ms considerable detalle relativo a la variabilidad. Por ejemplo, en el Experimento 1, la extinción de una operante relativamente “simple” generó considerables nuevas formas de la respuesta con muy poca repetición de la forma de la respuesta reforzada previamente.

Palabras clave: Variabilidad de la respuesta, operante, joystick, adquisición, extinción, variación y selección, ratas

The acquisition of operant behavior in nonhuman animals is customarily illustrated and studied with the lever press or key peck, characterized by their short duration (e.g., 50 - 200 ms) and clear onset and offset boundaries (defined usually by switch closure). Such responses can be acquired after very few reinforcements and are easily maintained with repeated reinforcement (e.g., Skinner, 1938). Skinner (1933) also demonstrated increases in response rate lasting a few minutes after a single reinforcement after emission of a single response, a finding that Skinner later referred to repeatedly as a fundamental feature of operant behavior (cf., Iversen, 1992, 2016). In clinical or educational application situations, operant response forms are not always of the same nature as key pecks and lever presses. Relevant responses that may extend in time and have vague boundaries, such as moving about in a room or engaging in arm or hand movements, are not ordinarily studied in the animal laboratory because of the difficulties involved in recording such responses reliably or automatically (see also Manabe, 2017, this issue). A main difference between short, clearly defined responses and longer responses with vaguely defined boundaries is that responses with clearly marked onset and offset, such as pressing a key, customarily provide tactile feedback to the subject in the form of resistance to the movement when the response is "on" or engaged all the way to switch closure, additional feedback may be in the form of auditory or visual feedback. Responses that extend in time with vague boundaries may not provide much feedback during execution other than their scheduled consequences at the end of the movement. A few cases of previous research have examined acquisition of response forms that extend in time such as the studies of response force by Notterman and Mintz (1965) and joystick movement by Scott and Platt (1985). These prior experiments established the techniques as viable methods to examine response variability. However, the very early acquisition of operant behavior, how the first few reinforcers modify the target response and create variability around the target response is understudied in the literature.

Variability in operant behavior has been studied extensively (e.g., Antonitis, 1951; Eckerman & Lanson, 1969; Iversen, 2002). Customary findings are that the topography of reinforced operant behavior becomes highly efficient with very self-similar topography (and location) from response to response (sometimes referred to as response stereotypy), and that the topography and location become highly variable when the operant is undergoing extinction. However, the role of response variation in acquisition is not well examined. How much variation has to happen before the target response is emitted repeatedly? Is variation necessary for acquisition? Is the variation only a result of extinction or temporary lack of reinforcement during acquisition? The method of shaping by successive approximations (e.g., Gleeson, 1991) is often used to establish response forms more complex than lever presses and key pecks or response forms that may in fact not exist in the subject's baseline prior to training. During such shaping sessions, the trainer often observes a tremendous amount of variability (e.g., Iversen, Ragnarsdottir, & Randrup, 1984) before the target response occurs reliably and in the desired form. Such

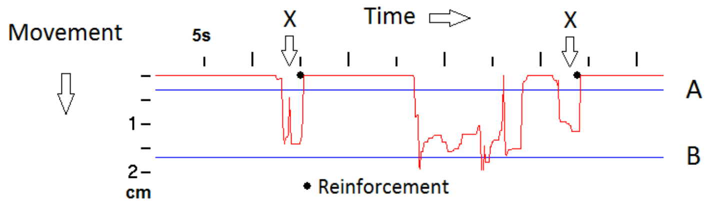


Figure 1. Example of actogram of lever movement in real time produced by a data file. The 50-s sample illustrates the lever movement from the resting position. Red curve shows lever movement. Blue horizontal lines A and B represent possible criteria for reinforcement regarding extent of the lever movement: 1) the required minimal movement (A) away from the resting position, and 2) the maximal movement allowed for the contingency (B), an additional requirement for reinforcement is the duration of the response (X) that satisfies the two criteria for movement. Thus, a reinforced response has to extend beyond the upper boundary at A but not extend beyond the lower boundary at B and should last Xs. Reinforcement is indicated by a black dot.

variability is rarely if ever recorded, and the role it plays in acquisition is not well understood and often not mentioned during coverage of shaping by successive approximation in influential graduate textbooks (e.g., Cooper, Heron, & Heward, 2007).

The purpose of developing the equipment described here was to establish a method by which one can easily record behavior in detail in real time in studies of acquisition and extinction. The behavior is a response that is very similar to a customary "lever press" except that the movement is extended beyond the usual few mm that a lever ordinarily has to be pressed to enable a switch closure. Rats are placed in a box with a lever that can be moved down up to 2 cm with very little resistance and force and without the use of switches for response recording. The movement is measured in detail by attaching the lever to a joystick that records lever position (downward distance from the top, resting position). The movement of the lever is tracked in 100-ms units and is presented in an online record displayed on the PC's monitor during experiments and stored in a data file for later analysis. Figure 1 shows a 50-s sample of such a display. Time moves from left to right. The red line shows the position of the lever relative to the resting location. Downward displacement of the lever moves the red line down in perfect synchrony with the lever movement. Thus, for the first 12 s the lever is at rest, then it is moved down rapidly by about 1.5 cm, then moved up again and then immediately down again and held there until reinforcement, indicated by the black dot, after which the lever is released immediately and returns to the resting position. The criteria for reinforcement can be defined by three parameters: 1) how far the lever should be from the resting position (upper criterion shown at A in Figure 1), 2) how far the lever should be from the full extension of 2 cm (lower criterion shown at B in Figure 1, and 3) how long the response should last inside the criterion window (X in Figure 1). The first response in Figure 1 illustrates a response that satisfies the three criteria (in this case down 0.25 cm from the top, up 0.25 cm from the bottom and lasting 2 s). The criterion was specified such that the lever position had to be within the upper and lower boundary to satisfy the duration requirement; if the response strayed outside the criterion, the duration timer was disabled and could only be restarted after a return of the lever to the resting position. An additional criterion was that a reinforced response should not previously have been outside the criterion windows in a continuous movement (see *Method* and *Results*). Thus, responses should be continuous and not interrupted by upward or downward movements of the lever to outside of the target criterion. The right-hand side of the record in Figure 1 shows a response that first goes beyond the lower bound (moved too far) and then is held within the criterion for nearly 10 s before being released to the resting position very briefly. Reinforcement was not delivered even though the response-duration requirement (i.e., 2 s here) was fulfilled. Then the lever is held within the criterion window, but slightly too short and is released without reinforcement. After a few seconds the lever is again held within the criterion window and this time also satisfies the duration requirement and is therefore reinforced. Thus, with these three criteria one can develop responses of a variety of forms and lengths. The record of the lever movement shows the form and extent of the reinforced response and variations of the reinforced response within the reinforcement criteria. In addition, the record shows variations of nonreinforced responses in time and space. Such variations cannot be displayed on customary cumulative records that display the position of the target response in time; variations of the response form, reinforced or unreinforced, do not appear on such cumulative records.

This demonstration of the use of the joystick method to record lever movement in detail was tried with two experimental setups. First, any short (0.6 s) lever movement within a wide criterion range of 10-190 (in 0.1 mm units) is reinforced each time it occurs. After a few sessions, the response is placed under extinction to examine the induced variability in response forms and durations. Second, response variability during acquisition was examined for a longer response of 2 s with a narrower criterion range of 50 – 150.

Method

Subjects

Five female Sprague Dawley albino rats, approximately 9 months old, were used. All rats were experimentally naïve before the experiment. The rats were maintained at 85% of their free-feeding body weights. Water was available in the individual home cages, and the colony was maintained on a 12:12 hr light/dark cycle.

