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USING REVEALED OPERANTS TO STUDY THE STRUCTURE AND PROPERTIES OF HUMAN OPERANT BEHAVIOR

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The "revealed operant" is described as a practical research tool. It differs from traditional types of operants that are recorded as single instantaneous events, in that some of the revealed operant's sub-operants can be recorded conveniently, and that the first and last of these are made on separate manipulanda. A revealed operant can be studied by examining multiple measures relating to the internal structure of individual occurrences of the operant, including incomplete occurrences. A practical method for implementing revealed operants for human subjects, using only a personal computer and keyboard, is used in pilot studies of (a) resurgence after extinction and after an abrupt increase in the revealed operant's work requirement, (b) variability changes during and after extinction, (c) effects of fixed ratio size and of the revealed operant's work requirement, (d) sensitivity of different components as a function of their distance from the end of the revealed operant, and (e) changes in the revealed operant's internal patterns as a function of long-term repetition.

In traditional operant behavior experiments, operant responses are usually recorded only as single instantaneous events, like the closure of a switch, registering the operant at the instant of its completion as an all-or-none event (the "effect" that defines the operant). This makes it very difficult to study response structure because the topography of the response is not automatically recorded. Mechner (1992) has described a model of an operant response, termed the revealed operant, that combines a sequential response with elements of chained and second-order reinforcement schedule technology. Its purpose is to provide a practical way to record and study the internal structure and properties of

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operant responses. This article will describe its application to study operant behavior in humans.

For all operants, including instantaneously recorded operants, one could identify "sub-operants," that is, components of the stream of behavior that comprise the operant. In bar pressing, for example, before the rat can close the switch, it must place a paw on the response bar and move it downward. When instantaneous operants are used, such sub-operants are determined unintentionally by the physical construction of the response device and are normally unrecorded and disregarded. Only the last member of the sequence of sub-operants, that is, the single event that defines the operant (switch closure), is recorded. Recording and analyzing earlier members of the sequence can be cumbersome, as was seen when Stokes and Balsam (1991) made videotapes of bar pressing and then analyzed some sub-operants frame by frame. In other cases, special measuring equipment may be required, as when Allan and Zeigler (1994) attached electrodes and magnets to pigeon beaks to study the topography of gapes as part of autoshaped key-directed behavior (see also Bermejo, Houben, & Zeigler, 1994).

A revealed operant differs from an instantaneous operant only in that some of its sub-operants are specified deliberately rather than unintentionally, in a way that allows them to be recorded conveniently, that is, in a way that *reveals* them. Hence the term "revealed operant" (hereafter abbreviated as rO.) This does not mean that the rO captures all of the sub-operants involved in response emission; there will always be some response components not detected, but more of the operant is made observable than with standard instantaneous operant preparations. The issue of whether the rO's sub-operants, by virtue of being specified, may impart different properties on the operant than the "natural" sub-operants of a bar press, was discussed extensively by D. M. Baer and Mechner in Mechner (1992). To summarize that discussion, Baer considered the possibility that rOs may have different properties than instantaneous operants because the sub-operants of rOs are imposed, and therefore constrained, by the experimenter. Mechner argued that the sub-operants of instantaneous operants are also constrained in comparable ways by the experimenter. In choosing a response manipulandum with certain physical features such as height, width, and force requirements necessary for operation, the experimenter is inadvertently imposing constraints on sub-operants such as body position and head or paw movements; thus, sub-operants are imposed to some degree in both rOs and instantaneous operants.

The rO provides a convenient and practical way to address certain questions that cannot be addressed as easily with instantaneous operants. Examples of such questions are: Is a particular response rate change caused by a change in the response durations or in the time between responses? What are the effects of a single presentation of a reinforcer on a stream of operants, and on what do those effects depend? What are some of the mechanisms of behavior shaping?

Structure of a Revealed Operant Occurrence

An rO, by definition, must have an initiating sub-operant R_a, made on a separate manipulandum, to define the beginning of the rO behaviorally and unambiguously. For many kinds of experiments, it is also important to define the rO's end point in terms of the subject's behavior by means of a terminating sub-operant R_c (rather than by aborting the rO by experimental intervention). Between the R_a and the R_c there can be a sequence of R_bs, a required wait, or any other specified behavior, according to how one wishes to define and specify the rO. In the present studies, R_a consisted of pressing the spacebar on a computer keyboard, R_c consisted of pressing the return key, and the R_bs were character key presses (see Figure 1). A minimum number of R_bs were required but the particular character keys chosen, from an array of eight that were exposed, were at the subject's option.

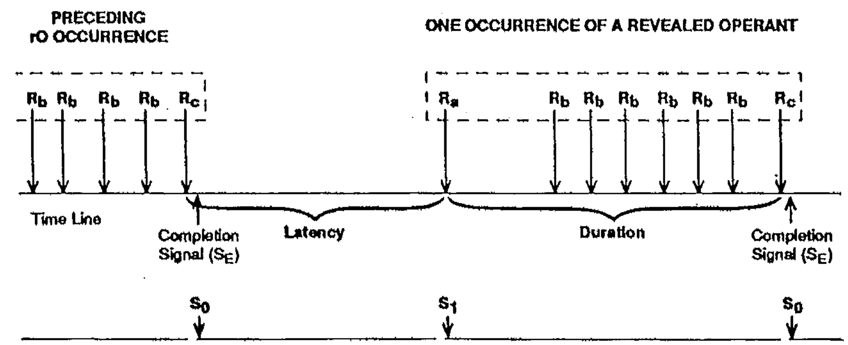

Figure 1. Generic diagram of a complete individual occurrence of an rO and the end portion of the preceding occurrence. The diagram shows the time relationships between the initiating sub-operant (R_a), the other sub-operants that can comprise the rO, and the on-screen stimulus presentations that marked response initiation and completion.

A variety of behavioral measures can be recorded for each individual occurrence of an rO: (1) Duration: the R_a-R_c time; (2) time between R_a and the first R_b; (3) run length: the number of R_bs made in each rO; (4) the rate at which the R_bs are made within an rO, (5) the time between the last R_b and R_c, (6) latency: the time between the end of one rO and the initiation of the next, the R_c-R_a time; and (7) patterns: recurring sequences of particular keystrokes, and rhythms (defined in terms of patterns of time intervals between R_bs).

These measures fall into two categories: criterial and noncriterial measures. Criterial measures are those which are part of the specification of the operant, and noncriterial measures are those which are not (Herrnstein, 1966, p. 38). Examples of criterial measures used in the past are the force exerted on the bar (because if it does not exceed a minimum level the bar will not move), the length of time the bar is held down where a minimum time is specified, and thumb muscle potentials where a minimum potential was required (Hefferline, Keenan, & Harford, 1959). Examples of noncriterial measures are: Length of time the bar is held down when the operant is bar release (Margulies, 1961), where no minimum time is required; the sequence in which four keys are pressed, where no particular sequence is required, and sequence is not part of the specification of the operant (Bruner & Revusky, 1961); position along a long horizontal slot where the rat can poke its nose through (Antonitis, 1951); and position along a long horizontal strip where a pigeon can peck (Herrnstein, 1961). In both of these last two studies, all positions were equivalent for meeting the criterion.

