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CONTINUOUS VERSUS DISCRETE DIMENSIONS OF REINFORCEMENT SCHEDULES: AN INTEGRATIVE ANALYSIS

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An approach to reinforcement-schedule contingencies is presented that accommodates continuous as well as discrete effective dimensions of responses and reinforcers. College students' wheel turning was reinforced by projected reading material according to four schedule contingencies that incorporated either a discontinuous (count) or continuous (duration) dimension of the response and the reinforcer. The contingencies arranged a 1:1 correspondence between (a) response count and consequent stimulus count, (b) response duration and stimulus count, (c) response count and stimulus duration, and (d) response duration and stimulus duration. Contingencies incorporating response count produced moderate to high rates of very short-duration responses. Contingencies incorporating response duration produced very low-rate, long-duration responding. The dimension of the reinforcer had minimal or no additional effect. We suggest that incorporating duration and other continuous dimensions into schedule contingencies may improve our understanding of both laboratory and nonlaboratory behavior.

Key words: reinforcement schedules, extinction, continuous dimensions, response duration, reinforcer duration, wheel turning, college students

A reinforcement schedule is a formal description of an operant contingency that specifies the conditions that must occur in order for responding to produce reinforcing consequences. A schedule specifies values of three distinct elements: the effective response dimension, the dimension of the reinforcer, and the contingency or relation between them. Within this framework, a wide range of variations is possible. Some of these variations have been studied fairly extensively; others have received little or no attention. Some schedule contingencies that are seldom studied may be quite prevalent in the natural environment.

In laboratory research, operant behavior is most often studied under contingencies that relate occurrences of brief, easily repeatable responses and reinforcers (see Morse, 1966). Typical ratio and interval schedules specify the response requirements for reinforcement in terms of either number of occurrences or the relationship of a single occurrence to other events. Responses and reinforcers that vary significantly across occurrences in duration or other continuous dimensions have been infrequently studied with free-operant schedule procedures, perhaps partly because such variation is not readily accommodated by the procedural framework of traditional reinforcement schedules.

The present paper delineates the dimensional aspects along which reinforcement procedures may vary, provides a conceptual framework for integrating some disparate procedures into the analysis of schedule contingencies, and offers a series of experimental contingencies that illustrate arrangements involving continuous response and reinforcer definitions.

Effective Response Dimension

Any response class may be described by multiple dimensions (e.g., force, count, duration, etc.; Johnston & Pennypacker, 1980). Some of these quantities may be irrelevant to how a class of responses participates in a schedule contingency. Others may define the occurrence of responses for experimental purposes. Still others may define how the behavior is effective in the contingency. For example, in the case of a pigeon's key pecking under a typical ratio schedule, force is one of the dimensions that contribute to defining the occurrence of a response, but countability is the dimension along which a value is specified that determines how responses are effective in earning reinforcers.

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A schedule contingency usually specifies only one of the dimensional quantities of a response class that will be effective in satisfying the requirements for reinforcement. The effective dimension can be discontinuous or continuous (Johnston & Pennypacker, 1980). Table 1 summarizes some characteristics of response and reinforcer dimensions, ways of incorporating them into contingencies, and examples of how these alternatives have been used in the literature.

Discontinuous effective response dimensions. Response classes for which the effective dimension is discontinuous are informally called discrete response classes (e.g., key pecking), even though continuous dimensions (e.g., force) may be part of how their occurrence is defined. When the effective response dimension is discontinuous, reinforcement is based on the occurrence of response cycles. A response cycle is defined as beginning when a threshold amount of some defining dimension is detected and ending when behavior falls below the threshold amount (Notterman & Mintz, 1965). For example, the force on a lever must exceed, and then fall below, 0.1 N. In contingencies specifying discontinuous effective response dimensions, all values equal to or greater than the 0.1 N threshold are functionally equivalent. Values below 0.1 N do not contribute to the outcome of responding. In the laboratory, detection of response occurrences is often based only on the initial event of exceeding the threshold (e.g., the operation of a switch). In such cases, the complete response cycle is implicitly part of the definition because behavior must fall below threshold before another occurrence can be counted. Regardless of whether occurrence is measured at the beginning or end of the cycle, it is some number or count of occurrences that determines reinforcement.

These features tend to constrain variability in the dimension defining the response class (e.g., force; Notterman & Mintz, 1965). Variability in dimensions that are not effective in the schedule contingency, such as duration in the case of a lever press or key peck, may be constrained as well (e.g., Margulies, 1961; Millenson, Hurwitz, & Nixon, 1961). In addition, standard manipulanda and instrumentation are designed to restrict variation in certain dimensions. For example, in the prototypic discrete response class, the pigeon's key-peck responses are usually of very brief duration.

Response-differentiation procedures (Skinner, 1938) are similar to typical schedule procedures in their treatment of the effective response dimension (Galbicka, 1988; Platt, 1973). Responses are defined and related to reinforcement as discrete events. Reinforcement is delivered on the completion of response cycles, as defined above, only if, within that cycle, some criterion amount of the dimension being differentiated has occurred. For example, only occurrences of responses (with a force above 0.1 N) exceeding 1 s in duration might be reinforced. Occurrences of responses (above 0.1 N) shorter than 1 s are not effective (e.g., Kuch, 1974; Notterman & Mintz, 1965). Thus, the effective dimension remains count, and the response is again treated as a discrete event in the contingency.

Continuous effective response dimensions. When the effective response dimension is continuous, the count of response occurrences is not the basis for reinforcement, although responses can still be counted by defining a response cycle as discussed above. However, continuous responses may vary from cycle to cycle along the effective dimension to such an extent that counts of cycles are not meaningful.

One method that has been used to incorporate continuous response-class definitions into operant contingencies allows all detectable amounts of the effective dimension to contribute by summation to the outcome of responding. In Skinner's early work on wheel running in rats (Skinner, 1938; Skinner & Morse, 1958), the distance run was allowed to sum across episodes of wheel running, and the number of cycles of responding was irrelevant to the contingency. Reinforcing cumulative distance on an interval schedule produced bouts of continuous running of varying durations. Rider and Kametani (1984, 1987) employed similar procedures involving the duration of rats' lever holding in analogues of fixed-ratio schedules, producing fixed and variable cumulative-duration schedules. Under such procedures, occurrences of individual cycles are irrelevant. Terminations of responding were not necessary in order to emit additional effective behavior or to produce reinforcement.

Much behavior in the natural environment resembles the continuous responding described by Skinner and Morse (1958). Such behavior is not readily characterized by brief initiation/termination cycles (see Baer, 1986). The count of response occurrences may be irrelevant because consequences are not based primarily on

Table 1

Characteristics of schedule contingencies.

Characteristics	Examples
Responses and reinforcers	
Discontinuous effective response dimensions	
Occurrences of individual response cycles. All counted responses equally effective. Responses with values below a specified criterion do not contribute to reinforcement. Reinforcer presented either at the instant responding exceeds or drops below the defining threshold. Responding must terminate before another occurrence can be counted and reinforced.	Typical procedures using key pecks, lever presses, and button pushes. Classic simple schedules (CRF, FR, and FI) defined by such responses (e.g., Ferster & Skinner, 1957). Response-differentiation procedures (see Galbicka, 1988; Lang & Twentyman, 1974; Notterman & Mintz, 1965). Count-count schedule.
Continuous effective response dimensions	
Counts of occurrences irrelevant. Measurement of effective dimension above minimal threshold for response class definition. Reinforcement when a criterion amount of the effective dimension attained. Criterion attained by cumulating amounts of effective dimension across response cycles. Response termination not required.	Cumulative distance of wheel running (Skinner, 1938; Skinner & Morse, 1958); cumulative duration of lever holding (Rider & Kametani, 1984, 1987). Duration-count schedule.
Discontinuous reinforcer dimensions	
All dimensions of stimulus constant across occasions. Participation in schedule in terms of count only.	Typical schedule procedures (e.g., FR, FI, VR, VI). Count-count schedule, duration-count schedule.
Continuous reinforcer dimensions	
Variation in continuous dimension across occurrences. Occurrences specified in terms of amount of continuous dimension.	Logan's (1960) incentive schedule procedures. Count-duration schedule, duration-duration schedule.
Contingency	
Procedures allowing response–reinforcer variation	
Procedures allowing response variation: Variation in the number of response occurrences. Variation in continuous effective response dimensions.	Intermittent reinforcement schedules (FI, VR, VI, etc.). Response-differentiation procedures. Duration-count schedule.
Procedures specifying consequent stimulus variation: Variation across occasions in dimension of the reinforcing stimulus. Value of the dimension specified by the experimenter.	Logan's (1960) varied reinforcement procedure (Davis & North, 1967; Harzem et al., 1978).
Procedures allowing response–reinforcer covariation	
Variation in effective response dimension produces variation in consequent stimulus dimension. Amount of the consequent stimulus determined by performance.	
Discrete procedures: Consequent stimulus presented after termination of responding. Amount of dimension determined by amount of effective dimension of the terminated response cycle.	Correlated reinforcement procedures (Logan, 1960); free-operant correlated reinforcement (Buskist et al., 1988; Gentry & Eskew, 1984; Gentry & Marr, 1982; Hendry, 1962; Hendry & Van-Toller, 1964).
Continuous covariation: Dimension of responding determines amount of the consequent stimulus dimension from moment-to-moment.	Conjugate reinforcement (e.g., Lindsley, 1962), continuous repertoires (Holland & Skinner, 1961), analogue biofeedback procedures (Colgan, 1977; Lang & Twentyman, 1974; Shapiro & Surwitt, 1979), and skilled motor performances. Duration-duration schedule.

crossing a definitional threshold. For example, a retarded individual's self-injurious behavior might be reinforced by a caregiver's attention based on the intensity and/or duration of self-biting. Countability may be measured, but it may be the duration and intensity of responding that change systematically with variations in attention. It is noteworthy that the description and manipulation of behavior in applied settings are increasingly based on recording the number of intervals in which targeted behavior occurs rather than on the count of discrete responses (Springer, Brown, & Duncan, 1981), thereby providing an approximate measure of cumulative duration.

Consequent Stimulus Dimension

The distinctions concerning dimensions of discrete and continuous response classes may also be made for the stimuli that function as reinforcers (or punishers). In laboratory contingencies, reinforcing stimuli are most often treated as discrete events in which the amounts of various dimensions are held constant across occasions. The contingency prescribes either occurrence or nonoccurrence of the consequent stimulus in relation to responding, which means that reinforcing stimuli participate in the contingency in an all-or-none fashion. For example, the specified reinforcer may be 4-s access to mixed grain, five points on a counter, or one monkey biscuit (see Catania, 1963).