Apparatus

Operant equipment. A Med Associates®, Inc., modular test chamber (ENV 008-VP) 30 cm wide, 24 cm deep, and 20 cm high was equipped with a 45-mg pellet feeder (ENV-203). One wall had a centrally located feeder opening that was 1.5 cm above the floor, 5 cm wide, 5 cm high, and 3 cm deep. Pellets were delivered to this opening from the back, and delivery was accompanied by a 200-ms "beep" from a Sonalert (Model SCG28). Levers that ordinarily are placed on the sides of the food tray, for the Med Associates equipment used, were removed for this experiment and replaced with flat panels.

Recording of lever movement. The lever was a 4-mm diameter steel rod attached to a modified videogame controller (PS3 Controller for Play Station 3, GameStop®, approximately $10-20, in 2015). The cap for the left Thumbstick on the controller was removed. A 4-mm hole was drilled in the plastic fixture under the Thumbstick. The steel rod was glued into this hole (See Figure 2, Frame A). A custom-made plexiglass panel, for insertion into the modular Med Associates® equipment, held the controller behind the panel with four screws and had a 6-mm wide and 1.5 mm long slit through which the lever extended into the experimental chamber (Figure 2, Frames B, C, and D). The slit restricted lever movement to only downwards movement. The lever was centered on the back wall and extended 6 cm into the chamber and was 6 cm above the floor at the resting position (Figure 2, Frame E). The lever could move 2 cm downwards. By means of a spring system built into the GameStop® unit used for recording (see below), the lever gently swung back to the resting, top position when released by the rat. The force necessary to operate the lever was .12 N as measured at the tip of the lever with a Dial Tension Gauge (Teclock Corporation, Japan). Frame F in Figure 2 shows the entire experimental setup with the GameStop® controller positioned outside the chamber on the left side, the lever extending into the chamber on the back wall, and the feeder opening on the right side.

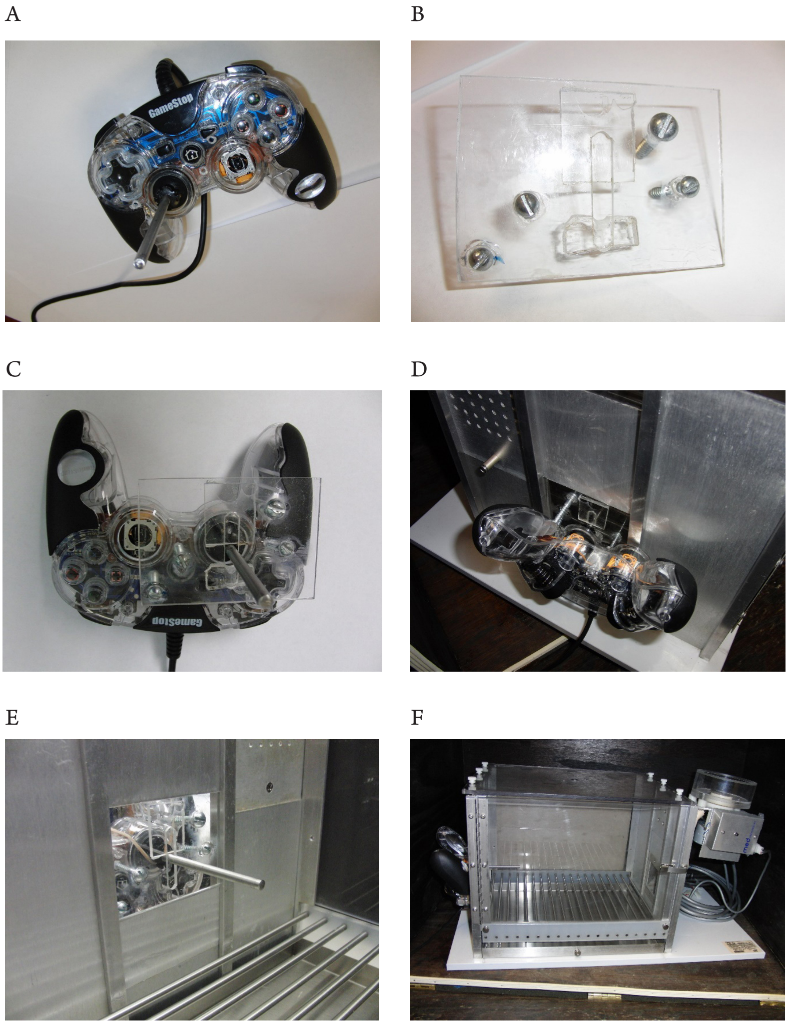


Figure 2. Photographs of the GameStop® unit with a steel rod attached to the left Thumbstick (A). This rod served as the operandum (lever). A piece of Plexiglas (B and C) was mounted on the front of the GameStop® unit with four screws and had a small slit that restricted the movement of the lever. The GameStop® unit was placed outside the Med Associates® experimental equipment (D). Frame E shows the lever extending into the experimental chamber. Downwards lever movement was a maximal 2 cm measured from the tip of the lever. Frame F shows the completed assembly with the GameStop® outside the chamber on the left side, the lever extending into the chamber, and the opening to the pellet feeder on the right side.

Response definition. The lever could be pushed down by 2 cm. This movement was recorded as distance from the top, resting position to the end position in 0 – 200, 0.1 mm units. For simplicity of exposition, the unit dimension is omitted in subsequent text. To count as a recorded response, the minimal requirement was that the movement should be at least 10 units from the top, resting position for at least one time unit (i.e., 100 ms). Responses can be divided into criterion and non-criterion responses. A criterion response is the target response reinforced by the program that controls the experimental flow. The three criteria for reinforcement are defined by the criterion window and the response duration. The response must pass the upper criterion, say 10 units, but not exceed the lower criterion, say 190 units, and last for X s (e.g., Figure 1). Noncriteria responses are those that count as a recorded response but then exceed the lower limit or briefly go back above the lower limit. For reinforcement, the last emitted response should be a criterion response. Appendix A describes simple algorithms for how the joystick input is converted to data for experimental control and analysis. Supplement 1 (see Appendix C) is a short video of a rat engaging the response lever followed by reinforcement.

A Dell Optiflex 980 PC computer controlled the experiment using a program written in LibertyBasic by the experimenter. Control of pellet delivery was accomplished using an ADU200 USB 4 Channel Relay I/O Interface from Ontrak Control Systems (www.ontrak.net). Input from the GameStop® controller was through the PC's USB port (see Appendix A).

Procedure

Experiment 1. The purpose of Experiment 1 was to establish a fairly "simple" response of engaging the lever for a short duration of 0.6 s and have a very wide criterion window of 10-190 units. Full movement where the lever stops due to the physical boundaries of the equipment is 200 units. The criterion was set at 190 deliberately to avoid tactile feedback from when the lever reached its lowest position. Thus, a response that extended just 1 unit into the criterion window and lasted 0.6 s would be reinforced, and a response that extended all the way to the upper limit of 190 also would be reinforced. Three rats received magazine training in the same equipment by means of a variable-time (VT) 60-s schedule that delivered food pellets independently of any responses made by the rat. The lever was available for recording during magazine training, but movement of the lever was only sporadic. Magazine training sessions lasted 1 hr.

After magazine training, the rats were exposed to continuous reinforcement of a criterion response defined as within 10-190 units and lasting at least 0.6 s. Reinforcement was delivered when the criterion was fulfilled; that is, while the lever was being held down (the rat did not have to release the lever to activate the pellet dispenser). The first two sessions had 120 reinforcers each. The third session changed from reinforcement to extinction after delivery of 40 reinforcers without removing the rat from the chamber at the transition point. During extinction, the feeder did not operate but the "beep" from the Sonalert did sound when a pellet would have been delivered. Then a fourth session had continuous reinforcement. Sessions were scheduled once each day.