For the rO used in the present study, only run length (number of R_bs) is a criterial measure, and all the other measures listed in the paragraph preceding the last are noncriterial measures. Any noncriterial measure becomes a criterial measure if it is made part of the criteria that define the operant. It is important to distinguish between criterial and noncriterial measures because they are often differentially sensitive to various types of independent variables (Mechner, 1959; Mechner, Guevrekian, & Mechner, 1963; Mechner & Latranyi, 1963). Guthrie was clearly referring to noncriterial measures and the internal structure of operant occurrences when he wrote that for psychology to make real progress, psychologists will need to measure "movement series," "movement patterns," and "partial or subresponses," and not just the all-or-none occurrence of "acts" (e.g., Guthrie, 1959, pp. 184-185).

Marr (1992) has pointed out that the rO is a type of behavioral unit. In this respect, the rO shares much in common with other "complex operants," that is, operant units consisting of identifiable sequential components. Interest in these extended operant units has a long history in the experimental analysis of behavior (Thompson & Zeiler, 1986). Forms of complex operants have been studied with multi-operandum preparations requiring certain response sequences (e.g., Galbicka, Kautz, & Jagers, 1993; Mechner, 1958a; Page & Neuringer, 1985; Schwartz, 1980) and as higher order units composed of many operants in chained or second-order schedules of reinforcement (Ferster & Skinner, 1957; Kelleher, 1966a; Marr, 1971). They have been variously identified as chains (Boren & Devine, 1968; Kelleher, 1966b; Kelleher & Gollub, 1962; Lattal & Crawford-Godbey, 1985; Skinner, 1938), multi-operant repertoires (Findley, 1962), sequential operants (Schwartz, 1982), and behavior combinations (Thompson & Lubinski, 1986). Relatively little experimental work has been conducted with human subjects in the analysis of complex operants as such, though chains have been used as tools to investigate rule-governed behavior (Danforth, Chase, Dolan, & Joyce, 1990; Vaughan, 1985) as well as drug effects in humans (e.g., Higgins, Rush, Hughes, Bickel, Lynn, & Capeless, 1992). An interesting conceptual treatment of extended operant units in human behavior is offered by Lubinski and Thompson (1986).

Marr (1992) also suggested that putting an rO on a reinforcement schedule is similar to a second-order schedule preparation. In a second-order schedule, a schedule unit is itself reinforced on some schedule, such as fixed-ratio units reinforced on a fixed-interval schedule (Kelleher, 1966a). One could view all of the keystrokes involved in completing an rO as a response requirement on a ratio schedule, but the schedule specifies certain topographical elements in addition to a minimum number of keystrokes (which may be exceeded) so it is more complicated than the simple response requirements of standard ratio schedules. Placing completed rOs themselves on ratio schedules (e.g., so that one has to emit 10 rOs to produce points exchangeable for money) does have elements of second-order scheduling, at least in the sense that fulfilling the rO completion contingency makes this behavior eligible for reinforcement according to another contingency.

The rO differs from other types of operant units in that its beginning and end points are marked by *behavioral* events as opposed to experimentally imposed events. In the final component of a chained schedule, for example, the operant unit is terminated when responding is interrupted by the automated delivery of a reinforcer as soon as the schedule requirement is met. Similarly, the response sequences studied by Page and Neuringer (1985) and Schwartz (1980) did not have a behaviorally marked end point, although the first peck after the intertrial blackout may be functionally similar to an rO's R_a. In an rO preparation, subjects indicate when they begin and when they finish each operant. The rO's sequence of keypresses is intended to be analogous to the structure of a keypeck or bar press from its beginning to its end, if one could detect subtle aspects of the movement toward the key or bar and record the time between those aspects.

One advantage of arranging for behavioral events rather than experimentally imposed events to mark the beginning and end points of each occurrence is that occurrences that are distorted or incomplete in their internal structure can be readily identified as instances of the operant unit and analyzed. Comparable recording of incomplete instantaneous operants, such as incipient keypecks ("air pecks") or off-key pecks, is rarely done and presents some measurement challenges (see Bachrach, 1966; Gleeson, 1991; Iversen, 1991). A second advantage of behaviorally marked beginning and end points is that measures of response duration are easily obtained and distinguished from what we have earlier called latency. These measures are normally confounded because they are subsumed as part of conventional measures of interresponse time. Johnston and Hodge (1989) discussed the fact that this confounding obscures some behavioral relations that may be of interest.

There is evidently no limit to the variety and range of rOs that can be defined. But for many types of studies, it is advantageous to use rOs that can be executed in less than a few seconds. The higher the rO rates, the more observations can be made in a single session, thereby reducing variation in subjects' behavioral states such as session-to-session variations. Accordingly, another characteristic of an experimentally practical and useful rO is that it can be emitted by the subject at high rates.

Our first objective was to answer some preliminary questions of method: What is a practical way to implement rOs in human subjects? How many R_bs should be required, and how much money should be paid per reinforcement? What rates of occurrence can be expected for our rO? How long should each session be? What is a good way to define and measure repetitive patterns and rhythms in the intra-operant sequences of R_bs? But our main objective was to demonstrate the feasibility of using the rO methodology to address some of the issues raised by Mechner (1992). Specifically, we wanted to begin to examine questions such as: What long-term drifts are there in the properties of an operant as a function of repetition? What kinds of resurgence of, or regression to, earlier response patterns occur when reinforcement is discontinued or other stressors are introduced? In what ways and how quickly is an operant affected when a new contingency is introduced? We will illustrate the application of the rO methodology to human operant behavior by describing sample data from a series of pilot studies on a wide range of topics and issues. These pilot studies fall short of being definitive experiments due to having fewer than three subjects, unbalanced order effects, and inadequate numbers of replications, but we believe that they demonstrate the general practicality and potential usefulness of the rO method.

Method

Subjects, Apparatus, and General Procedure

The subjects were 6 undergraduate students, 3 females and 3 males, recruited from introductory behavior analysis classes at the University of North Texas. Each subject sat in front of an 80386 IBM®-compatible personal computer. All sub-operants, stimulus events, and time intervals between R_bs were recorded with an assembly language timer program developed by Creeger, Miller, and Paredes (1990). With this type of apparatus and software, the resolution of time intervals between keystrokes and the accuracy of the recorded time intervals depends on the engineering specifications of the particular computer and keyboard used. The error range for our equipment was approximately ±7.5 milliseconds according to calibrations and estimates reported by Segalowitz and Graves (1990).

The keyboard was partially masked by a cardboard cover. The only exposed keys were the return key, part of the spacebar, and a horizontal array of the eight adjacent character keys (to the right of J and N) at the extreme lower right of the keyboard. A cushion was made available as an armrest.

The usual specification of the rO was a press of the spacebar followed by at least 10 presses of some combination of the eight character keys (R_bs) and then a press of the return key (R_c). In case of two or more consecutive presses of the same character key, only the first one counted toward fulfilling the R_b requirement. This entire sequence, which most subjects usually completed in 1 to 2 seconds, comprised a single occurrence of the rO.