Although it is less common, dimensional quantities of the reinforcer may vary across presentations. For instance, the reinforcer may range from 1- to 8-s access to grain, 1 to 10 points, or 0.5 to 5 g of monkey chow. In such cases, the contingency specifies the amount of the dimension to follow a given effective response (see Crespi, 1944; Davis & North, 1967; Harzem, Lowe, & Priddle-Higson, 1978; Logan, 1960).

Of course, continuous dimensions of stimuli that function as reinforcers may vary widely, and this variability is common in nonlaboratory settings. In the example of the retarded individual's self-injurious behavior, dimensions of the caregiver's attention may also vary along a number of continuous dimensions (e.g., duration, latency, or topographical features).

Contingency

The reinforcement contingency specifies a relation between values of a particular dimension of responding and values of a dimension of a consequent stimulus. The contingency determines the quantities that actually participate (the effective response dimension and the reinforcer dimension) by denoting these values. As previously noted, traditional reinforcement contingencies usually treat responses and consequent stimuli as discrete events. That is, reinforcement is typically contingent upon the occurrence of some specified number of discrete, easily repeatable responses that have been completed when the reinforcer is delivered, and reinforcing stimuli are usually presented on an all-or-none basis. However, contingencies may allow continuous response or reinforcer variation, as in the cumulative distance and duration schedules already described (Rider & Kametani, 1984, 1987; Skinner & Morse, 1958).

When variation in response and reinforcer dimensions is incorporated into contingencies, responses and reinforcers may be programmed to covary. For example, in Logan's (1960) correlated reinforcement procedure, the measured amount of the dimension of behavior that enters into the contingency is summed, and the amount of reinforcement per presentation depends on the amount of responding. This contingency has been most often used with discontinuous effective response dimensions (e.g., Buskist, Oliveira-Castro, & Bennett, 1988; Gentry & Marr, 1982; Hendry, 1962; Hendry & Van-Toller, 1964).

A second type of covariation contingency is possible when the effective response and consequent stimulus dimensions covary on a moment-to-moment basis, as in conjugate reinforcement procedures (e.g., Lindsley, 1962; Lindsley & Skinner, 1954); this represents a special kind of response–reinforcer covariation that we will refer to as continuous covariation. Typically, the rate of responding and the intensity of a consequent stimulus are correlated such that the higher the response rate, the more intense the consequent stimulus, and the lower the response rate, the less intense the consequent stimulus. Conjugate reinforcement shares some features with other correlated reinforcement procedures, varied reinforcement-magnitude procedures, and response-differentiation procedures. However, conjugate reinforcement arranges a moment-to-moment correspondence between changes in responding and changes in the consequent stimulus;

changes in ongoing responding produce corresponding changes in ongoing stimulation.

A variety of response and reinforcer dimensions have been related in a variety of subjects under conjugate reinforcement procedures (see Rovee-Collier & Gekoski, 1979, for a review). Conjugate relations have proved powerful in demonstrating conditioning in subjects with whom conditioning was previously difficult to obtain, such as very young infants (Lipsitt, Pederson, & Delucia, 1966; Rovee-Collier & Capatides, 1979) and psychotic (Lindsley, 1963; Lindsley & Skinner, 1954), retarded (Switzky & Haywood, 1973), sleeping (Lindsley, 1957), anesthetized (Lindsley, Hodika, & Etsten, 1961), and comatose (Lindsley & Conran, 1962) human subjects.

A General Model

We propose that reinforcement and punishment contingencies be viewed in a broader dimensional context than has become customary. The various dimensions that fully characterize a response class or that define its occurrence should be distinguished from those that are effective in satisfying the contingency's requirements. The construction of the contingency should involve distinct consideration of whether the effective dimension of the response class and of the consequent stimulus class is discontinuous or continuous. Finally, the functions of the contingency relating response and stimulus dimensions should be considered in terms of the options provided by discontinuous versus continuous effective dimensions.

The present experiment was designed to probe some of the implications of this model. Discontinuous and continuous dimensions were selected (count and duration, respectively), and four schedules were constructed (Figure 1). The contingency relating the number or countability of responses to the number of reinforcers on an all-or-none basis (upper left) corresponds to traditional reinforcement schedules using discontinuous dimensions. Two of the contingencies result from mixing discrete and continuous dimensions across response and stimulus classes (lower left and upper right), and the fourth represents a relation between two continuous dimensions allowing continuous covariation (lower right). The details of these four contingencies will be presented below.

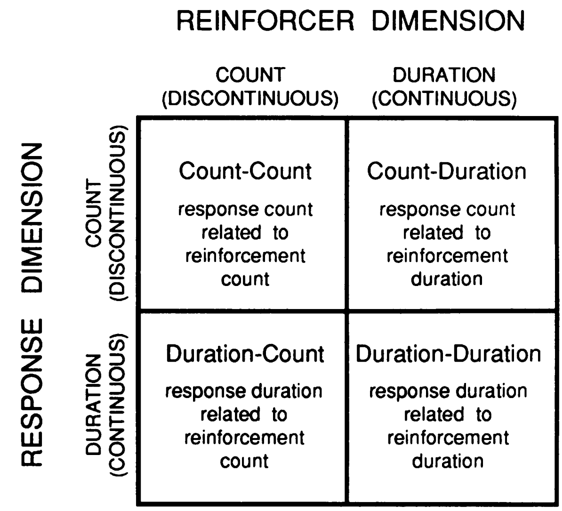

Fig. 1. The four possible relations incorporating the dimensions of duration and count into a simple schedule. Count-count: One response produces one stimulus event. Duration-count: Accumulation of the unitary amount of response duration produces one stimulus event. Count-duration: One response produces one unit of stimulus duration. Duration-duration: Each unit of response duration produces an equal amount of stimulus duration.

METHOD

Subjects

Forty-one subjects were recruited from the introductory psychology subject pool at the University of Florida. They participated in partial fulfillment of a research participation requirement for that course.

Apparatus

The apparatus was a wooden cabinet housing a motorized filmstrip projector (reading machine) that back-projected images onto a translucent screen (58 cm by 30 cm) mounted in the front panel (64 cm wide and 56 cm tall) of the cabinet facing the subject. The manipulandum was an acrylic plastic disk, or wheel, 1 cm thick and 15 cm in diameter. The friction on the wheel was adjusted such that it would not rotate without constant pressure (i.e., it could not be spun). A response was counted when the wheel was rotated in either direction with a force of at least 1.42 N (142 g) for a distance of at least 1 cm (7.6°). A 7-W green lamp was mounted behind the translucent screen 3 cm from its left edge.

The stimulus material consisted of commercially available 35-mm filmstrips (Educational Developmental Laboratories series LK) composed of reading passages 1,680 to 1,800 words long broken into single frames containing a line of text averaging six words. The reading passages were rated as suitable for low-average to average college freshman reading ability. The image of text (2 cm by 20 cm) was projected one line at a time onto the center of the screen by the projector at a rate of 55 lines per min. The film advanced only when the projector lamp was illuminated. The stimulus was presented and removed by turning the projector on and off, and the 50-W projector bulb darkened immediately when the voltage was removed. The printed comprehension tests (Taylor, Frackenpohl, Schleich, & Schick, 1964) were composed of 10 multiple choice questions.

Experimental sessions were conducted in a room (2.4 m by 3 m) containing the apparatus on a table and a chair. The room was illuminated at office levels. Electromechanical control and recording equipment was located in an adjacent room. During the sessions, the subject wore sound-attenuating headphones and was alone in the room. The experimenter observed the subject through a one-way mirror.

Procedure

Preliminary treatment and instructions. The subject was given a copy of the instructions (see appendix) and was told to read along silently as the experimenter read the instructions orally. The instructions stated that the subject was to read the material presented on the screen as well as he or she could. The function of the green light, which was illuminated throughout the session, was explained, and the subject was informed that he or she could do anything while in the room as long as he or she remained seated. Questions from subjects were handled by repeating or paraphrasing the pertinent part of the instructions or by saying, "It will become clear soon." A copy of the instructions remained in the room with the subject throughout his or her participation.

Each subject was exposed to one of the four schedule types. Performance was evaluated for stability by visual inspection of cumulative records, but time constraints necessitated terminating some phases before stability could be reached. Subjects served for periods of 60 min per day for 4 or 5 days, depending on availability. Individual sessions lasted for one reading passage or for a maximum duration of 30 min. The average session length was 10 min, and on average, four sessions were completed each daily period.

Shaping and conditioning. The wheel-turning response was shaped during the first session. The experimenter manually operated the projector for 1 s following approximations to the wheel-turning response (e.g., reaching toward or touching the wheel). If a criterion response was not emitted after 5 min, the experimenter entered the room and modeled the response by moving the wheel to produce a frame of reading material. Five subjects required modeling (2583, 7508, 7642, 8613, and 8701). The number of subjects exposed to each contingency and the number of sessions for each subject can be determined from the summary figures in the Results section. The experimental contingency was instituted after the first criterion response. Subsequent sessions began with the programmed contingencies in effect.

Following the conclusion of each session (except extinction sessions), the subject was given a multiple choice test form covering the passage just completed and told to mark the correct answers on the form. Meanwhile, the experimenter changed filmstrips. The tests were scored in the presence of the subject, and the experimenter commented briefly on the subject's test performance.

Schedule contingencies. A response occurrence was counted at initiation, which was defined as each superthreshold movement of the wheel from its resting state for 0.1 s or longer. Response termination was defined as the point at which movement of the wheel was not detected for at least 0.1 s. Response duration was always the time between response initiation and termination. A consequent stimulus event was defined as the illumination and then termination of the screen with the textual material from the film strip.