Experiment 2. The purpose of Experiment 2 was to establish a more "complex" response of engaging the lever for an extended continuous duration in a narrower criterion window. Several different criteria were explored. To simplify the description of the overall method, only one example will be provided here. Two rats received magazine training in the same equipment by means of a VT 60-s schedule that delivered food pellets independently of any responses made by the rat. The lever was available for recording during magazine training, but movement of the lever was only sporadic. Four magazine training sessions each lasted 1 hr.

For Rat 8, pressing the lever was first accomplished with a wide criterion and short duration (20 – 180, 0.4 s) for two sessions and then at 30 – 170 units with a gradually increasing response duration requirement from 0.6 to 2 s over 5 sessions. Then the criterion was fixed at 30 – 170 and 2 s for three sessions. For Rat 5, the criterion was gradually narrowed from 20 – 180 to 50 – 150 units over 5 sessions, and the response duration was gradually increased from 0.2 s to 3 s. Then the requirement of 50 – 150 and 3 s was maintained for 5 sessions. If during a response, the lever was moved beyond the upper or lower limit, the opportunity for reinforcement was voided even if the duration requirement was met. Thus, reinforcement was only delivered if all three criteria were fulfilled for a single response. Sessions lasted about 1 hr.

Results

Experiment 1

An important impetus for developing the recording system described here is the opportunity to display response forms and duration in real time during sessions and to be able to create time-series graphs, or actograms, for viewing and analysis after data collection. The upper part of Figure 3 shows a 10-min display for Rat 6 of all responses for 40 reinforcer deliveries from the beginning of the third session of continuous reinforcement of a response with a 10-190 criterion window (blue

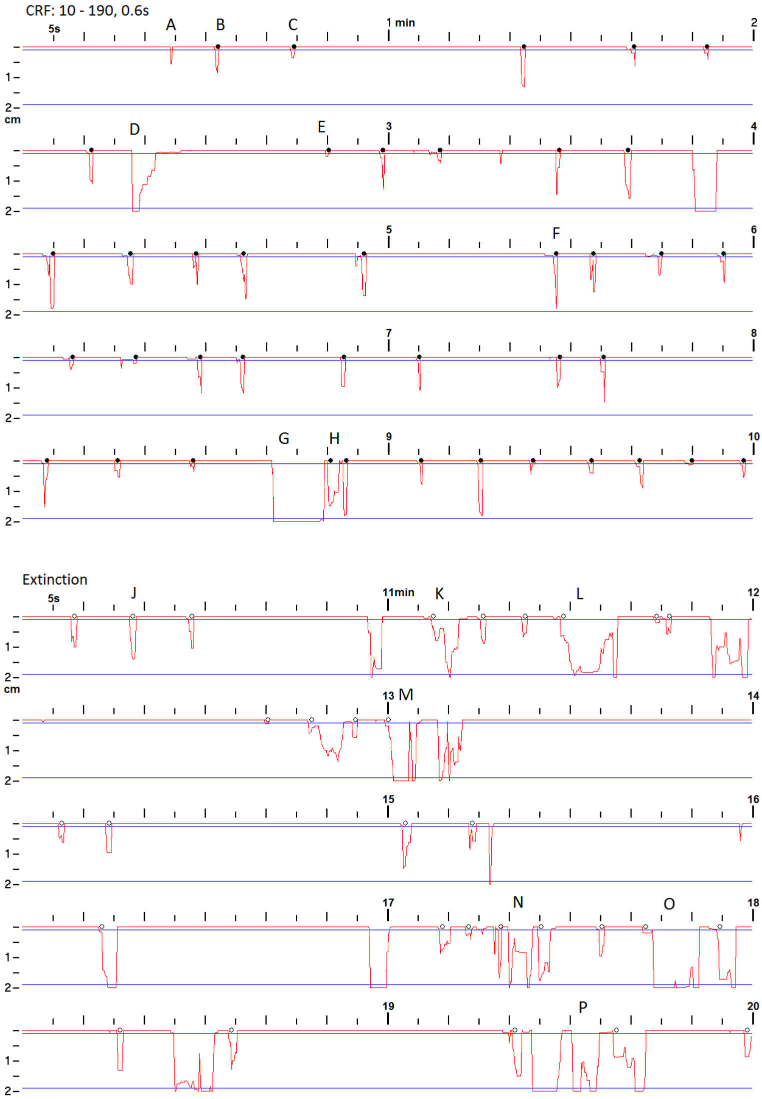


Figure 3. Actograms of lever movement for Session 3 for Rat 6. The first 40 criterion responses (upper display) were reinforced and thereafter reinforcement was withheld (pellet delivery ceased but the associated "beep" was maintained). The lower display shows the first 10 min of extinction. Red line represents downward lever movement. Blue lines represent movement criteria for reinforcement (upper boundary of 10 and lower boundary of 190 units). Reinforcement is indicated by a black dot. Criterion responses in extinction are marked by an open circle at the position where a reinforcement would have been delivered had the session continued reinforcement delivery upon completion of a criterion response. Each row shows responses in real time for 2-min periods. Selected responses are marked by letters for correspondence with the text.

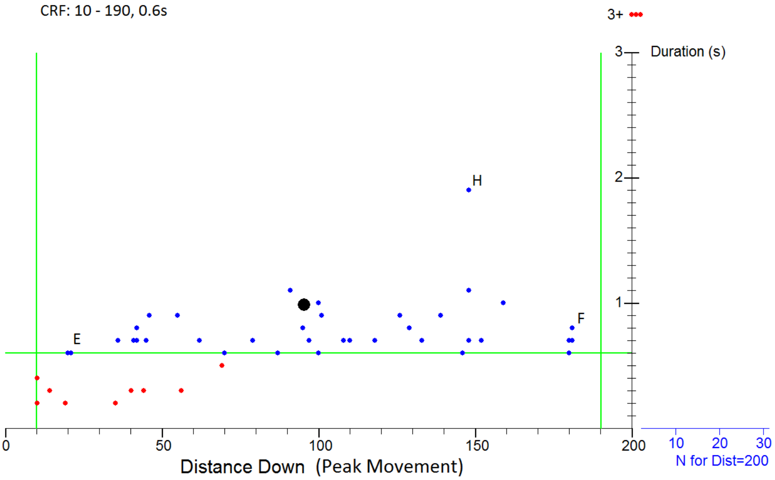
horizontal lines) and a duration of 0.6 s. Each row represents the passing of 2 min. Downward displacement of the red line reflects downward movement of the lever. For example, the response at A (about 25 s into the session) is within the criterion but is too short. The next response, at B (about 32 s into the session), is within the criterion and of sufficient duration of 0.6 s and is reinforced, as indicated by the small black dot above the red trace. The third response, at C, is pressed down much less than the response at B. The second response, at D, in the second row (minutes 2 to 4), represents the rat pressing the lever all the way to the bottom of the range of movement (reaching the physical limit of the lever) and holding it there for about 1 s and then releasing it gradually over several seconds. This response is not reinforced even though it fulfills the duration requirement; the response was outside the criterion of 10-190 (i.e., it went above 190). The response marked at E is an example of a lever press with very little movement, just passing the upper movement criterion of 10 units for the required duration. Conversely, the response marked at F is an example of a response that went almost all the way to the lower criterion but still was within the criterion range and therefore reinforced. Thus, many different response forms or movement extensions are reinforced with this method. A meaningful characterization is the peak movement, the furthest point the lever went to from the resting position during a given response. Thus, the response at F peaked at 185 units, while the response at E peaked at 13 units; the response at D peaked at the maximal value of 200 units.