Stimuli were presented on the monitor screen. Before an rO was initiated, the screen was red. An R_a changed its color to blue (S_1), and the next R_c changed it back to red (S_o). A beep (S_E) was produced by each R_c that completed an rO. An 800-ms flash of the term "$0.01" on the screen, accompanied by a tone, was used as the reinforcer. The total amount earned was paid in cash at the end of each session.

The subjects were instructed as follows: "Your job is to make money. The computer will keep track of how much you earn. You will be paid at the end of the session. Use your right hand only. Arrange the pad so that your arm is comfortable."

The subjects learned to execute rOs with a computer-administered shaping program. At the start of shaping, the screen was blue with an inserted white square (S_2) The first reinforcer was delivered the first time the return key was pressed. Return keypresses were reinforced twice more and then S_1 (blue screen without white square) was presented for the first time. An R_b was required to change S_1 to S_2, and the next R_c was reinforced. After three such cycles, the screen turned red (S_o). Now an R_a was required to produce S_1, and the number of R_bs required to produce S_2 was gradually increased to ten. Finally, S_2 was eliminated, at which point the subject no longer had the visual cue for when to make R_c. Each subject's entire shaping process took less than 3 minutes. The length of subsequent experimental sessions was limited to 10-12 minutes to minimize hand fatigue. Two sessions were usually conducted each day, separated by 5-minute breaks. The average number of rOs per session ranged from about 200 to 350.

The six subjects were maintained on the procedure described above for 30 to 90 sessions, corresponding to a total of about 5-20 hours per subject, and 10,000 to 25,000 rOs. The various independent variables discussed below were tested at various stages. Because the objective of the studies was to develop and demonstrate a practical and feasible methodology, most of the independent variables were tested in only two, three, or four of the subjects.

Results and Discussion

Long-Term Changes with Number of Repetitions

A noteworthy finding was that change in noncriterial measures was still occurring even after thousands of rO repetitions. Figure 2 shows how median latency (the R_c - R_a interval, or time between rOs) decreased over the first 27 sessions for Subject S1. A continuous reinforcement schedule was in effect throughout. Missing points correspond to equipment failures. Phase changes indicate when the R_b requirement was increased; this manipulation did not affect what appears to be a long-term decreasing trend in this measure. The average number of rOs per session for S1 was approximately 200, so that means that latency was still decreasing after 5,000 rO repetitions.

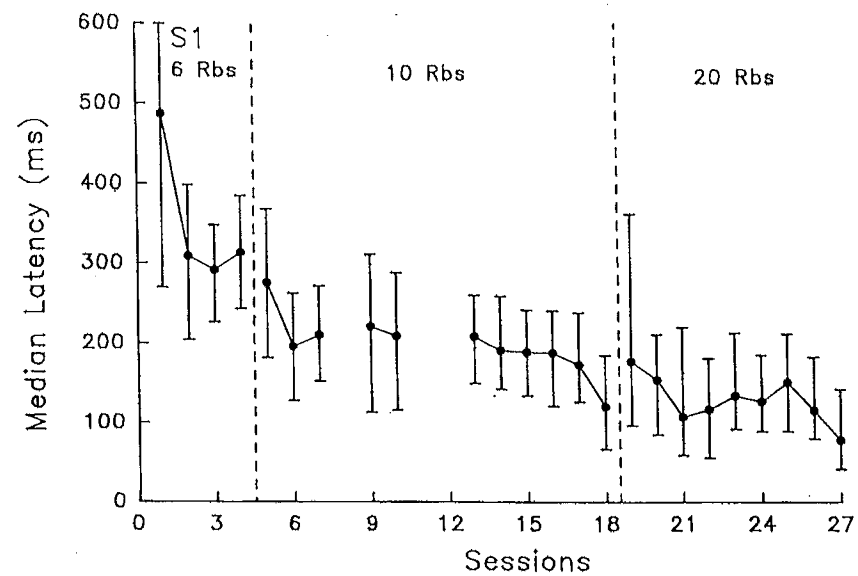

Figure 2. Median latencies across sessions for Subject S1 under continuous reinforcement. The number of R_bs required for an rO was increased from 6 to 10 after Session 4, and from 10 to 20 after Session 18. Vertical bars indicate interquartile ranges.

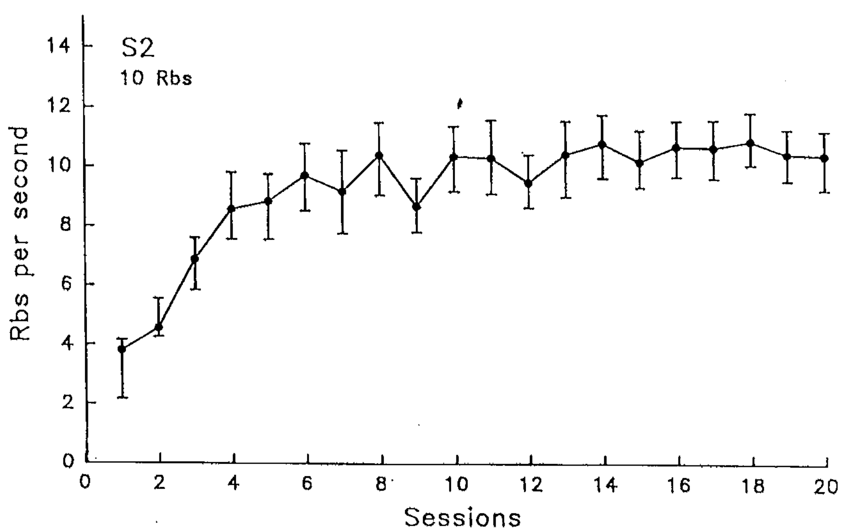

Figure 3. Median rate at which R_bs were executed within the rOs, in successive sessions of continuous reinforcement for Subject S2. The number of R_bs required per rO was 10.

Figure 3 shows how the R_b rate (within the rO) gradually increased from about 4 to about 11 R_bs per second during Subject S2's first 20 sessions. This subject averaged approximately 325 rOs per session, so the rate did not begin to stabilize until after 2,500 repetitions (by Session 8.) Observation of subjects revealed that they achieved such high R_b rates with various multifinger movements, including sequential little-finger-to-index-finger drumming on the keys (the finger movement one makes when impatient or bored in other contexts). The data in Figures 2 and 3 were typical of all subjects.

Changes in Variability

In our data analysis, a "sequence" was defined as three or four consecutive R_bs made on particular character keys (e.g., L, K, M) separated by particular time intervals (e.g., 350 ms between the L and K, and 200 ms between the K and M). Any sequence that occurred more than once was called a "pattern," provided that the inter-R_b intervals were within 100 ms of those in the original sequence. Thus, a pattern was a repeated sequence of particular keys pressed as R_bs with a certain internal rhythm. The pattern analysis program searched each rO first for possible patterns of four R_bs and if none were found it started over scanning for patterns of three R_bs. Overlapping patterns could be identified from a given sequence of R_bs.

The more stringent the criteria for defining repetitions (e.g., the lower the accepted range of variation of a pattern's inter-R_b intervals, such as ±50 ms rather than ±100), the fewer the number of patterns that will be registered. We set the ranges so that less than about 100 different patterns would comprise most of the patterns seen. For rOs that required a minimum of 20 R_bs, there could be more than 20 different patterns within any single occurrence. This could occur because the subject could emit more than 20 R_bs per rO, and consecutive R_bs could yield overlapping patterns. This type of pattern analysis can evidently be performed on any recorded sequence of topographically heterogeneous operants. But the pattern analysis performed here has the special significance of involving noncriterial patterns within single occurrences of operants.