The four experimental contingencies and possible performance-schedule interactions under these contingencies are illustrated in the form of event records in Figure 2, and the following descriptions refer to those traces. Note that the arbitrary designation of the unit of duration is necessary when a discontinuous dimension is related to a continuous dimension as in the count-duration and duration-count

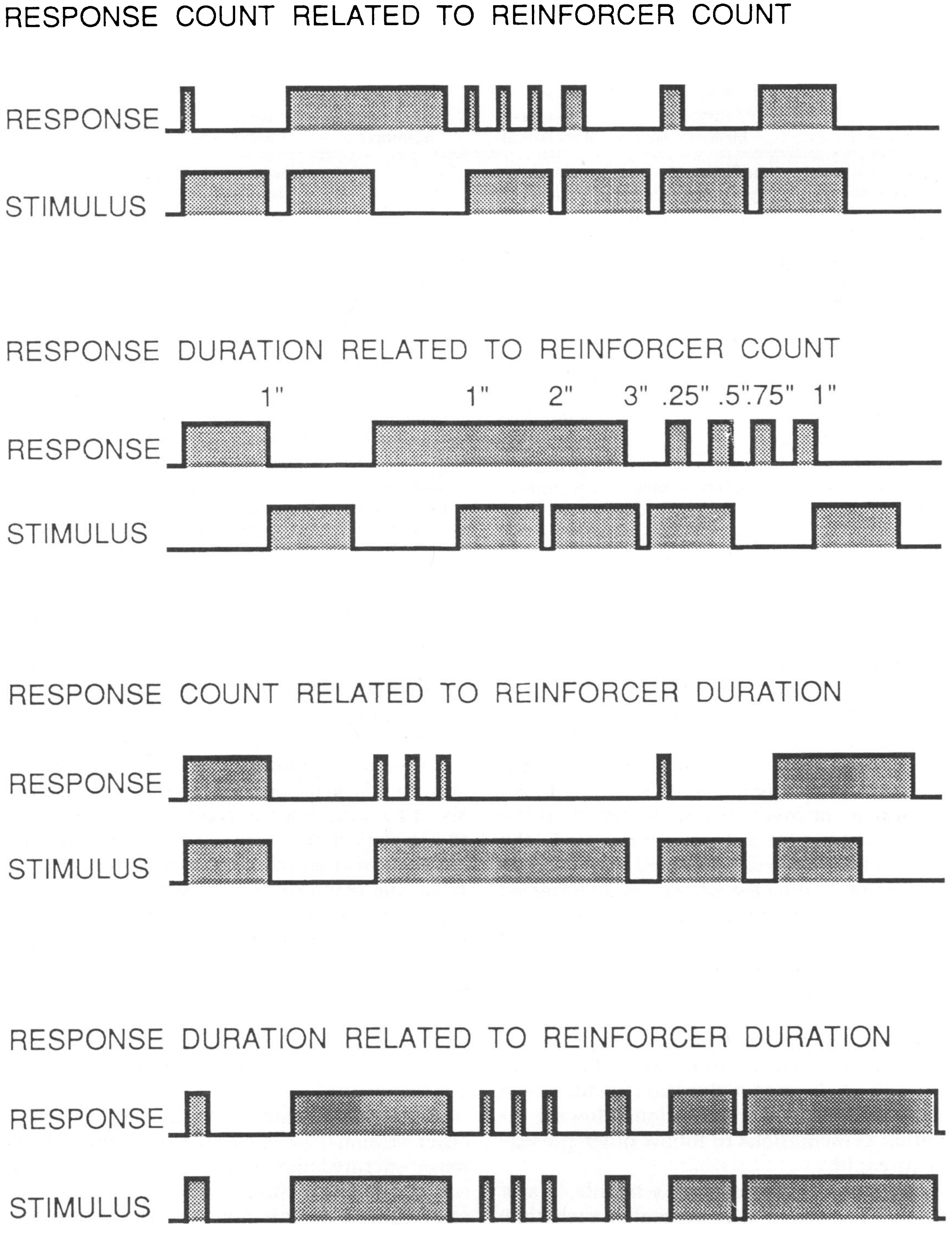

Fig. 2. Schematic of the four possible relations incorporating count and/or duration under a continuous reinforcement schedule. The event (response or reinforcing stimulus) is occurring when the trace deflects up and is not occurring when the trace deflects down. The durations of events are indicated by horizontal distance. The values above the response trace under the second panel from the top indicate cumulative seconds until a consequent stimulus presentation.

Table 2
Summary of procedural details for the four schedule contingencies.

Schedule	Basis for stimulus presentation	Basis for stimulus termination	Responding effective during stimulus?	Response termination required?
Response count–reinforcer count	Initiation of wheel turning	1 s fixed duration	No	Yes—ongoing response must end for another response initiation
Response duration–reinforcer count	Accumulation of 1 s of wheel turning	1 s fixed duration	Yes—response duration accumulates during stimulus	No—reinforcement is dependent on total accumulated response duration
Response count–reinforcer duration	Initiation of wheel turning	End of accumulated duration	Yes—response count accumulates during stimulus	Yes—ongoing response must end for another response initiation
Response duration–reinforcer duration	Initiation of wheel turning	Response termination	Yes—stimulus maintained for duration of response	No—reinforcement is dependent on total accumulated response duration

schedules; a minimum unit value of 1 s was selected.

The count-count schedule related response count to consequent stimulus count. As illustrated in the top pair of traces of Figure 2, initiation of wheel turning turned the projector on for a fixed period (1 s). Responses initiated during the stimulus had no effect. If the response was not concluded by the time that the stimulus presentation was terminated, the screen could not be reilluminated until the subject stopped turning the wheel and then started again when the stimulus was not present.

Under the duration-count schedule, response count was formally irrelevant to the contingency. Instead, each cumulative second that the wheel was turned (indicated by the cumulative values above the response record in Figure 2) turned the projector on for a fixed period (1 s). Response duration accumulated during the stimulus presentation, allowing individual presentations to follow other presentations rapidly.

Under the count-duration schedule, 1 s of stimulus projection was presented each time the subject initiated wheel turning. Responses initiated during a stimulus presentation prolonged that presentation for an additional second (as represented by the series of three brief, closely spaced responses that earned 3 continuous seconds of the stimulus). Note that duration of responses was irrelevant except that long-duration responses precluded initiating another response and producing or prolonging the stimulus.

Under the duration-duration schedule, the duration of responding and the duration of the stimulus covaried on a moment-to-moment basis. The stimulus projector was activated by the initiation of a response and remained on for the duration of the response, terminating when the response terminated.

Table 2 summarizes procedural features of these relationships. In particular, it identifies the response feature that produced the consequent stimulus, the basis for terminating that stimulus, whether responding during the stimulus was effective, and whether response termination was required for the presentation of additional stimuli.

Extinction. Extinction sessions began like all other sessions, except that the projector was never operated and stimulus presentations did not occur. Extinction sessions lasted for the approximate duration of the last conditioning session. At the conclusion of an extinction session, the experimenter entered the room and told the subject that there would be no test this time. The experimenter then opened the top of the apparatus, advanced the film 10 frames

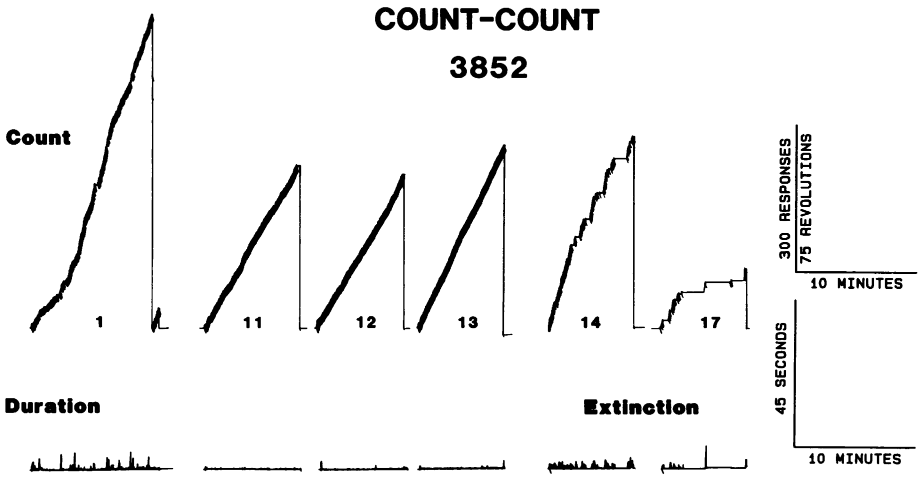

Fig. 3. Cumulative records from a representative subject under the count-count schedule. For records in the rows labeled "count," the pen stepped once for each response initiation and four times per revolution of the wheel. Therefore the vertical distance of the record represents a combination of the number of responses and distance of wheel turning for each response. Slash marks indicate response termination, and their spacing indicates response rate. For records labeled "duration," the pen stepped seven times per second of responding (wheel turning), and reset when turning stopped or when the pen reached the top of the record.

to simulate loading a new film, and left the room. Extinction phases lasted until the subject ceased responding for 5 consecutive minutes or until it was necessary to dismiss the subject because of time constraints.

RESULTS

Cumulative Record Conventions

Performance under the four schedules is shown by cumulative records in Figures 3, 5, 7, and 9. In the top record for each subject (labeled "count"), the pen was stepped once for each response initiation and, thereafter, for each quarter turn of the wheel. Termination of each response produced a slash mark on the record. The vertical distance of the record represents a combination of the number of response initiations and the distance that the wheel was turned for each response, as represented by the scale on each record. The horizontal distance on these records represents the session time, and the slope of the line represents the speed of responding (i.e., distance divided by time). Individual slash marks are difficult to discern on records depicting high rates of response initiations because slash marks appear as a thickened line (see Figures 3 and 5 for examples of high-rate and low-rate patterns, respectively).

The bottom set of records (labeled "duration") is temporally aligned with the top set and shows response duration. The pen stepped seven times per second while the subject turned the wheel and was reset when the response was terminated. Therefore, the height of each line represents the duration of each response. The pen was also reset at the top of the record, and when response durations were very long, the count record had to be checked to verify whether a reset was due to response termination or to the automatic reset mechanism (e.g., Figure 9).

Count-Count Schedule

Figure 3 shows the cumulative records for the first session (1) and the last three sessions (11, 12, and 13) of conditioning, as well as the first (14) and last (17) sessions of extinction for Subject 3852, whose patterns of responding are representative of 6 of the 7 subjects exposed to this contingency. In general, performance was characterized by a short transition period in which rates of response initiations increased and response durations decreased. Response rates were quite high and durations very short during the final sessions. Under extinction conditions, the rate of response initiations decreased (slash marks), durations initially increased, and pauses became longer and more frequent.