Responses quickly become self-similar with just a few notable exceptions as marked at G where the lever is held in the downward position for nearly 10 s. Typically, the rats released the lever as soon as the pellet was delivered. However, in a few rare cases, the lever was held briefly beyond that moment, as indicated at mark H.

The lower part of Figure 3 shows the first 10 min of the extinction period that followed immediately after the first 40 reinforcers (the upper part of Figure 3). To indicate that a response would have been reinforced had reinforcers been scheduled, an open circle appears at the temporal location where a food pellet would have been delivered. This mark helps to identify criterion responses during the extinction session, even though they obviously were not reinforced. The first three responses, marked at J, are very similar to the brief criterion responses reinforced earlier (upper part of Figure 3). Then responses begin to expand in duration as shown at K where the rat does not release the lever at the time of the "beep" but continues to move the lever. The same happens at L where the response lasts about 10 s with considerable variety in movement. Many responses move the lever to the end position, and in several cases the rat holds the lever at the end position (this movement was never reinforced in prior sessions), as at M, O, and P. The rat also occasionally engages the lever in clusters of responses marked by very varied up and down movements, as at mark N. The responses generated during continuous reinforcement (upper part of Figure 3) are nearly absent during extinction. The reinforcement delivery controlled a very quick release of the lever during reinforcement but this control is lacking during extinction, and the rat typically engaged the lever for much longer durations than the reinforcement criterion of 0.6 s. Only few responses, as at J, resemble the reinforced responses. Thus, responses in extinction quickly ceased to resemble the criterion responses during reinforcement and quickly extended in duration but also appeared in considerably more varied forms than during continuous reinforcement.

The recording system generates highly accurate, quantitative information about each instance of the response in space (movement up and down) and time (duration and location within the session). However, quantitative analysis of the highly variable response forms in extinction and representation of these response changes beyond the display in the "raw" record shown in Figure 3 is a considerable challenge. In one attempt to go a step further, two dimensions of each response instance, 1) the peak movement of the response (the furthest point the lever was moved down from the resting position), and 2) the duration of the response are plotted for Rat 6 in Figure 4 for the first part of Session 3 with reinforcement (upper display) and for the second part with extinction for the remainder of the session (lower display). Each blue dot represents one criterion response. A red do represents a non-criterion response. The horizontal green line shows the duration criterion of 0.6 s and the vertical green lines the movement criteria of 10 - 190 units (lever movements that did not reach the lower criterion of 10 units are not shown). The peak movement is plotted on the X-axis. Duration of the response is plotted on the Y-axis. For responses that reach the end position (distance of 200 units from the resting position), the duration is plotted as a histogram on the Y-axis. Those responses were not reinforced and therefore also appear in red. Response durations exceeding 3 s are plotted above the Y-axis. The large, single black dot represents the average of each dimension. For comparison, the criteria are plotted by green lines for both reinforcement and extinction even though there were no reinforcement criteria under extinction.

To connect this display with the actual real-time actogram display in Figure 3, a few responses have been identified by letter as they appear in Figure 3. For example, the response marked at H in Figure 3 has a peak movement of 148 units and a duration of 1.9 s. Under continuous reinforcement, the majority of the criterion re-



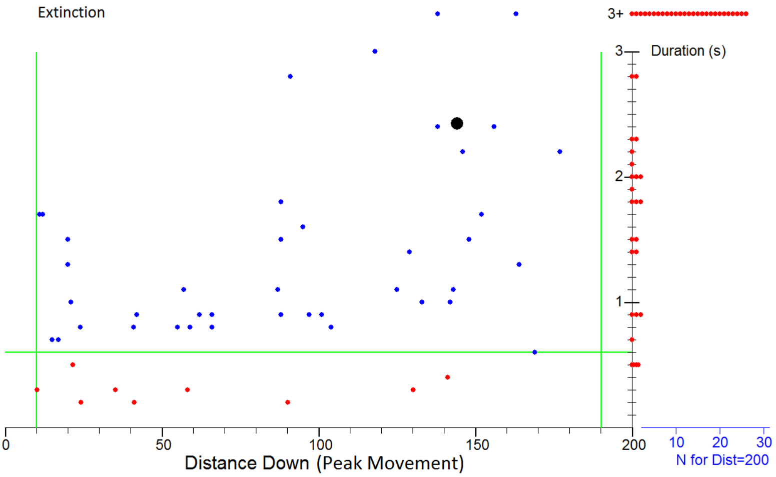


Figure 4. Two-dimensional plot of response peak movement and response duration for Session 3 for Rat 6. The peak movement is plotted on the X-axis. Duration of the response is plotted on the Y-axis. Blue dots represent reinforced response, and red dots represent unreinforced responses. The horizontal green line shows the duration criterion of 0.6 s, and the vertical green lines represents the movement criterion of 10-190 units (responses that did not reach the lower criterion of 10 units are not shown). For responses that reach the end position (distance of 200 units from the resting position), the duration is plotted as a histogram on the Y-axis. Those responses were outside of the 190 upper criterion and are therefore not reinforced and thus appear in red. Durations exceeding 3 s are plotted above the Y-axis. The large, single black dot represents the average of each dimension. The upper display is for the period with reinforcement, and the lower display shows extinction.

sponses are between 0.6 and 1.1 s. The duration exceeding the 0.6 s criterion appears when the rat does not release the lever immediately upon reinforcement delivery. Unreinforced responses were all short movements within the movement criterion or were much longer than the 0.6-s duration requirement (i.e., the three responses for this session seen at 3+). Under extinction (lower part of Figure 4), the dense band of responses seen during continuous reinforcement in the 0.6 to 1.1- s range is largely gone, with response durations far exceeding the previous reinforcement criterion of 0.6 s; there is a large increase in responses moving the lever to the end position (200 units) with 27 responses exceeding 3 s. Responses were not interrupted by pellet delivery and therefore continued considerably beyond the previously conditioned value of 0.6 s. This two-dimension plot gives an overview of the data yet does not do full justice to the richness of information regarding response variability seen in the actograms in Figure 3. The averages plotted (i.e., black dots) are difficult to use as representations of the actually obtained data. Especially during extinction, the average duration is pulled up compared to during reinforcement sessions because of the many responses that exceeded 3 s. The remaining two rats showed very similar data.

Experiment 2

To illustrate the response changes that take place within one session of acquisition, data are presented as an actogram for the entire 1-hr session for one rat. Figure 5a shows the first 20 min of the session, Figure 5b shows the next 20 min, and Figure 5c shows the last 20 min of the same session. The criterion was 30 - 170 units with a response duration of 2 s throughout the session. Each row shows response recording for 2 min. The first two responses satisfied the criterion, marked at A. Then the rat engaged the lever erratically, and often pressed the lever all the way to the end position for many successive responses, marked at B. After two more reinforced responses, the rat continues the erratic lever movements almost continuously for over one minute, as marked at C. This mixture of criterion responses and noncriterion responses of high variability continues for about 25 min. Gradually, criterion responses begin to occur successively without interruption by noncriterion responses between minute 19 and 20, marked as D. Noncriterion responses become rare in the last 20 min of the session, as shown in Figure 5c (mark E), and in general are much shorter, as at mark F, than the noncriterion responses that occurred within the first 20 min of the session (Figure 5a). Criterion responses became very self-similar with little variation from response to response looking almost like a square wave with only slight movement while the rat is holding the lever in a fixed position, as marked at G and H in Figure 5c.