In the data analysis process, each new pattern was assigned a code number according to the order in which it appeared, and the number of different patterns in each block of 100 rOs was counted, each pattern being counted only once. Figure 4 shows the number of first-time sequences and the number of different patterns in each successive block, with each point representing one block. There were between 1 and 5 (usually 3) 100-rO blocks per session.

In the top graph, for S2, the number of patterns increases gradually as sequences became classified as patterns (by virtue of occurring a second time). The total number of first-time sequences in each block, as well as the sum of the number of different sequences and patterns, decreases from a total of approximately 200 in Session 5 to less than 100 by Sessions 18-20. This decrease shows increasing stereotypy of

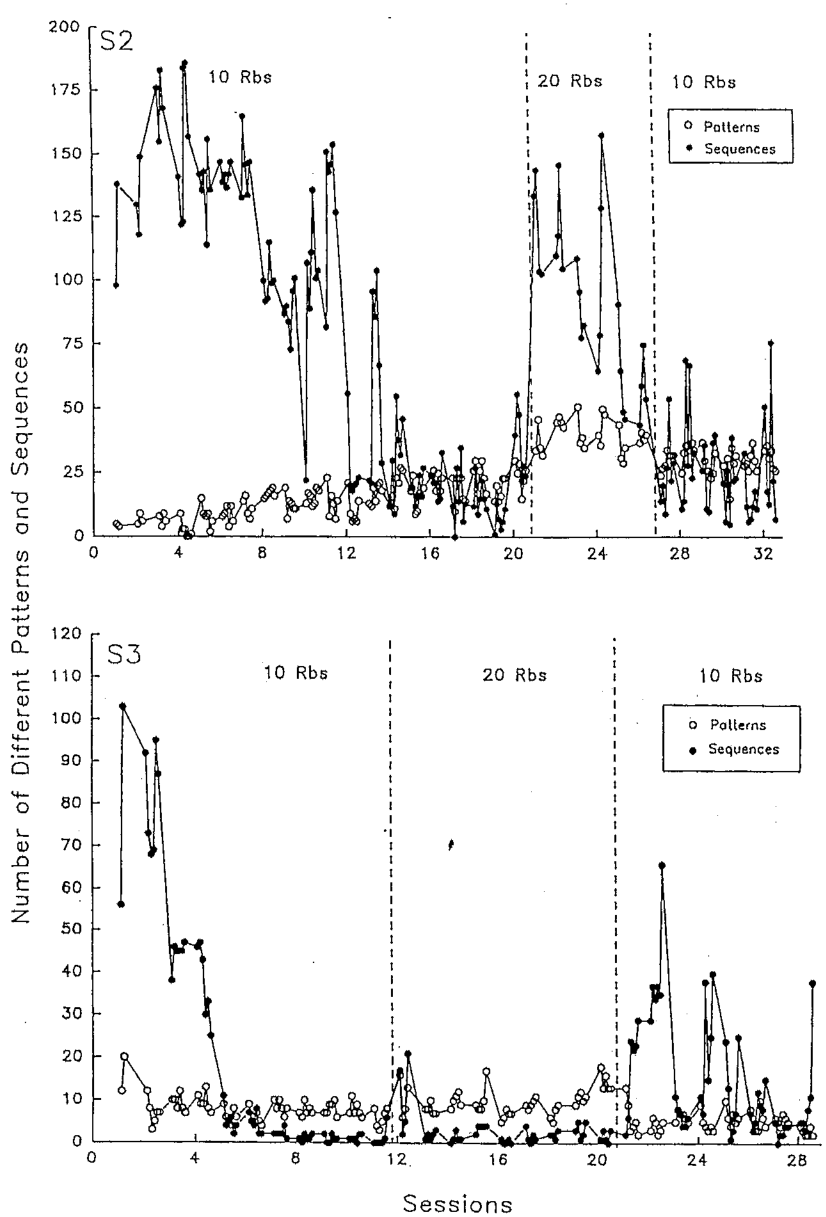

Figure 4. Number of different patterns and sequences across sessions of continuous reinforcement for Subjects S2 and S3. "Patterns" are rhythmic sequences of three consecutive R_bs that have occurred at least once before, and the term "sequences" is applied to rhythmic sequences occurring for the first time. Each data point depicts counts from a block of 100 rOs, with session boundaries disregarded. Phase change lines indicate when the required number of R_bs per rO was changed.

the internal structure of rOs. Both graphs show a crossover point where the number of first-time sequences drops below the number of patterns. In the lower graph, for S3, these same phenomena occur much faster, the total dropping from about 120 per block in Session 1, to about 10 per block by Session 11. Both graphs in Figure 4 show that when the required number of R_bs per rO was abruptly increased from 10 to 20, the number of new sequences and patterns increased, though the increase was small for S3. For S3, the reduction in the R_b requirement in the third phase also was associated with an increase in the number of sequences and a decrease in the number of patterns.

These results suggest that increasing or decreasing the work requirement per occurrence can produce a transient increase in the variability of the internal structure of the operant. It should be noted that sequences and patterns are noncriterial measures, while most traditionally used measures of variability are criterial measures. It is possible or even likely that criterial and noncriterial measures would not be affected in the same way when the work requirement is altered.

Resurgence When the Contingency is Changed

Resurgence is defined here as the reappearance of old patterns that have not been seen since much earlier in the subject's experimental history (cf. Epstein, 1985). The pattern identification program recorded patterns in the ordinal sequence of their occurrence across all sessions. This record was searched to determine the "antiquity" of any single occurrence of a pattern. Our definition of the "antiquity" of a pattern is how many patterns one has to go back in the recorded stream of patterns, from the occurrence of interest, to find the mean location of that pattern's five most recent occurrences. The number five was chosen arbitrarily.

Figure 5 shows how certain types of contingency changes produce resurgence in the behavior of S1. The changes tested were (a) instituting extinction after continuous reinforcement of rOs, and (b) abruptly increasing the required number of R_bs from 10 to 20. Both graphs in the figure show, for baseline purposes, the antiquity of each of several hundred patterns that immediately preceded the contingency change. The top graph shows that about 160 such consecutively occurring baseline patterns were mostly less than 10 patterns old (the height of a bar represents the pattern's antiquity), and 11 patterns were over 100 patterns old. First-time sequences are indicated by gaps between the bars. The high density of the bars means that most of the sequences were patterns, and few were first-time sequences. The rarity of new sequences in the baseline performance indicates repetition of a limited set of patterns. The subject had been exposed to the prevailing conditions (continuous reinforcement, 10 R_bs required per rO) since Session 5.