Figure 4 shows the mean response initiation

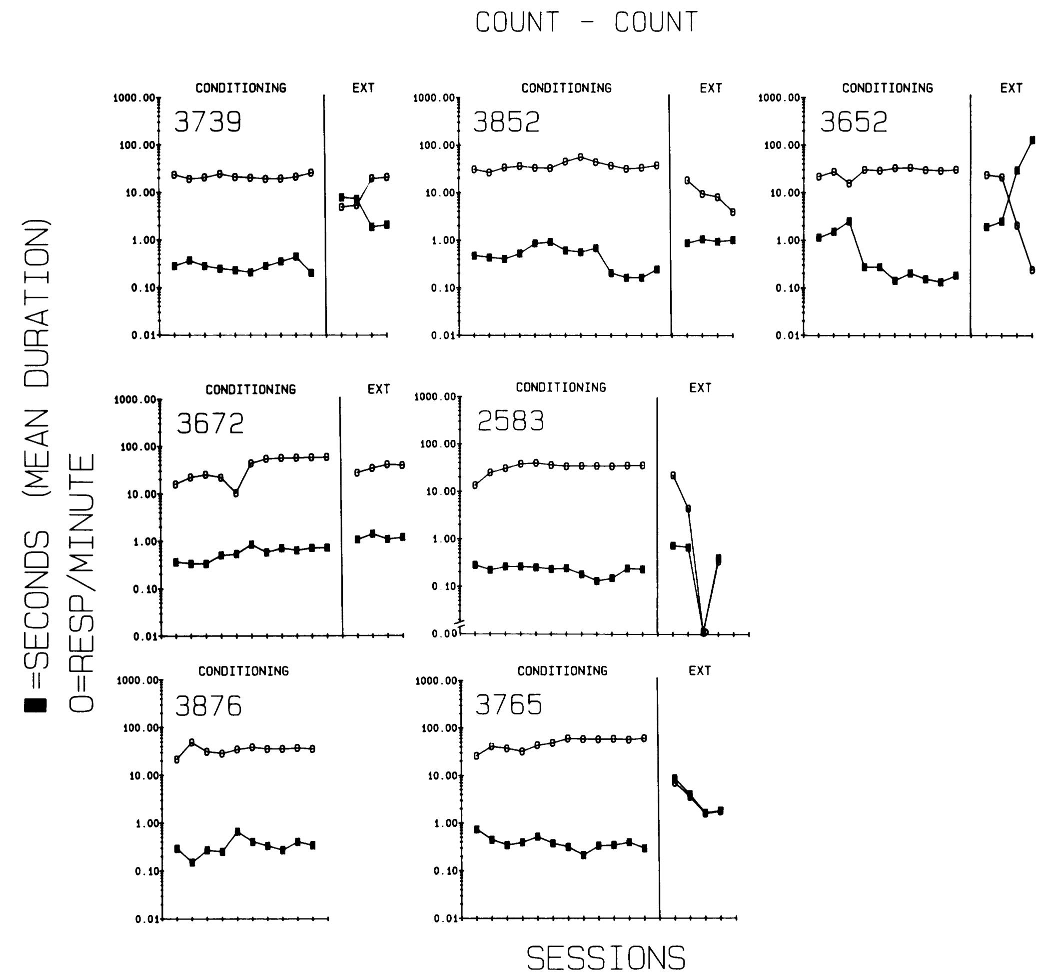

Fig. 4. Response duration (closed symbols) and rate of response initiations (open symbols) under the count-count contingency. Numbered graphs present data from all sessions for individual subjects. The zero value was added to the logarithmic scale for Subject 2583, who did not respond during an extinction session.

rate and mean response duration in seconds across all sessions for each subject exposed to the count-count schedule. The count-count schedule produced moderate to high response rates that were somewhat lower than the maximum functional rate of 60 responses per minute, indicating that responses were not emitted during the 1-s stimulus period. The responses were of very brief duration, and most subjects spend the majority of session time (about 70%) not responding (i.e., not turning the wheel). Response rates and durations were highly stable during the conditioning phase. Under extinction conditions, the rate of response initiations initially decreased and durations increased; for most subjects variability was greater in both dimensions than during conditioning.

Duration-Count Schedule

The cumulative records for the first session (1) and last three sessions (6, 7, and 8) of conditioning and the first (9) and last (12) sessions of extinction for Subject 7772 are presented in Figure 5. This performance is typical of that of 7 of the 9 subjects exposed to this contingency. During Session 1, response rate was initially quite high and durations were short, but by the end of this session, the rate of response initiations had decreased (as shown by the decrease in the frequency of slash marks), and durations had increased markedly. Stable

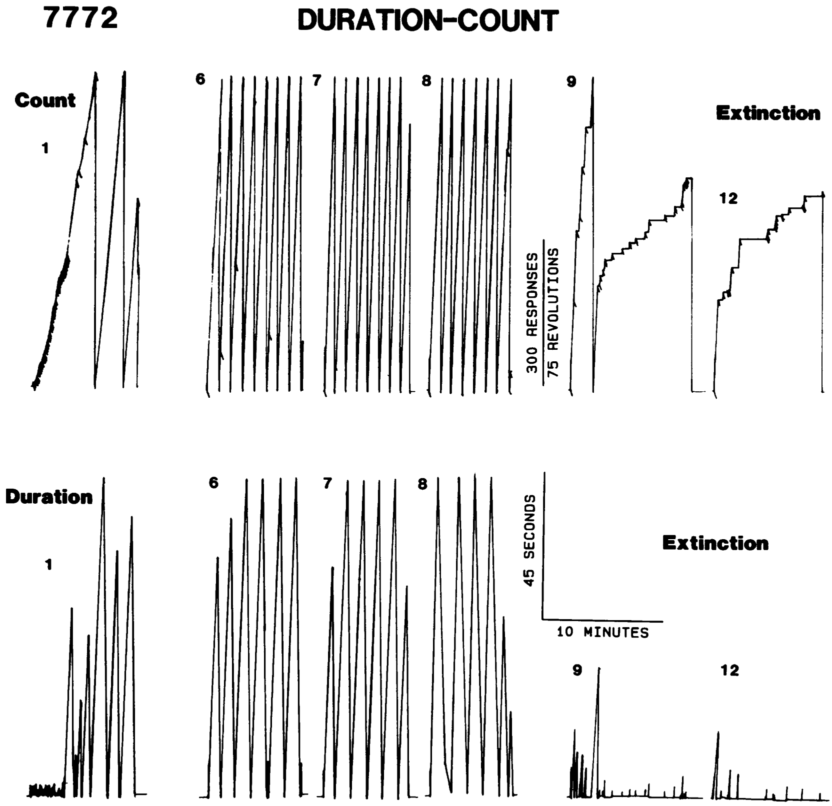

Fig. 5. Representative cumulative records from Subject 7772 under the duration-count contingency. For records in the row labeled "count," the pen stepped once for each response initiation and four times per revolution of the wheel. Therefore, the vertical distance of the record represents a combination of the number of responses and distance of wheel turning for each response. Slash marks indicate response termination, and their spacing indicates response rate. For records labeled "duration," the pen stepped seven times per second of responding (wheel turning), and reset when turning stopped or when the pen reached the top of the record.

performance during the last three sessions was characterized by a very low rate of response initiations and long-duration responses. During the extinction phase, response rate increased, duration decreased, and periods of no wheel-turning became evident.

Response rates and mean durations for all duration-count schedule subjects are presented in Figure 6. Variability in both response rate and durations was relatively high across sessions for the majority of the subjects. Five subjects showed low-rate, long-duration responding. Two subjects (KT and 7616) showed high response rates and short response durations, and 2 other subjects (7508 and 7576) exhibited performances intermediate to these extremes.

A high degree of variability across subjects was evident during the extinction condition. For most subjects who had exhibited low-rate responding, response rates increased and durations declined during the first extinction session. The opposite effect occurred in the performance of subjects who showed high-rate, short-duration performance during conditioning (KT and 7616). Responding continued throughout the extinction condition, with clear decreases evident only in Subjects 7799 and 7508, but rates and durations were different than under conditioning. Reinstatement of the contingency produced a partial return to preextinction levels of responding in 3 of 4 subjects (the exception being Subject 6682), although the number of sessions was inadequate to assess the full effects of this reversal.

There was considerably greater intersubject variability under this schedule contingency than under the count-count schedule. The gradual transition in rate and duration to terminal val-