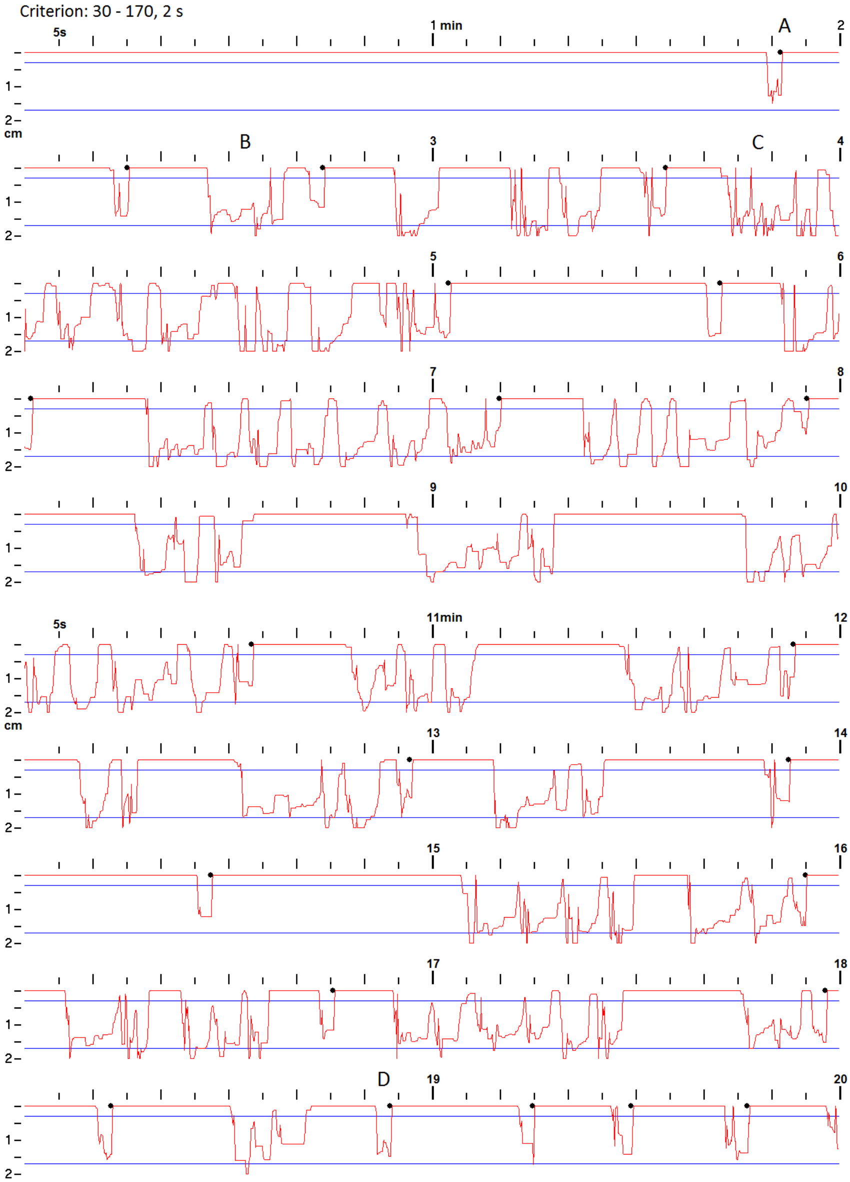


Figure 5a. Actogram for the first 20 min of one session for Rat 8. The criterion for reinforcement was 30-170 units with a response duration of 2 s. This criterion was in effect for the whole session. Red line indicates the lever movement. Blue lines indicate movement criteria. Reinforcement is indicated by a small black dot. Selected responses are marked with letters for correspondence with the text.

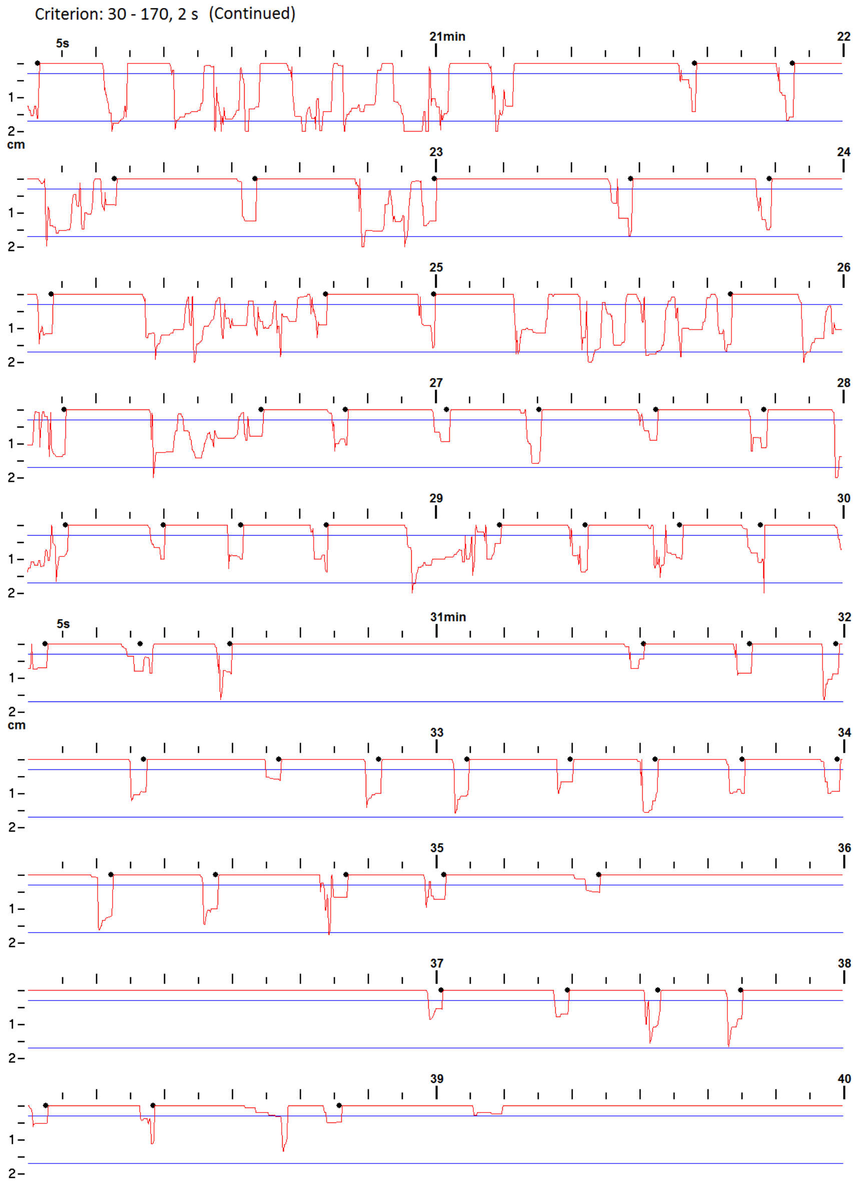


Figure 5b. Actogram for the second 20 min of one session for Rat 8. The criterion for reinforcement was 30-170 units with a response duration of 2 s. This criterion was in effect for the whole session. Red line indicates the lever movement. Blue lines indicate movement criteria. Reinforcement is indicated by a small black dot.