When the R_b requirement was abruptly changed in Session 19, patterns with antiquity over 2,000 began to emerge; two had antiquity over 5,000. A pattern with an antiquity of 5,000 would last have occurred a number of sessions previously. Instances of very antique patterns

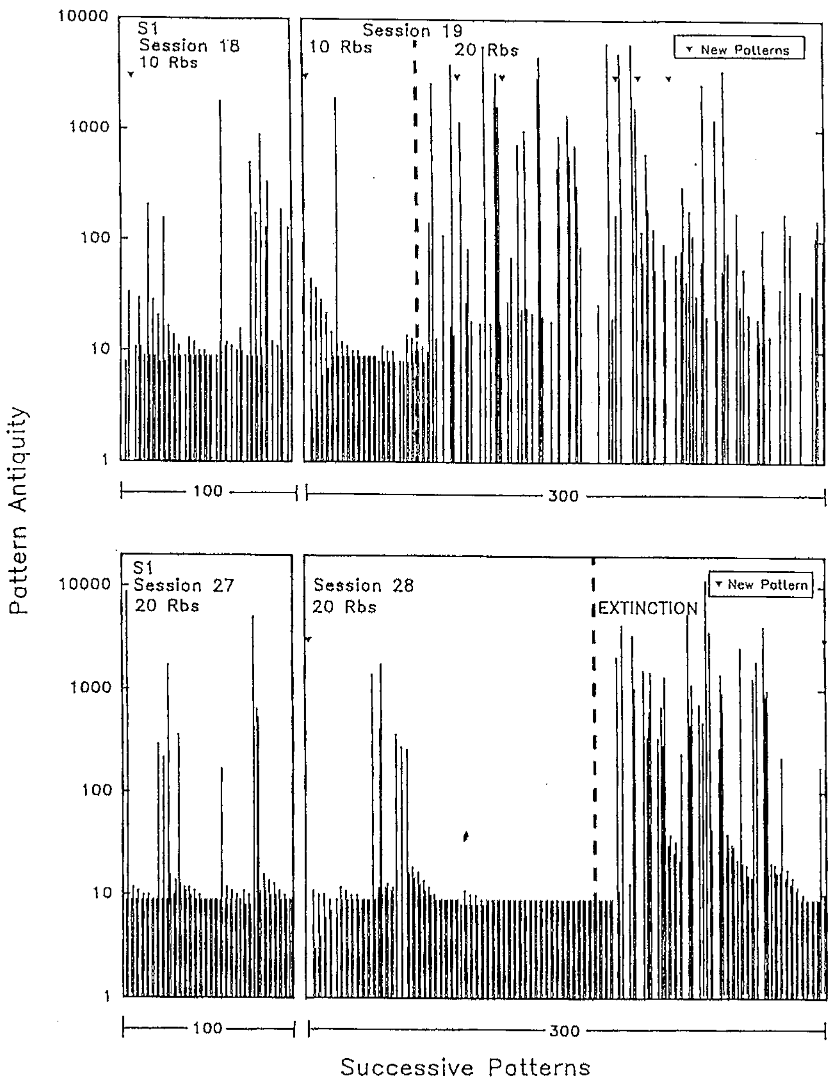

Figure 5. Pattern antiquity of successive patterns in parts of four sessions for Subject S1. The higher the bar, the older the pattern. The last 100 patterns from the session preceding a phase change are shown in the leftmost panels. In Session 19 the number of R_bs required was increased from 10 to 20, and in Session 28 extinction was instituted after the requirement had been at 20 R_bs under continuous reinforcement. Spaces between adjacent bars represent sequences that occurred for the first time. Triangles indicate points at which new patterns were first identified.

continued to emerge over the next 100 pattern occurrences. The subsequent gradual return to more recent patterns could be caused by either a diminution of resurgence or by the fact that increasing numbers

of the antique patterns (say, those with antiquity of more than 100) were registering as recent patterns when they recurred.

A similar resurgence effect can be seen in the lower graph, after extinction was instituted for this subject later in the experiment. There was also an increase in the incidence of first-time sequences (as shown by the increase in gaps between bars). But given the fact that there existed less than 200 antique patterns, and an almost infinite number of potential new sequences, the vast preponderance of the sequences that occurred after instituting extinction, or criterion increase, consisted of antique patterns, and relatively few consisted of recent patterns or new sequences. This analysis precludes the argument that the increased incidence of antique patterns is the inevitable statistical result of increasing the total number of different patterns that appear, and that as that number is increased, increasing numbers of them are likely to be antique. Evidently, only a very small proportion of all mathematically possible patterns ever occur, while a disproportionately large percentage of the increased number of patterns is antique.

Similar results were observed in a second subject. We feel that the phenomenon should be explored further with more subjects, more independent variables, and more searching data analyses. Here we have demonstrated how the rO provides a technique for the quantitative study of resurgence. Additional research will be needed to resolve such questions as whether the patterns become *increasingly* antique during resurgence (i.e., the Freudian sense of the term regression, where the operant's history is recapitulated in reverse sequence; see Mowrer, 1940) and whether criterial and noncriterial measures exhibit different resurgence characteristics.

Resurgence effects may provide part of the explanation for the variability increase normally seen in extinction or under other conditions of "stress" such as punishment, increased performance requirement, changes in stimulus conditions, or decreased amount or probability of reinforcement. Depending on how the operant is defined, and on what types of data are recorded, resurgence can register as increased variability. For example, Migler and his colleagues (Migler, 1964; Migler & Millenson, 1969) analyzed such variability during generalization tests carried out in extinction with rats. Although the phenomenon was not discussed as resurgence, Migler observed that generalization gradients containing response rates intermediate between those generated by two training stimuli were actually composed only of the two response rates that occurred to the training stimuli. That is, during extinction probes with novel stimuli, subjects emitted one of two previously reinforced patterns and averaging these resurgent patterns produced what appeared to be intermediate response rates. Thus, resurgence can contribute to some kinds of generalization effects.