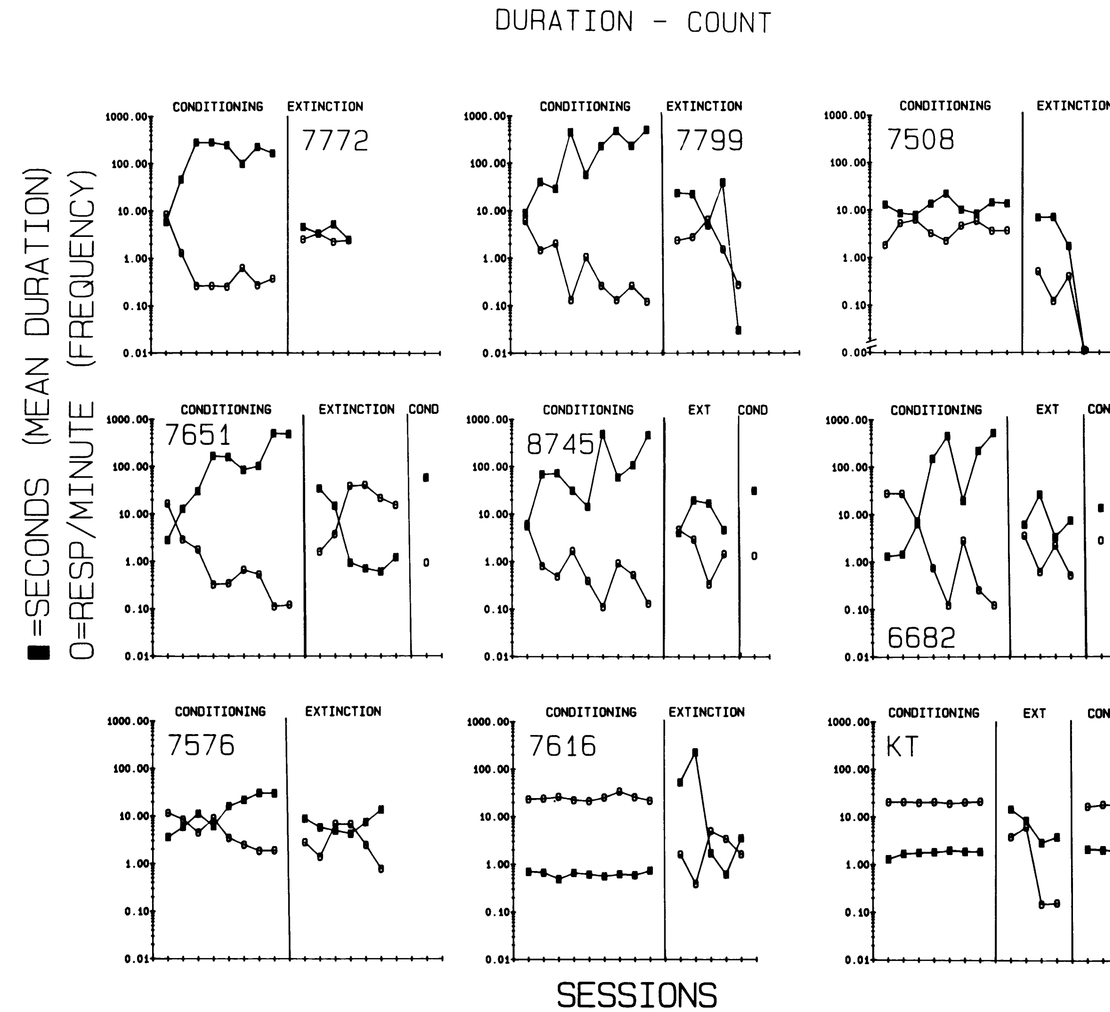

Fig. 6. Response duration (closed symbols) and rate of response initiations (open symbols) under the duration-count contingency. Numbered graphs present data from all sessions for individual subjects. The zero value was added to the logarithmic scale for Subject 7508.

ues was quite different from the rapid attainment of terminal values under the count-count schedule.

Count-Duration Schedule

Figure 7 presents cumulative records from the first (1) and last three (7, 8, and 9) sessions of conditioning and the first (10) and last (16) sessions of extinction and brief reconditioning period (last half of 16) for Subject 7652, as representative of all 11 subjects under the count-duration schedule. There was a brief transitional period early in the conditioning phase. Terminal performance consisted of short-duration responses and a high rate of response initiations.

Under the first extinction session, the response rate decreased, and pauses became more frequent and longer throughout the session. In general, response initiations occurred in bursts. Response durations remained relatively short and did not change greatly during extinction. Reinitiation of the schedule produced a rapid return of the high response rate.

Figure 8 presents the rates of response initiation and mean response durations for all subjects exposed to the count-duration schedule. Response rates were quite stable under conditioning and reached their terminal values early in the conditioning phase. Performance resembled that of subjects under the count-count schedule and contrasts with the slower

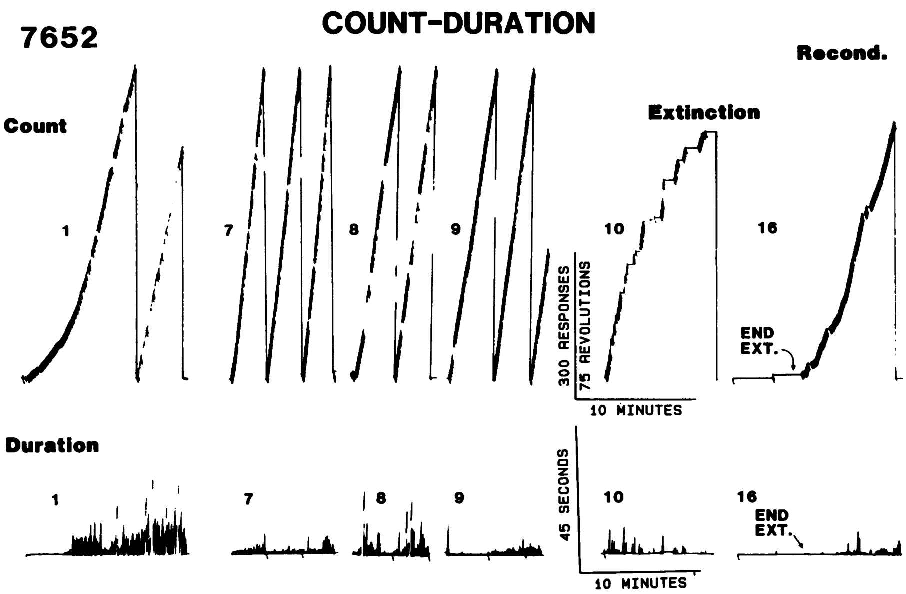

Fig. 7. Representative cumulative records form Subject 7652 early and late in conditioning and extinction and early in reconditioning (numbers indicate session numbers). For records in the rows labeled "count," the pen stepped once for each response initiation and four times per revolution of the wheel. Therefore, the vertical distance of the record represents a combination of the number of responses and distance of wheel turning for each response. Slash marks indicate response termination, and their spacing indicates response rate. For records labeled "duration," the pen stepped seven times per second of responding (wheel turning), and reset when turning stopped or when the pen reached the top of the record.

transition and greater variability under the duration-count schedule.

During the first extinction session, the rate of response initiations generally decreased and response durations were unchanged or increased only slightly. Further rate decreases occurred for 4 of the 6 subjects exposed to several extinction sessions, but duration did not change as much as rate, except when responding essentially ceased. Subject 8538 showed little change under extinction. Both measures returned to near preextinction levels upon reinstatement of the schedule contingency.

Duration-Duration Schedule

Figure 9 presents cumulative records from the first (1) and the last two (7 and 8) conditioning sessions, the first (9) and last (13) extinction sessions, and the reconditioning session (14) for Subject 6740, whose performance was representative of all 14 subjects in this condition. Response-initiation rates were high and response durations very short during Session 1, in contrast to Sessions 7 and 8, during which a single response was emitted that lasted for the remainder of each session.

Under extinction, response durations decreased and the rate of response initiations increased rapidly. Pauses began to occur and became longer and more frequent until responding virtually ceased in Session 13. Reinstatement of the schedule contingency produced a rapid return to preextinction levels and patterns of responding.

Figure 10 presents response-initiation rate and duration data for the subjects exposed to the duration-duration schedule. Subjects generally showed a relatively gradual transition to stable terminal levels for both rate of response initiation and average response duration. All subjects showed the same low-rate, relatively long-duration pattern in their terminal performance under conditioning (Subject 8613 might be an exception). The mean response-initiation rate for the three final sessions of the conditioning phase was 0.6 per minute, and the mean response duration for these three sessions was 209 s. During the extinction phase, response-initiation rates increased in the first session, while durations decreased. These measures then both generally decreased during additional extinction sessions for 9 of the 12 subjects exposed to the extinc-

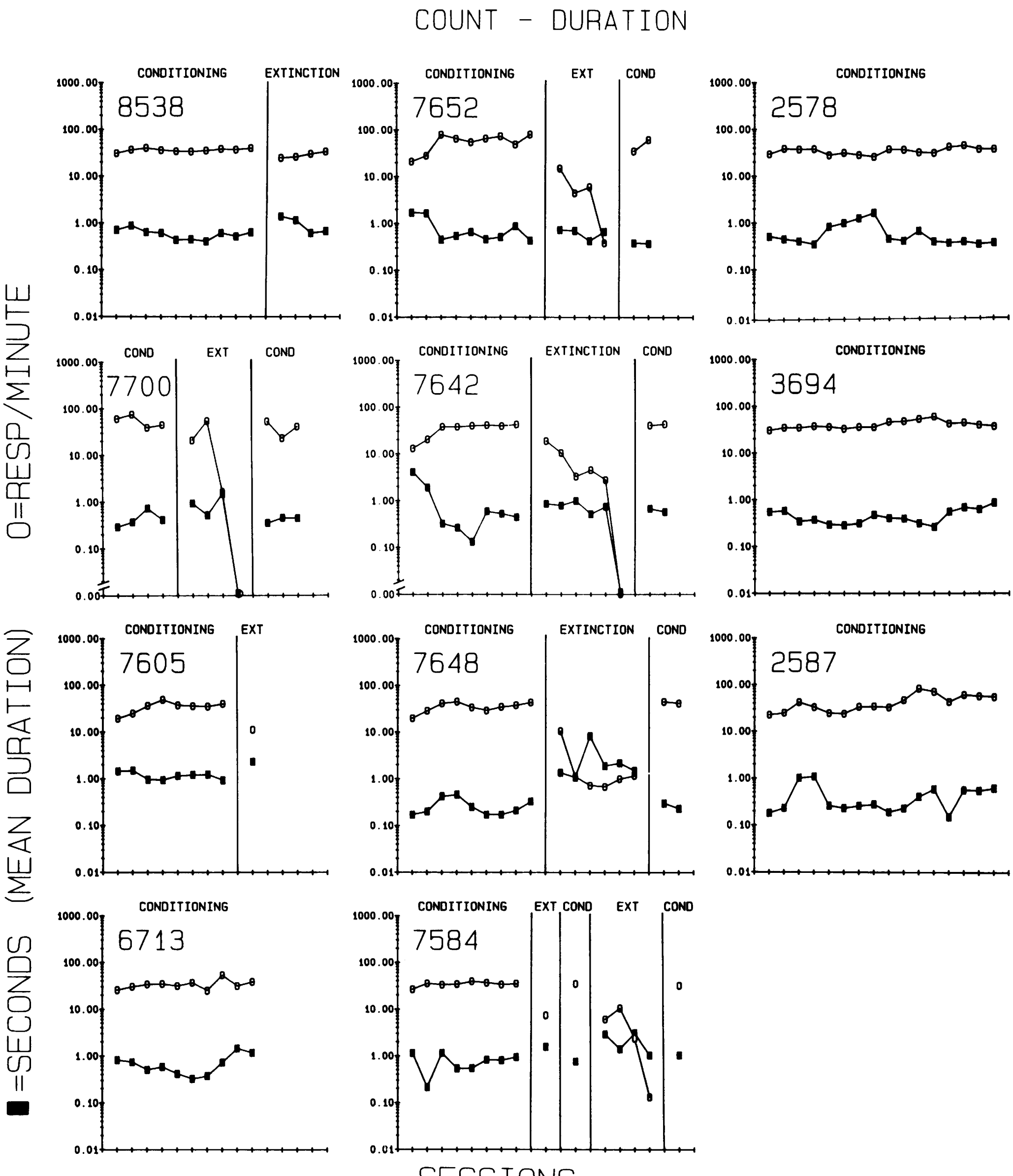

Fig. 8. Response duration (closed symbols) and rate of response initiations (open symbols) under the count-duration schedule. Individual graphs present data from all sessions for individual subjects. The zero value was added to the logarithmic scale for Subjects 7700 and 7642.

tion condition. Rates and durations returned to near preextinction levels for all 6 subjects reexposed to the contingency.