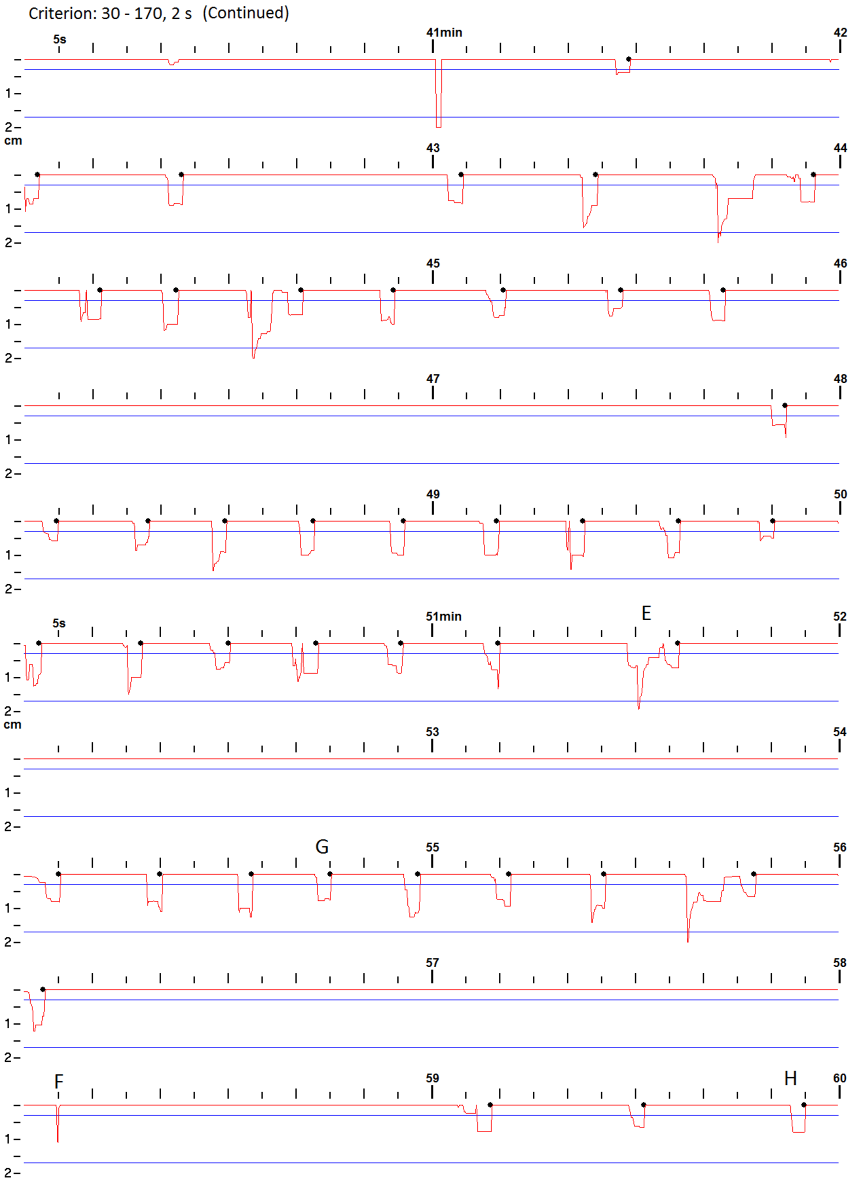


Figure 5c. Actogram for the last 20 min of one session for Rat 8. The criterion for reinforcement was 30-170 units with a response duration of 2 s. This criterion was in effect for the whole session. Red line indicates the lever movement. Blue lines indicate movement criteria. Reinforcement is indicated by a small black dot. Selected responses are marked with letters for correspondence with the text.

Thus, for the first 20 to 25 min, criterion responses are intermixed with tremendously variable noncriterion responses, often lasting 10 s or longer. Within about 30 min, the contingency has created a criterion response that begins to occur regularly with little variability from instance to instance. Noncriterion responses become very short and rare. The beginning of the session is characterized by a mixture of reinforcement of criterion responses and considerable "induction" of noncriterion responses. For the present experiment, it is difficult to disentangle the effect of no reinforcement of noncriterion responses, as marked at C in Figure 5a, from induction of general activity on the lever by reinforcement of criterion responses. Data similar to that displayed in Figures 5a, b, and c were obtained for the other rat and from earlier sessions for the same rat.

As for Experiment 1, quantitative analyses beyond display of the raw data in the actograms are difficult to approach given the high degree of variability during acquisition that is revealed with this recording method. However, some pattern analysis is possible with relatively modest quantification. The actograms in Figure 5 show that the noncriterion responses with long durations with high variability mainly appear in the beginning of the session. Figure 6 shows a print of the peak movement distance (the furthest point down during a given response) for all response during a session. Criterion responses (reinforced) appear in blue with a dot under the response, and noncriterion responses appear in red without a dot under the response. Responses are printed successively with the first on the left side. Data for Rat 8 appear at the top and is for the same session as the data displayed in Figure 5. This data pattern reveals that the noncriterion responses gradually drop out and the criterion responses become more self-similar with less variation in peak distance (as could also be seen in Figure 5c for Rat 8). Because of the frequent noncriterion responses at the beginning of the session, one can consider all responses to be intermittently reinforced and only criterion response reinforced continuously. A simple calculation of "intermittency" is responses (criterion and noncriterion added together) per reinforcer. The numbers above each graph show this calculation in blocks of 10 reinforcers. For example, for Rat 8, 53 noncriterion responses were emitted along with the first 10 criterion responses, yielding 63 responses in total. With 10 reinforcers, this ratio becomes 6.3 (responses/reinforcer). For both rats, the intermittency decreases through the session as noncriterion responses drop out. One may consider these data as an illustration of the criterion responses being maintained by a gradually decreasing variable-ratio like schedule (from lean to rich). The noncriterion responses gradually drop out and concomitantly the responses per reinforcer decreases (or one may say that the overall reinforcement density increases).

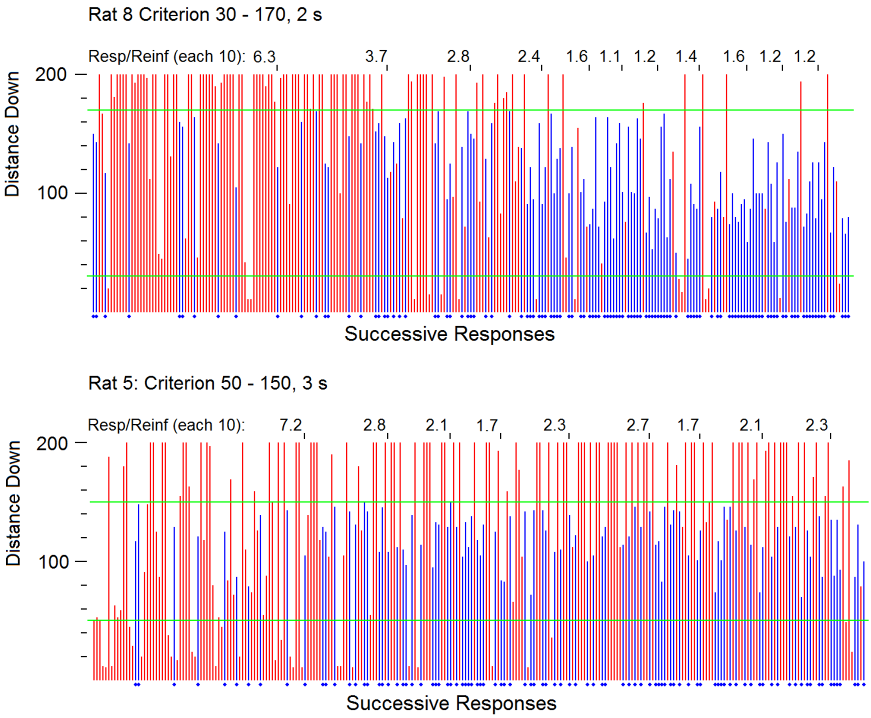


Figure 6. Display of successive peak movement distances of each response for a whole session. Peak distance is the furthest down the rat moved the lever for a given response. Red lines refer to non-criterion responses and blue lines to criterion (reinforced) responses. Dots under lines also indicate criterion responses. Green horizontal lines indicate the movement criteria. For each block of 10 reinforcers, the ratio of responses/reinforcer, as an indication of the degree of intermittency of reinforcement of all responses, appears above the display; tick marks indicate the 10th reinforcer in a given group of successive responses. Data are presented for two rats. The data for Rat 8 cover the same session as displayed in Figure 5a, b, and c. Criteria for reinforcement were 30 - 170 with a response duration of 2 s for Rat 8; for Rat 5, the criteria were 50 - 150 with a response duration of 3 s.