Increased Stereotypy Following Extinction

Figure 6 shows the effects of extinction on run length (number of R_bs

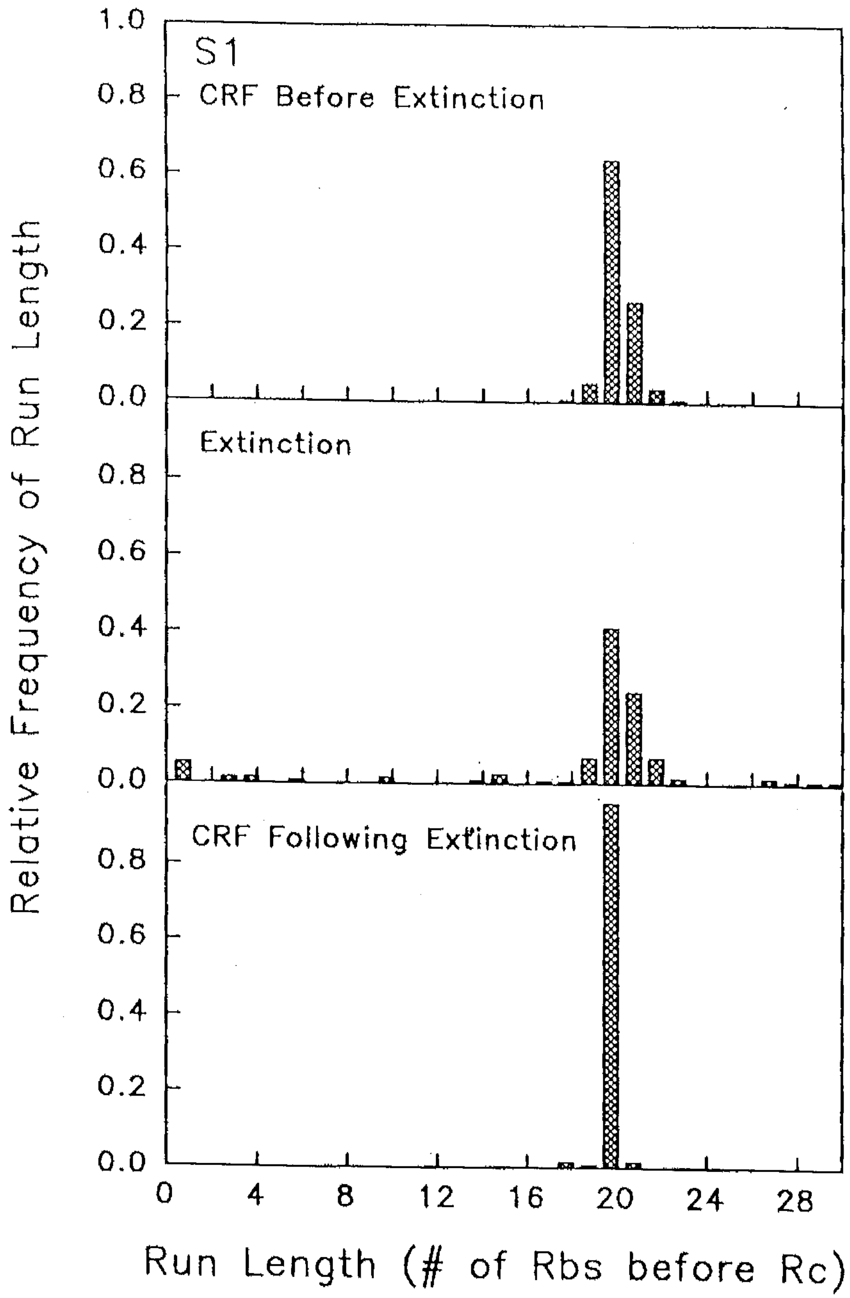

Figure 6. Relative frequency of different numbers of R_bs per rO ("run length") before, during, and after extinction for Subject S1. Before and after extinction, continuous reinforcement was in effect with an R_b requirement of 20.

per rO) variability. The requirement for minimum number of R_bs was 20. The top panel shows the frequency distribution of run lengths (the criterial measure) for the continuous reinforcement session immediately preceding extinction, following 27 sessions of continuous reinforcement. As in Mechner (1958a, 1958b, 1962), the average run length usually falls somewhat above the requirement. This was observed in all six subjects, whether the requirement was 20 or 10.

The middle panel shows the frequency distribution of run lengths during the single session of extinction. The shape of the main distribution seems identical to that for CRF except for a sprinkling of very short and very long runs. The bottom panel shows the distribution of run lengths for the first continuous reinforcement session following extinction. The mode of the distributions remains near 20 (and the mean somewhat above 20), but the apparent effect of the extinction session was to decrease the distribution's spread (standard deviation) greatly, with most of the runs being exactly 20 R_bs long, showing that the postextinction performance was much more stereotyped. Antonitis (1951), Herrnstein (1961), and others have shown a stereotyping effect of extinction sessions on noncriterial measures. Figure 6 suggests that the stereotyping effect also obtains in criterial measures.

Effects of Fixed-Ratio Schedules

After approximately 30 sessions of training on the rO (with the requirement at 10 R_bs for most of those sessions), the rO, with a requirement of 10 R_bs, was reinforced on various fixed-ratio (FR) schedules. Each subject was exposed to some or all of the following: FR1 (continuous reinforcement), FR2, FR4, FR8, and FR20. FR4 means that every fourth occurrence of a complete rO receives reinforcement. Latency is the R_c-R_a interval, that is, the interval between the end of one rO and the start of the next. In a fixed ratio of 4, every fourth latency is also a postreinforcement pause (PRP).

Figure 7 shows the PRPs (with the reinforcer delivery durations of 800 ms not included) and the other latencies for successive rOs under FR4 for Subjects S1 and S4. The longer pauses represented by every fourth point are PRPs, the other points being other latencies (intervals between unreinforced rOs). In both cases, PRPs were consistently differentiated from other latencies for over 50 consecutive rOs. Visual inspection of other parts of the FR4 sessions indicated that this differentiation was common after several sessions of exposure to the schedule. Note that the pauses for S1 are mostly under 200 ms and those of S4 average a full second in length. Subject 1 had 12 prior sessions of exposure to FR4 altogether, though the data are taken from the first third of Session 83, her first session returning to FR4 following 10 sessions on a variable-interval 30-s schedule. Data for S4 are from the first third of her eighth consecutive session on FR4.

Figure 8, based on data from three subjects, shows that the

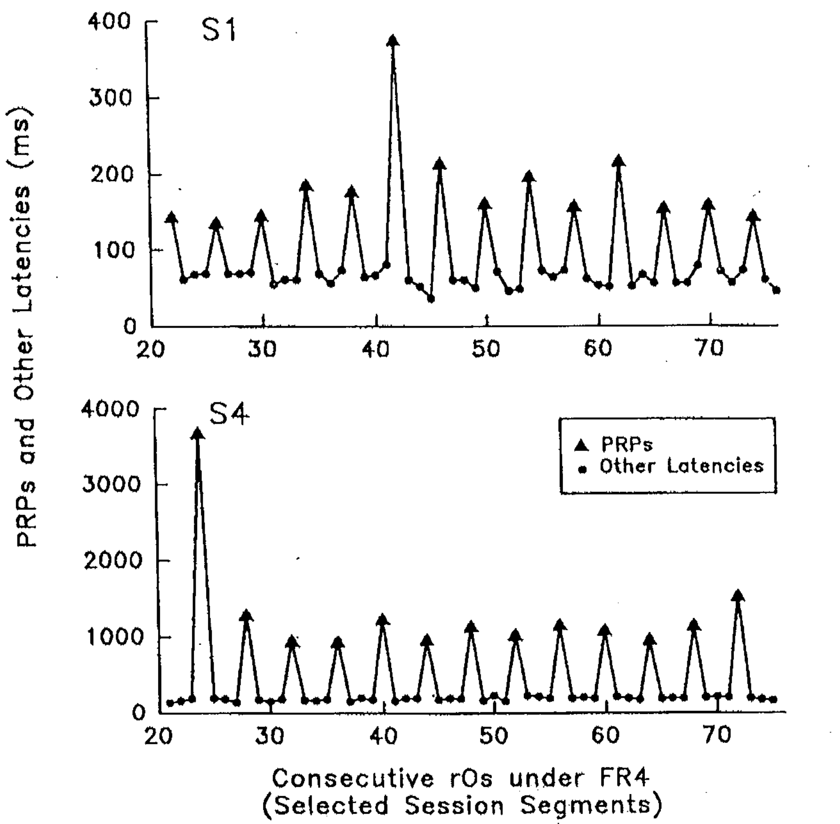

Figure 7. Length of postreinforcement pauses and other latencies (R_c-R_a intervals) for each rO in selected segments of the FR4 performance of two subjects. The rO was the unit that was reinforced on the FR4 schedule.

median R_a-R_b interval was positively related to FR size. Because of some overlap in the ranges shown, a conservative assessment is that the interval was shorter under continuous reinforcement than under any other tested intermittent reinforcement. This observation raises the question of whether other schedule parameters that change the frequency of reinforcement would affect the R_a-R_b interval similarly. The observed effect of FR size must be interpreted with caution because the FR schedules were presented only in an ascending sequence in these pilot studies. Nevertheless, Figure 8 demonstrates how the rO method provides a way to examine changes in the internal structure of the rO as a function of changing reinforcement contingencies. Examples of internal structure are length of the R_a-R_b interval, inter-R_b intervals, and patterns.