Percentage of Session Spent Responding

Figure 11 presents group means and ranges of the percentage of the session time spent responding across the four schedules for each of the first five and the last three sessions of conditioning, the first and last sessions of extinction, and the first session of reconditioning (when available). The mean percentage of the session time spent responding under the count-count and count-duration schedules were relatively low and variable. Large numbers of responses were emitted under the conditioning

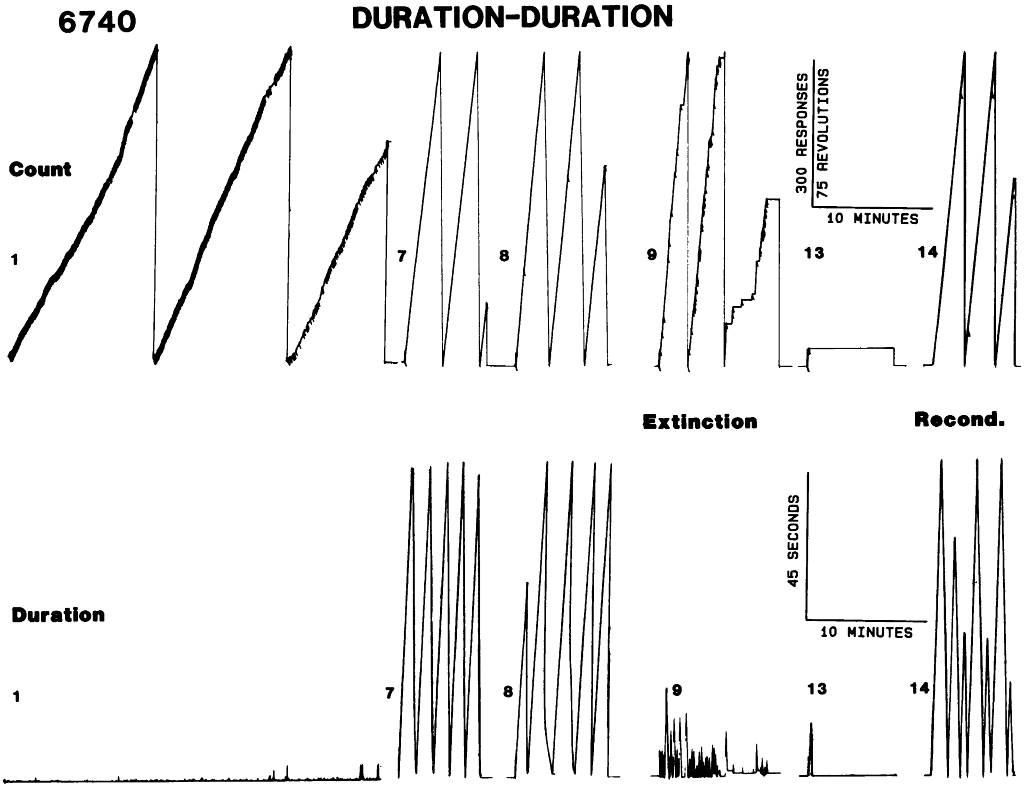

Fig. 9. Cumulative records showing performance of Subject 6740 early and late in conditioning and extinction and early in reconditioning (numbers indicate session numbers) under the duration-duration schedule. For records in the rows labeled "count," the pen stepped once for each response initiation and four times per revolution of the wheel. Therefore, the vertical distance of the record represents a combination of the number of responses and distance of wheel turning for each response. Slash marks indicate response termination, and their spacing indicates response rate. For records in the bottom row labeled "duration," the pen stepped seven times per second of responding (wheel turning), and reset when turning stopped or when the pen reached the top of the record.

phase, but subjects tended to spend less than half of the available time turning the wheel. Extinction produced essentially no change in this measure under the count-count schedule (half of the subjects showed an increase and half showed a decrease). However, all subjects under the count-duration schedule showed consistent decreases in the percentage of time spent responding. This measure increased to near preextinction levels in the first reconditioning session.

In general, responding occupied most of the session time in the conditioning phase under the duration-count and duration-duration schedules. The ranges for the last three conditioning sessions were smaller for the duration-duration schedule than for the duration-count schedule, and were smaller for both of these schedules than for the count-count and count-duration schedules. The mean percentage of the session spent responding quickly decreased under extinction. This measure increased to near preextinction levels in the first reconditioning session, although the ranges were quite large.

Comparison of Schedule Effects

Figure 12 compares the group mean response-initiation rates, group mean response durations, and group mean percentage of time spent responding under conditioning, extinction, and reconditioning for each schedule. Error bars represent one standard deviation from the mean (note that error bars are either above or below the mean). Under conditioning, data are from the final three sessions. In the middle panel showing extinction data, the open bars represent the first extinction session, and the

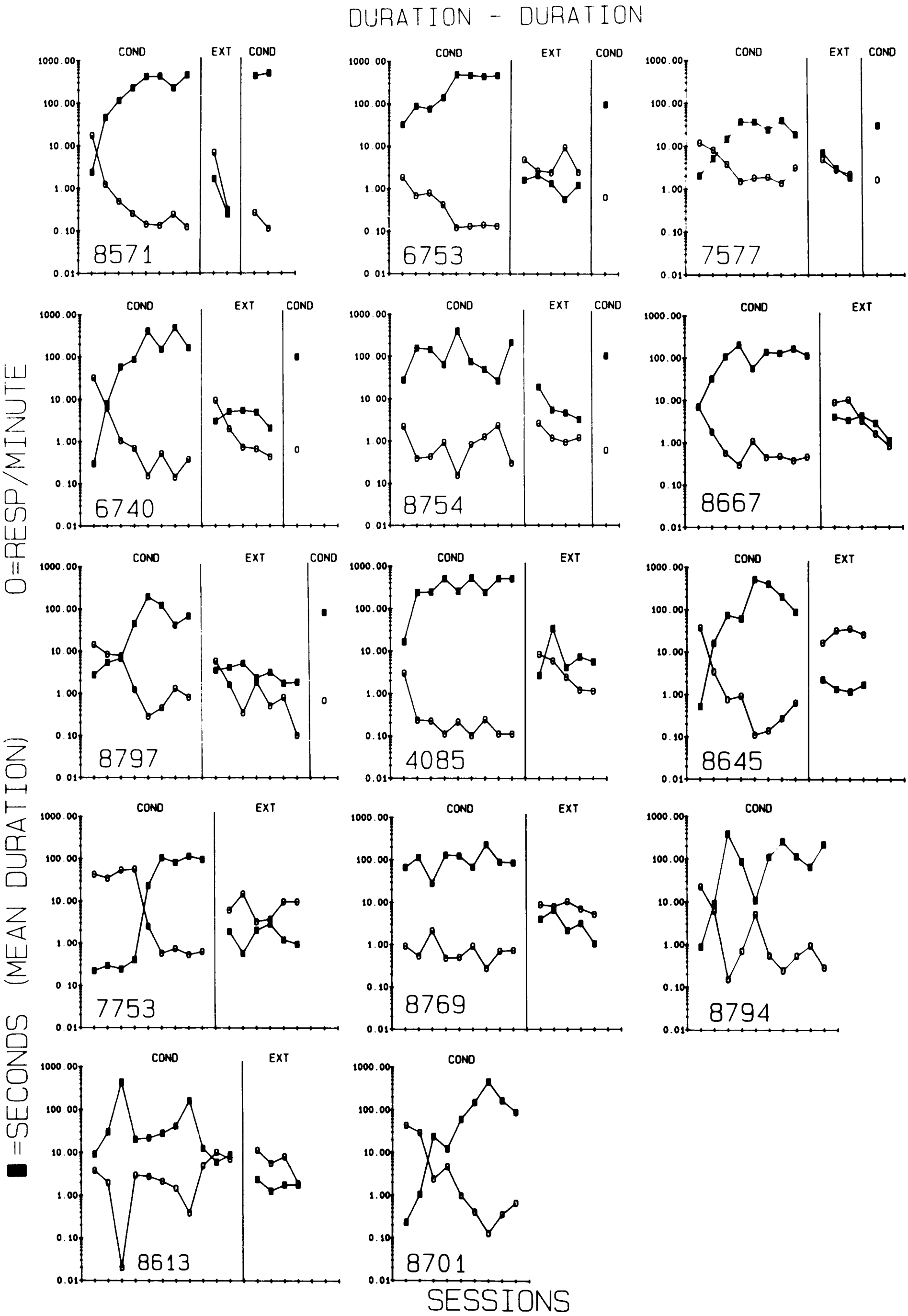

Fig. 10. Response duration (closed symbols) and rate of response initiation (open symbols) under the duration-duration contingency. Numbered graphs present data from all sessions for individual subjects.

shaded bars represent the last extinction session (from subjects who had more than two extinction sessions). Under reconditioning, data are from the first session of reexposure to the schedule.