Discussion

Using simple tools, an inexpensive video game controller was modified to function as a joystick for recording of detailed movement of downward direction of a response lever in an operant chamber. The controller plugs directly into the USB port of a PC without the need for any intervening interface. Algorithms for response detection can be arranged with relatively simple programming due to the existence of a command that reads the joystick parameters (i.e., “readjoystick”) and which is built into modern programming languages (as described in Appendix A). With a time resolution of 100-ms of recording, for the arrangement described here, movement of the lever can be displayed in real time in actograms on the monitor of the PC while an experiment is ongoing just as a cumulative recorder provides information regarding the status of an ongoing experiment. Data about the lever movement can be stored in data files (see Appendix A) for later *post hoc* analysis and creation of actograms that display all data for a given session, as presented in Figures 3 and 5 (see also Appendix B).

The main purpose of designing the equipment and method of recording was to examine response variability during acquisition and extinction. Prior studies have demonstrated large increases in response variability during extinction (e.g., Antonitis, 1951; Eckerman & Lanson, 1969; Iversen, 2002). For example, Iversen (2002) demonstrated in images taken at the moment a response starts that response topography is very self-similar from response to response under continuous reinforcement but begins to vary considerably under extinction. However, responses also extend in time, and methods have not been established to record and analyze response variation in the detail provided with the current method. Prior joystick methods, where rats can move a rod in any direction (e.g., Scott & Platt, 1985), were used to test conditioning models and did not provide the kind of detail needed for analysis of response variability in acquisition and extinction.

With customary response measures such as lever presses and key pecks for rats and pigeons response variability is ordinarily studied as fluctuations in local response rate, for example, during extinction sessions (e.g., Skinner, 1938). Cumulative records are ideally suited to display acquisition, maintenance, and extinction of operant behavior in the form of short and fixed movement responses. Changes in response forms and duration cannot be displayed with the cumulative record. The method developed here with the joystick, even for restricted movement of a downward press up to 2 cm (for rats), presented a considerable richness of information regarding behavioral variability in real time. Particular suggestive findings illustrated here with demonstration experiments were that criterion responses, reinforced prior to extinction sessions, disappeared very quickly in extinction sessions and were replaced by “novel” noncriterion responses. For example, the rats in this experiment never produced reinforcement by pressing the lever all the way down to the end position. Yet, responses that moved the lever all the way down were frequent during extinction. Response duration also increased during extinction. With responses such as lever presses and key pecks, a part of the equipment construction ordinarily provides some feedback as to termination of the response either in the form of a relay that provides sound or resistance to movement when the lever is pressed all the way (ordinarily just a few mm). With the current method, this feedback is deliberately lacking. The lever movement is terminated for criterion responses by reinforcement delivery. Therefore, under extinction, the control of response termination by the sounds of pellet delivery is missing, and the responses quickly grow in duration. The present method can be used to examine extinction in great detail. For example, the criterion response may be either a hold response as in the present experiment or can be arranged as a hold and release response. That is, reinforcement is not provided for a criterion response until the response lever has been released. Thereby control of response termination is not sounds associated with the reinforcement delivery cycle. Such an experiment can establish how response variability and duration may differ in extinction after conditioning of a "hold and release" response versus a "hold" response.

The present demonstration in Experiment 2 with acquisition of a longer-duration response with more narrow movement criteria illustrated that considerable response variation takes place early in acquisition. Such variation is not easily observable in conventional preparations with lever presses and key pecks. The extended response duration and movement requirements served to slow acquisition and to enable detailed recording of response movement and response duration. Reinforcement of a few criterion responses quickly brought about a considerable increase in highly variable noncriterion responses. A simple calculation of responses per reinforcer illustrated that this induction (e.g., Segal, 1972) of noncriterion response forms increase intermittency of reinforcement. It is not clear from the present data and method attempted so far whether this increase in variation helps or hinders acquisition. The criterion response may occur early in the session but is not immediately repeated as is often observed with conventional lever press and key peck responses. Indeed, even undergraduate laboratory classes often feature live demonstrations of rapid response (i.e., lever press) acquisition after just a few reinforcers for the criterion response (e.g., the laboratory used by the author). The gradual increase in frequency of the criterion response and concomitant decrease in frequency and duration of noncriterion responses, shown in Figure 5 and the display in Figure 6, suggest that the criterion response not only produces reinforcement but also may increase the overall reinforcement rate. The noncriterion responses were in fact never reinforced so it is not entirely correct to state that they gradually extinguished during acquisition sessions (put simply, the noncriterion responses appeared along with reinforcement of criterion responses, were never reinforced, and then disappeared). Future experiments, using the methods described here may serve to determine the origin and role of the rise and fall of noncriterion responses during acquisition. For example, noncriterion responses may be limited if the criterion responses are introduced gradually with wide movement ranges and short duration with criteria changing gradually. Such procedures were attempted in preliminary experiments with the present method but are not yet ready for presentation.

The method documented here provides promising information about response variability. However, visualization of the data is problematic because the display of behavior in real time produces multiple displays that may be restricted for presentation in publications. Customarily, averaged single-session data are just one point on a graph or may even be averaged with other sessions to provide a single point that represents an average of performance sampled over many sessions. The present method obviously is of an entirely different nature because the focus is on studying behavior in real time and on analyzing changes in response form and duration. Data quickly build up with the present method. However, response variability and duration can be documented objectively and stored in data files to be shared with other researchers (e.g., Supplement 2, see Appendix C) for additional or alternative analyses.

Shimp (2014) articulated that behavioral variability has very different meaning in so-called molecular and molar analyses. In general, with molar analyses, behavioral variability at most is presented as standard deviations and is largely ignored for analysis. Molecular analyses, by contrast, present the problem that the "easy to see" variability, even when recorded with great precision as with the present method, is difficult to describe quantitatively. In fact, there may be no common consensus as to how to deal with molecular data sampled over very short time periods (e.g., Henton & Iversen, 1978; Iversen, 1991). Yet, this is the behavior that appears when one samples behavior in short periods, as with the present method. For situations of application from clinic to education for human participants, behavior has to be dealt with in real time with contingencies of reinforcement that have to be implemented as behavior occurs and not as an average performance is presented as a numerical value long after the target behavior is terminated.

The methods of recording and data presentation offered here may provide a starting point for more systematic studies of the role of response variability in acquisition and extinction of operant behavior.

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Appendix A

Demonstration of a simplified program written in LibertyBasic (LB) that in 100-ms units captures and stores the distance the lever is moved downward.