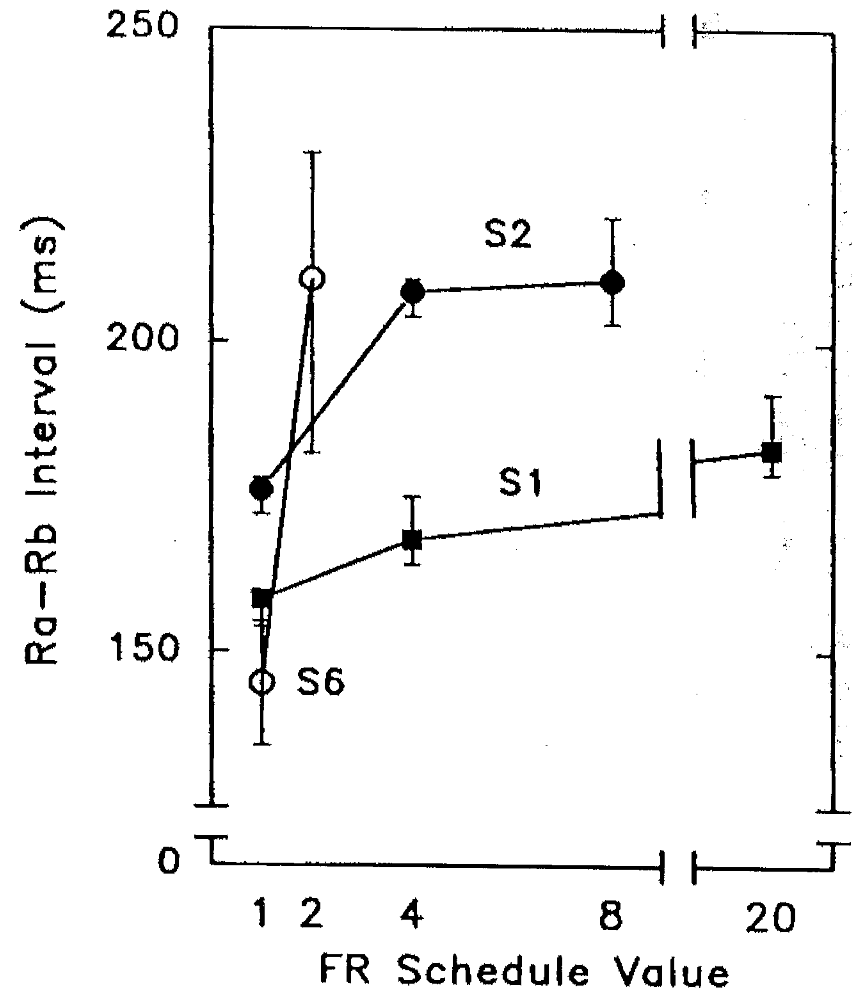

Figure 8. Median R_a-R_b interval as a function of fixed-ratio size for three subjects. Session medians were calculated for the last three sessions in each phase. Data points indicate the middle value of those medians; vertical bars show range to the other two session medians.

Effects of Different R_b Requirements

Figure 9 shows the effect of different R_b requirements on the number of different patterns that emerged per block of 100 rOs, each point representing the average of 3 to 36 blocks. All four subjects emitted a significantly larger number of different patterns when the requirement was 20 R_bs than when it was 10 or, in the case of S5, 6 R_bs. One might be tempted to explain this result by postulating that the larger number of R_bs per rO provides increased opportunity for more patterns to appear. But this explanation is not totally valid because patterns can be, and are, repeated both within and across rOs. A reasonable description of the

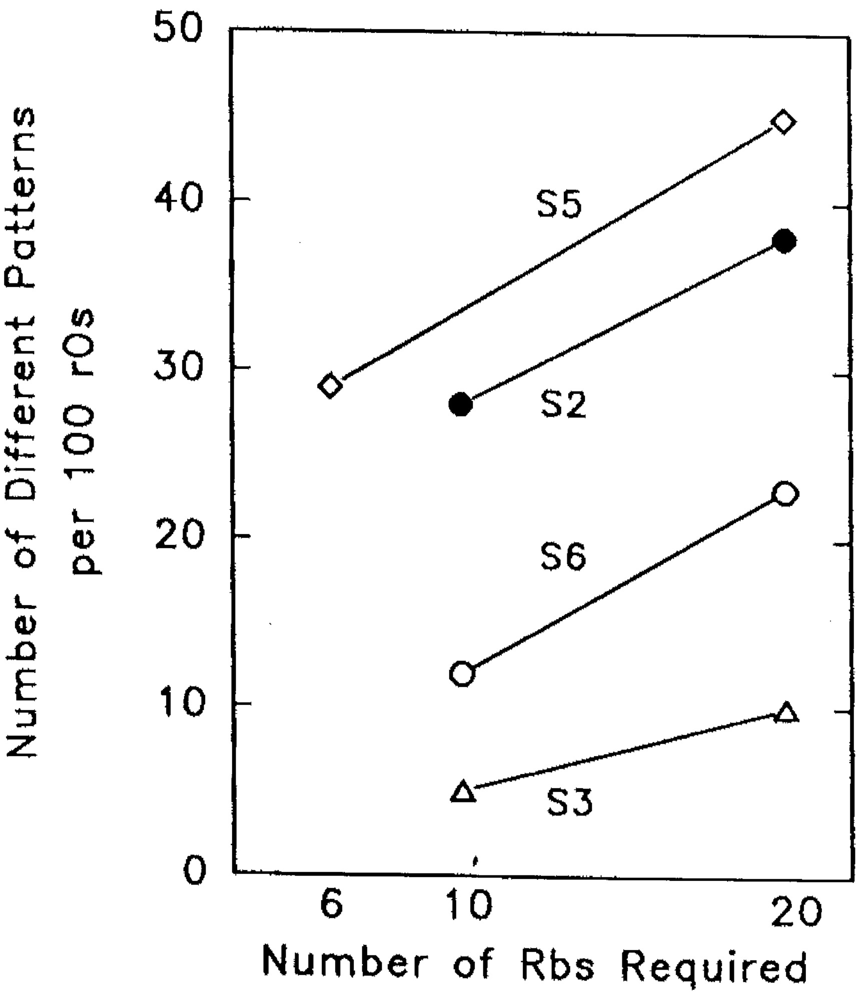

Figure 9. Average number of different patterns recorded in blocks of 100 rOs under continuous reinforcement as a function of the R_b requirement for four subjects.

finding is that the internal structure of the operant becomes more variable as the length of the operant increases.