These three measures show that the major differences in performance among the schedules were determined by the nature of the response dimension entering into the schedule contingency. The mean rates of response ini-

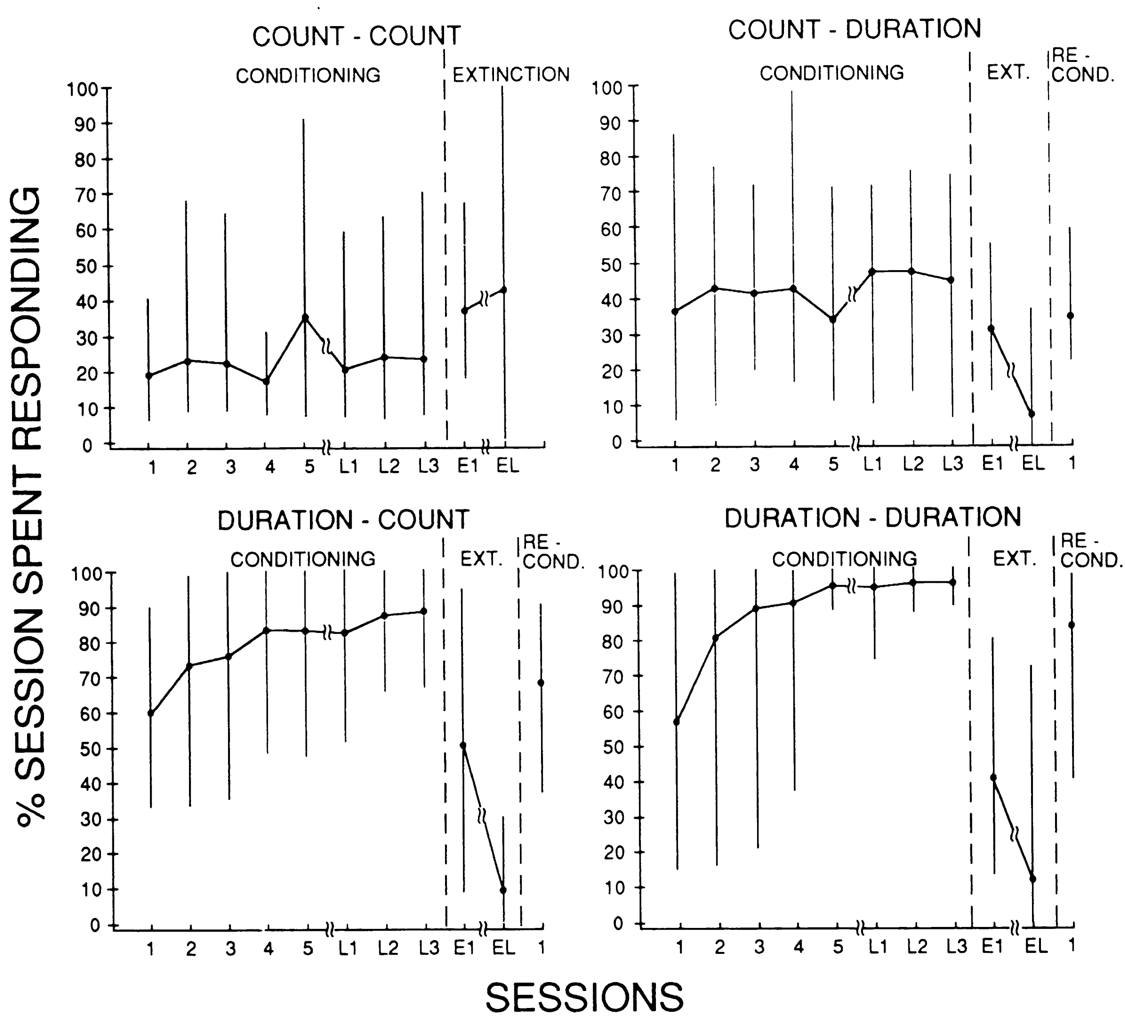

Fig. 11. Group means and ranges of the percentage of the total session time spent responding for the four schedule contingencies. Data are from the first five and the last three conditioning sessions (L1, L2, L3), the first and last extinction sessions (E1, EL), and the first reconditioning session.

tiations from the two sets of subjects exposed to schedules incorporating response count were consistently higher than the mean rates from the subjects exposed to schedules incorporating response duration, but response rates were not greatly different across the count-count and count-duration schedules. The means of response duration and the percentage of the session spent responding were both greater under the duration-count and duration-duration schedules than under the schedules incorporating response count, but were not greatly different across the two response-duration contingencies. The standard deviations were considerably larger for response duration than for the percentage measure.

The extinction condition had the general effect of reducing those measures maintained at high values under conditioning and increasing those maintained at low values. However, under the duration-count schedule, the mean response rate decreased under the first extinction session, and under the count-duration schedule, the percentage of the session spent responding was lower during both extinction sessions than under conditioning. Upon reinstatement of the contingencies, group-mean response rates returned to near preextinction levels in all three groups exposed to a second conditioning phase, but response duration and the percentage of the session spent responding were lower than during the original condi-

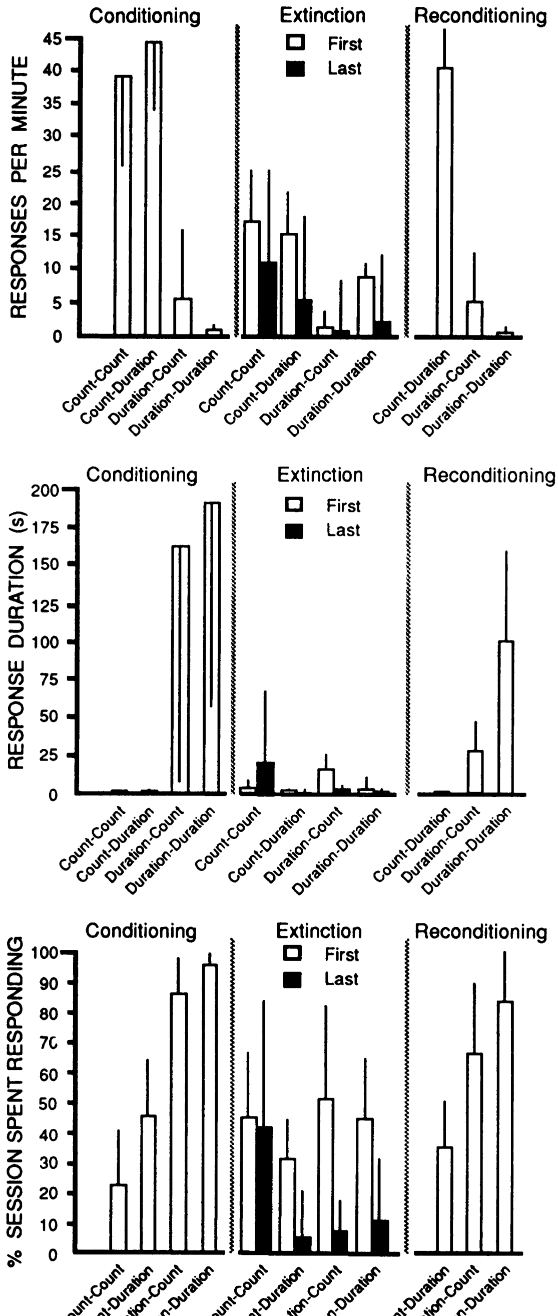

Fig. 12. Group means of response-initiation rate (top panel), response duration (middle panel), and the percentage of the session spent responding (bottom panel). Error bars represent one standard deviation from the mean. The graphs present data from the last three sessions across subjects for conditioning, the first session (open bars) and the last session (shaded bars) for extinction, and the first session of reconditioning phases (no subjects underwent reconditioning for the count-count schedule).

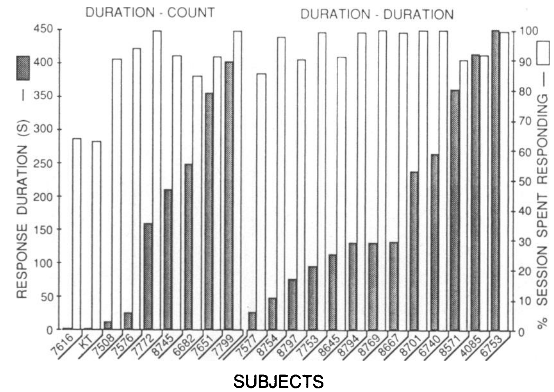

Fig. 13. Mean response duration (shaded bars) and percentage of session time spent responding (open bars) for each subject under the duration-count and the duration-duration schedules. Means are from the last three sessions under conditioning. Response duration is measured along the left ordinate, and percentage of time spent responding is measured by the right ordinate.

tioning phase for the duration-count and, to a lesser extent, the duration-duration schedules.

Under conditioning, the group means of response duration and the percentage of time spent responding were correlated under the duration-count and duration-duration schedules. However, there was considerably greater variability in response duration than in the percentage of the session spent responding, as indicated by the relative size of the standard deviations in Figure 12.

Figure 13 illustrates the relation of response duration and the percentage of time spent responding under the duration-count and duration-duration schedules in greater detail. Each pair of bars shows the means for the last three sessions under the conditioning phase for individual subjects. The percentage of session time spent responding was high and relatively stable across the wide range of average response durations.

Variability in the percentage of the session time spent responding was largely unaffected by the number of responses emitted (except when rate was high), unlike the average response duration. Because no specific duration of individual responses was specified under the duration-count and duration-duration schedules, the number of responses emitted during the session was free to vary. Response duration was accumulated by many short responses, a single long response, or any number of responses in between, for different subjects. Thus, across subjects, greater consistency was shown in the percentage of session time spent responding than in the duration of individual responses.

DISCUSSION

The count-count schedule generated responses of brief durations like those typically generated by traditional fixed-ratio (FR) 1 preparations. Performances were similar to those of studies that measured, but contained no programmed contingencies for, response duration (e.g., Antonitis, 1951; Herrick & Bromberger, 1965; Margulies, 1961; Millenson et al., 1961). It should be noted that the brief response durations resulted from contingencies that designated response count as the effective response dimension, and not from physical restrictions by the manipulandum.

The duration-count and duration-duration contingencies increased the duration of responding and decreased the rate of responding. The effects of these contingencies on the probability of wheel turning is more directly indexed by the percentage of the session spent responding than by the rate or mean duration of responses. There was greater consistency in the proportion of time spent responding than in the duration of individual responses. Therefore, the functional operant class may have been the duration of wheel turning rather than responses of specific durations (Catania, 1973; Thompson, 1986). This suggests that units of behavior based on continuous response dimensions (e.g., duration) can be treated as equivalent to the traditional units of discrete responses (see Notterman & Mintz, 1965; Skinner & Morse, 1958).

The probable mechanism for reinforcing duration of responding, rather than responses of a particular duration, is that the duration-based contingencies delivered the reinforcer during ongoing responding. The duration-duration schedule did this directly; under the duration-count schedule, the summation of response duration across occurrences made it likely that the stimulus would be presented during ongoing responding rather than at response initiation or termination.

The schedule contingencies that allowed variation in consequent stimulus duration to be correlated with responding did not produce substantially different performances than those incorporating stimulus count. That is, performance under the count-duration and duration-duration schedules was similar to that under the count-count and duration-count schedules, respectively. It made little difference whether responding produced the onset of the reinforcer or prolonged the reinforcer as well. This finding may be specific to FR 1 schedules that generated responding at maximal levels under all contingencies. Differences due to the consequent stimulus dimension may be more readily shown with intermittent schedules, which characteristically allow dynamic effects in the different measures to be shown (Ferster & Skinner, 1957; Zeiler, 1977). Interval schedules would be of particular interest because of the minimal response requirement.