1: ba = 32000	‘resting baseline value of joystick
2: sc = 160	‘scaling factor
3: sl = 180000	‘session length in 100-ms units - 30 minutes
4: file$=”J”+rat$+”S”+sess$	‘file name for given rat and session
5: open “c:\data\”+file$+”.dat” for output as #1	‘open file for storage of data
6: t = time$(“ms”)	‘store current time in milliseconds in variable t
7: Do	‘LB command Do…Loop (operates continuously)
8: if time$(“ms”) > = t+100 then	‘wait until 100 ms has passed since last reading
9: n = n+1	‘increment number of 100 ms periods
10: readjoystick1	‘LB command - reads joystick as input
11: dist = ba-Joy1y	‘distance of movement relative to resting value (ba)
12: print #1, n; “,”; int(dist/sc)	‘print to data file opened in Line 5
13: t = time$(“ms”)	‘store current time in variable t
14: end if	
15: Loop until n = sl	‘session length in 100 ms periods (sl)
16: close #1	
17: end	

For this simplified version of the program written in LibertyBasic (LB), the line numbers are added for explanatory purposes only and are not part of the actual running program. In a Do … Loop (LB command) that runs until the session ends (lines 7 through 15), the program reads the status of the joystick (line 10) by the “readjoystick1” LB command (the joystick is the modified Thumbstick on the GameStop® – see Method). This LB command returns three position values and two button values. For this experiment, only stick movement in one direction was needed; the variable "Joy1y" is a global LB variable filled by the "readjoystick1" command. For every 100-ms time tick, the program calculates the distance of the lever from the resting value (ba for baseline is a constant set in line 1, see below). This distance is placed in a variable "dist" and is calculated as ba-Joy1y (line 11). A scaling factor (sc, line 2) converts the distance to a range of 0 to 200, with 200 being the maximal movement of the lever (2 cm from the resting point). Every 100 ms the program prints two values to an opened data file (line 5, the name of the file should reflect the rat and session number – such input variables are omitted here): 1) the current time (expressed as number of 100-ms periods since session start, n), and 2) the scaled distance of the lever from the resting point (line 12, the LB command INT calculates the integer value to avoid decimals). The 100-ms increments are determined by comparing the current PC clock time in milliseconds to a previous point in time stored in variable t (lines 6 and 13).

For an actual experiment, additional information may be placed in the data file such as the moment of delivery of reinforcement, and criteria for reinforcement as they may change during an experimental session. The program displayed here is deliberately simplified to show the essentials of capturing lever movement with the LB readjoystick command.

Example of a simplified data file produced by this program. Time units (100 ms ticks from session start) are printed in the left column, and the distance the lever is moved downward for each 100-ms unit – maximum 200 distance unit is printed in the right column.

Time, Distance
1380, 0
1381, 0
1382, 0
1383, 5
1384, 55
1385, 176
1386, 64
1387, 21
1388, 18
1389, 16
1390, 10
1391, 0
1392, 0

An example of how data appears in the data file is illustrated above. The left column shows session time in 100-ms units, and the second column shows the distance of the lever from the resting point (ba) in a 0-200 scale (corresponding to 0 - 2 cm of lever movement). The resting value is zero. For example, at time 1383 the lever is moved down 5 units, and in successive 100-ms periods the lever is moved down further up to 176 in time unit 1385. The lever is at rest again in time unit 1391. The total lever movement duration for that example is 7 time units (lines), or 700 ms.

The baseline value (ba) for reading of the joystick is determined directly from the equipment used (see Method) and is the value read when the joystick is in the resting position. Conceivably, joystick equipment from other vendors may have different resting values. Ordinarily, without modification, the Thumbstick can move in two axes from the center, resting position. The current experiment uses only the values from one axis because the lever attached to the Thumbstick deliberately has restricted movement in one axis only (i.e., Figure 3, Frame E) as the lever inserted into the Thumbstick can only move from the center, resting position and down.

Appendix B

Example of a simplified program written in Liberty Basic (LB) to display stored data in a graph indicating downward movement of the lever in 100 ms units

LB Program:

1: basey=80		‘y value (pixels) for resting position on monitor
2: fa=2		‘scaling factor to modify amplitude
3: py= basey		‘previous y position
4: file$=”J”+rat$+”S”+sess$		‘file name for given rat and session
5: open “c:\data\”+file$+”.dat” for input as #1		‘Open data file to read stored data, LB command
6: open “Display” for graphics as #2		‘Open graphics window, LB command
7: Do		‘Do ... Loop reads data file, line by line
8:	input #1, tick, dist, reinf	‘read three values from one line from data file
9:	dist=dist/fa	‘scaling factor for graphics display
10:	x=x+1	‘time tick advances X-axis one pixel for each 100 ms
11:	y=basey+dist	‘calculate y value (distance from resting position)
12:	print #2, “line “; px; “ “; py; “ “; x; “ “; y	‘print line from previous point (px, py) to present point
13:	px=x	‘store present x value
14:	py=y	‘store present y value
15: Loop		

In this simplified version of a program used to display the stored data, line numbers are added for explanatory purposes and are not part of a running program. Data are displayed on a computer monitor and can be saved as a bitmap image file by screen capture (not included in the sample program). The sample program also does not show control of the axes tick marks and labels or inclusion of input variables. The location of the peak of lever movement is the vertical distance from the top of the monitor (the positive y axes for pixel display begins at the top of the monitor and extends down – rather than up as in regular coordinate systems). Line 1 indicates the base value for the y coordinate, the distance from the top of the monitor to the first actogram resting line, in pixels. As the data are presented on the monitor in several lines (as in Figures 5 and 6), the base value changes accordingly (not shown in the simplified version). The original data range for distance of lever movement is 0 – 200 and a scaling factor in line 2 reduces this to 0 – 100 (on the monitor, for the current application) so that more data can be presented on the monitor. The necessity for line 3 is explained below with coverage of lines 12 – 14. A data file is identified by input variables for rat and session number (line 4); for simplicity, input variables are not show here. Line 6 opens a graphic window. A Do … Loop, from lines 7 through 15, reads data lines in the data file successively one by one from the top. Data files have three data entries in each line, number of 100-ms ticks since session start, the distance of the joystick from resting position, and information about reinforcement (line 8); when reinforcement was delivered, the third value showed the successive number of that reinforcer since session start. Line 9 calculates the distance of movement to be shown on the monitor (original data scaled, in this case by the value 2, line 2, reducing the original distance to half). The graph advances one pixel to the right for each time unit; hence line 10 increments the x value by 1 for each reading from the data file. When the x value reaches the right-hand edge of the graph space (2 min for the figures shown here) the x value is reset to zero and the basey value is incremented by 300 to move the next graph down under the one above (algorithms for these maneuvers are not shown in this program). The y value representing the lever position in a given time unit is calculated as the distance from the basey value (line 11). The x and y values thus represent the position of the lever in a given time unit and for the displays designed for this article, the successive x and y values across time were connected by lines to generate the graphs shown in the figures. Line 12 prints this line on the monitor from the current x and y values in a given time unit, to the x and y values in the previous time unit, (px and py are set in lines 13 and 14 – and in line 3 because the first previous point in a session has a py of the basey value). The loop ends when the data file is exhausted (not included in this program).

Appendix C
Supplementary Files

Supplement 1: A short video clip of one rat engaging the lever followed by reinforcement. http://rmac-mx.org/wp-content/uploads/2017/10/IversenSupplement1Video.wmv

Supplement 2: The complete raw data file for the entire session depicted in Figures 5a, 5b, and 5c. Each line entry represents three values, left: 100-ms units since session start, middle: the distance of lever movement from resting position to end position (i.e., from 0 to 200), right: reinforcement counter. The line that has the reinforcement counter incremented gives the temporal location of reinforcement within the session (in 100-ms units since session start). http://rmac-mx.org/wp-content/uploads/2017/10/IversenSupplement2DataFile.txt