The duration-duration schedule made continuous, moment-to-moment covariation in response and reinforcer quantities possible. Although it produced long-duration responding like the duration-count schedule, different features of responding actually *produced* the reinforcer. Under the duration-duration schedule, the consequent stimulus began when wheel turning began rather than after 1 s of accumulated response duration (during ongoing responding). However, under both contingencies, long-duration responding may have been maintained by prolonging the ongoing stimulus or chain of stimuli rather than by initiating the stimulus.

The long-duration responding could also have resulted from a Type II punishment contingency for cessation of wheel turning. That is, ceasing wheel turning terminated the reinforcing stimulus. Operation of such a punishment process is described by Findley (1962; see also Thomas, 1966), in which lengthening the timeout following response cessation increased responding during the period in which reinforcers were available on an intermittent schedule. Such a punishment contingency might underlie extended responding in nonlaboratory circumstances as well.

The punishment process may play a lesser role relative to positive reinforcement in procedures that correlate responding with dimensions of consequent stimuli other than duration (e.g., brightness, loudness, hue, etc.). When duration is the specified dimension of the consequent stimulus, responses made during the period when the stimulus is present serve only to increase its duration. Hence, there is no immediate environmental change contingent on ongoing responding. If, however, brightness or loudness of the stimulus is correlated with responding, responses result in an immediate change in the stimulus. This seems more compatible with a positive reinforcement process. However, in any contingency of this sort, reinforcement and punishment processes are intertwined.

Lindsley has suggested that contingencies involving continuous covariation (as with conjugate reinforcement and our duration-duration schedule) may be the most common in nature (cited in Rovee-Collier & Gekoski, 1979). Many skilled performances seem to fall into this category (e.g., figure skating, singing, driving), and questions concerning instructional and maintenance contingencies are therefore pertinent. The natural contingencies of this sort shape behavior automatically. That is, every response produces some amount of a consequent stimulus without deliberate programming involving successive approximations, as is seen in the development of various driving skills in the novice driver. Such relations would be expected to operate widely in nature to produce persistent performances, whether desirable or troublesome. It is reasonable to suppose that there would be benefits to incorporating this type of contingency into formal training procedures and our analysis of problematic behavior patterns.

Response–Stimulus Covariation

The incorporation of continuous and discontinuous dimensions in these four contingencies raises the issue of agreement between the continuous nature of response and reinforcer dimensions. That is, schedules can be homogeneous (e.g., count-count and duration-duration) or heterogeneous (e.g., count-duration and duration-count) with regard to response and reinforcer dimensions. Although the present data were not clear on the effects of these combinations, it is interesting to consider the procedural ramifications of them, as well as the effects that might be forthcoming under slightly different arrangements.

Homogeneity may allow a greater point-to-point correspondence between responding and reinforcing stimulation, which might lead to greater control over responding than in heterogeneous arrangements. Under homogeneous relations, each response that is eligible for reinforcement is immediately followed by a change in the stimulus along the relevant dimension. For example, under the count-count schedule, each response initiation was immediately followed by a stimulus, and under the duration-duration schedule, response durations were immediately and identically matched by reinforcer durations.

Heterogeneous relations impose constraints on the correspondence of response and stimulus quantities that may affect performance by influencing the precision of response and stimulus covariation. This constraint is largely determined by the discontinuous element. If, in a heterogeneous relation, the consequent stimulus dimension is discontinuous, the effect may be evident in the ability of the stimulus to strengthen responding. For example, under the duration-count schedule, a change from low to intermediate values of responding can produce no contiguous change in the stimulus because the minimal unit value of response duration (1 s) is required to produce one reinforcer. One half second of responding cannot produce one half of a reinforcer. The feedback functions for such heterogeneous schedules are generally more molar than for homogeneous relations.

Consideration of how the point-to-point correspondence of response and stimulus quantities affects the formation and modification of response and stimulus classes within a schedule may be useful in studying the mechanisms of conditioning processes. For example, in studying the contingencies responsible for the dynamic effects of interval schedules, heterogeneous correlated reinforcement procedures have been used to reinforce the number of responses or rate emitted on fixed-interval (FI) schedules. Hendry (1962) and Gentry and Eskew (1984) successfully increased the number of responses under short FI schedules by correlating duration of access to grain with response count. However, Gentry and Marr (1982) were unsuccessful with longer duration FI schedules, perhaps because the longer interval reduced point-to-point correspondence (see Buskist et al., 1988).

Number of Effective Dimensions

The general model outlined here suggests the possibility of relations involving multiple concurrent effective response and stimulus dimensions that participate in the contingency. Although laboratory schedule preparations most often relate a single dimension of responding to a single dimension of the reinforcing stimulus, they could as well incorporate two or more dimensions of either. For example, if response force and duration were both effective dimensions, reinforcement would be produced by responses that met one of three types of criteria: involving quantities of both dimensions (conjunctive), either dimension (conjoint), or some combination of the two dimensions (interlocking). Multiple reinforcing stimulus dimensions may be similarly incorporated.

In nonlaboratory settings, contingencies often naturally involve covariation in multiple dimensions. Consider, for example, the bowing responses of a violinist. From one moment to another there may be variation in various features of the grip of the bow: the downward pressure exerted on it by the violinist's forefinger, the pitch angle of the bow relative to the strings it touches, the location of the bow on the length of the string and in relation to the sounding box, the rotational angle of the bow relative to the string it touches, and the speed of its movement across the string. Of course, these possibilities apply to just one bowing stroke, and even then they are only the most obvious dimensions that vary.

These moment-to-moment changes in responding produce moment-to-moment changes in the sounds produced. For example, a slight increase in the downward force of the bow or the speed of its movement immediately produces changes in the resulting auditory stimuli. Such multiple and continuously variable response and stimulus dimensions are related in a manner somewhat similar to our duration-duration schedule, but with covariation in a variety of dimensions.

Social contingencies similarly involve multiple response and reinforcer dimensions. A child's behavior of whining, for example, may produce variation in a parent's attention. Variations in the frequency, pitch, intensity, and duration of whining may covary with variations in frequency, latency, and topography of the parent's attention.

Extension to Some Traditional Concepts

Response differentiation and shaping. The increased duration of responding observed under the duration-count and duration-duration schedules resembles the effects of response-differentiation schedules involving response duration (e.g., Herrick, 1964). However, in response-differentiation procedures, the effective response dimension is discontinuous. That is, only those response cycles having durations longer than some specified value are reinforced. Responses shorter (or longer) than the criterion thus decrease in frequency, while response cycles that approximate the specified duration increase. This does not necessarily increase the total time spent responding. In contrast, our duration-duration schedule does not include this mechanism of differential reinforcement of criterion responses. Instead, every response earned some reinforcement in direct proportion to its duration. The result was maximum levels of responding on this dimension.

In response-differentiation schedules, the experimenter progressively increases the duration criterion while not exceeding the range of present responses (see Eckerman, Hienz, Stern, & Kowlowitz, 1980; Galbicka & Platt, 1986; Herrick, 1964). In contrast, the duration-count and duration-duration schedules produced their patterns of responding without ongoing changes in schedule parameters. In other words, under traditional procedures, differentiation is accomplished by progressively narrowing the functional response class, whereas the present schedules established a very wide functional response class that allowed covariation between response duration and stimulus parameters. The result did not so much differentiate with regard to a predetermined value as with regard to a maximum value.

Intermittent reinforcement. The present model can accommodate alternatives to intermittent schedules based on response count. Ratio schedules may be defined as contingencies in which some amount of a dimension of the response class is required to produce some amount of a dimension of the consequence (Rider & Kametani, 1984, 1987). Any dimension of the response or the stimulus class may be inserted without destroying the essential nature of the ratio relation. For example, an FR 10 schedule might refer to a ratio of 10 s of response duration to one cycle of the reinforcer, with the number of responses emitted to produce each 10-s requirement being irrelevant (see Rider & Kametani, 1984, 1987). Similarly, if the dimension were force, this ratio requirement would be met when 10 N of force had been accumulated, regardless of the number of responses or aggregate duration (e.g., Notterman & Mintz, 1965). The reinforcer can be defined in terms of other dimensions as well, independently of how the response class is measured. Thus, 10 units of the response-class dimension may produce a 1-s duration reinforcer presentation.

Applying this perspective to interval schedules opens up an equally wide array of interesting contingencies. Any dimension may be substituted for response or reinforcer count. Summation of the continuous effective response dimension might begin after the interval has expired.

Analysis of Natural Schedules

Contemporary applied research on behavior is largely therapeutic, educational, or corrective in focus, and often pays little attention to understanding the mechanisms by which behavior develops and is modulated (Johnston, in press). The vast literature on reinforcement schedules has had only the most general impact on the techniques that are used to manage behavior for practical ends in field settings. Why have applied researchers not found the basic literature a productive source of raw materials with which to construct practical and effective behavior management procedures? Perhaps this is because applied researchers encounter many situations in which the kinds of response classes, reinforcers, and contingencies found in natural settings are not congruent with the reinforcement schedules most familiar in the laboratory.

The issue of whether the literature on reinforcement schedules has more to offer than the few generalities presently in common applied use remains unresolved. Although this goal can be partly accomplished within the traditional perspective that has guided the literature to date, it may be even more effectively pursued if the conception of schedule relations is broadened in the manner described here.

In summary, this paper has proposed a general perspective of schedules of reinforcement that, although fundamentally consistent with existing traditions, broadens them. This approach is motivated by the desire to define and study schedule contingencies in ways that more fully represent the nature of schedule relations and their effects with humans behaving in everyday environments. This goal requires incorporating a greater range of dimensions that characterize behavioral and environmental events.

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APPENDIX

The following instructions were given to all subjects.

In general, this is a study of your responding to read and the variables that might affect it. Your task is simply to read the material that may be presented on the screen in front of you as well as you can. What you do on the panel below the screen will influence how the material will be presented. The material may be produced one line at a time, and you should read each line and try to keep up with the flow of the entire passage. A green light will come on when the material may be read and will go off when the task is over. At this time you will be asked to complete a short comprehension test on the material you have just read. After the task is over, you should remain seated until the experimenter reenters this room and tells you what to do next. Remember that what you do while in this room will influence how the material is presented. It is possible to read every line depending on what you do, and you may do anything as long as you remain seated in the chair. If you have any questions, you may ask them now. Please put the earphones on now. They are only to prevent distracting noise from the hallway. You may adjust them so they are comfortable, and we will start in a few minutes.