In experiments with pigeons as subjects, Nevin (1992) studied rO performance under variable interval (VI) 40-s and VI 200-s schedules in a multiple schedule with a 3-minute alternation cycle. Using three response keys for the rO, R_a was a peck on the left key, R_b s were a pecks on the middle key, and R_c was a peck on the right key. Ten R_bs were required to complete the rO, just as in our experiments with humans. The pigeons were exposed to 30 sessions under these conditions. Data from Nevin's experiment were compared to findings from our studies.

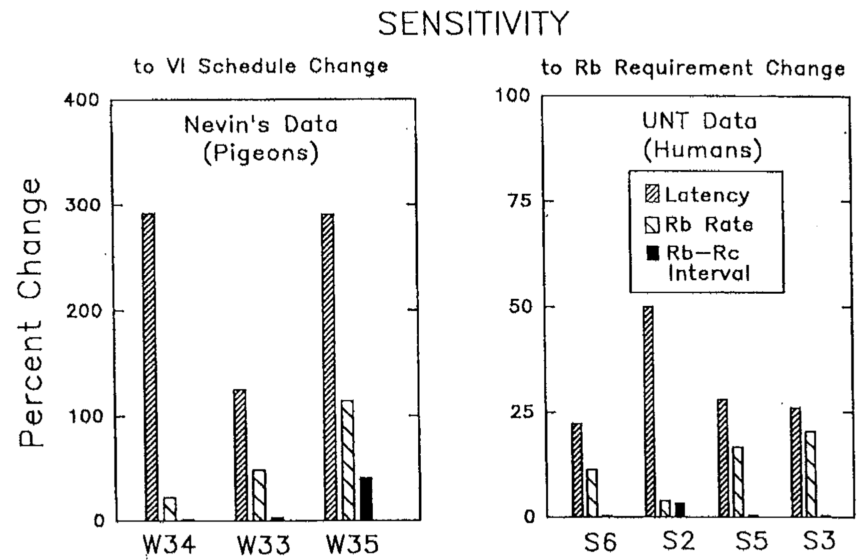

Figure 10. Sensitivity of three measures to changes in two different independent variables: Value of a VI schedule in pigeons in the left panel, and number of R_bs required under CRF for the rO in human subjects in the right panel. The measures are three components of the rO: (1) latency, (2) rate at which the R_bs are executed, and (3) R_b-R_c interval. Percent change indicates the percentage by which a measure increased or decreased when the parameter of the independent variable was increased.

Figure 10 shows the percentage by which each of three measures changed as a result of the different values of the independent variable (40-s vs. 200-s VI schedule for Nevin's data, and R_b requirement - 10 vs. 20 R_bs - for our data with human subjects). The three measures are (a) latency, (b) R_b rate, and (c) the R_b-R_c interval, defined as the time interval between the rO's last R_b and the R_c. The percentages were derived from comparing the mean (in Nevin's Table 1, Condition 1 data) or median (with our data) on each measure from the final three sessions under those conditions. All percentages for the human subject data reflect increases in the measures under the larger R_b requirement. For example, median latency for S2 increased by 50% when the R_b requirement was increased from 10 to 20. The R_b rate for S3 increased by 20% when the R_b requirement was doubled. In Nevin's multiple schedule format, R_b rate was slower in the VI 200-s component than in the VI 40-s component. The R_b rate for Pigeon W35, for example, slowed by 114% in the VI 200-s component. Latency measures for the pigeons increased dramatically under the larger VI schedule (note that the scale of the y axis for the Nevin data is larger than for the UNT data.) The mean R_b-R_c time decreased negligibly for W33 and W34, but increased by 41% for W35.

Each of the three measures is located progressively closer to the end of the rO. In all cases, the measure most sensitive to the independent variable is the one farthest from the end of the rO, latency, whereas the one closest to the end of the rO, the R_b-R_c interval, seems to be hardly affected at all in both cases. The phenomenon of interest here is the qualitative one, that the measure which is farthest from the end of the rO is the most strongly affected one. Nothing can be or should be made of the quantitative ratios of the three measures, or of comparisons of the absolute percentages between the human subjects and the pigeons. As Nevin (1992) pointed out, these data are similar to some results from studies of conventional chained schedules showing that the initial links in chains are especially sensitive to changes in independent variables. Several studies have observed that response rates in the initial links of chained schedules are more sensitive to changes in reinforcement frequency than are response rates in the terminal link that immediately precedes reinforcement (see Findley, 1962; Kelleher & Gollub, 1962; Nevin, 1964; Nevin, Mandell, & Yarensky, 1981). The rO appears to share some of the dynamic properties of performance on chained schedules.

The data in Figure 10 suggest that many variables that affect response rate may do so by affecting the latencies to respond more than the response durations. The response durations are simply the reciprocals of the R_b rates, plus the contributions of the proportionally short R_a-R_b and R_b-R_c intervals. Note that the "percent change" is mathematically the same regardless of whether the rate or its reciprocal is used. The finding may have bearing whenever there is a question as to whether a response rate change is caused by a change in response durations or in latencies (both of which are pooled and therefore obscured in conventional IRT measures). Mechner (1992, pp. 38-43) has suggested, for example, that this issue is relevant to the analysis of undermatching observed so frequently in matching law experiments.

Conclusions

The studies and results reported above demonstrate how the rO technique provides a practical way to study the effects of various types of independent variables on the internal structure and properties of operant responses. Examples of measures that are applicable to each individual rO occurrence are rO duration, the time between R_a and the first R_b, the number of R_bs made in each rO (the criterial requirement), the rate at which the R_bs are made within an rO, the time between the last R_b and R_c, the time between the end of one rO and the initiation of the next, and patterns (repeated sequences and rhythms of consecutive R_bs). As we noted earlier, very little research exists on complex operants in human behavior. Given the increasing interest in basic human operant research (Hyten & Reilly, 1992), descriptions of new laboratory techniques are likely to be useful in stimulating further interest and research. The methodology described in this paper, which uses commonly available personal computers, may provide a useful technique for those researchers who wish to study complex operants with human subjects.

The topics of the studies were chosen for (a) their significance to behavior analysis, (b) their diversity, and (c) the difficulty of studying them by means of traditional instantaneous operants. The studies were not intended to be definitive (as they were based on small numbers of subjects and limited numbers of repetitions of the values of the independent variables studied), so they can only provide preliminary data on each of the questions addressed. They were intended mainly to demonstrate the practical feasibility of the rO method and to provide methodological guidance for more complete studies of these and related topics. Note that an analogous apparatus and procedure can be devised for use with nonhuman subjects, as Nevin (1992) showed.

An example of a related topic that can be studied conveniently with the rO method demonstrated here is the effect of reinforcer presentations on various response dimensions. It is possible to compare the patterns of criterial and noncriterial measures in rOs that immediately precede and immediately follow a reinforcer presentation. During the process of shaping (when reinforcer presentations tend to be dense), there are times when a "parameter shift mechanism" may describe the effect of reinforcer presentations. The parameter shift mechanism states that a reinforcer presentation results in the repetition not of a preceding topographic variant, but rather of a recent topographic *shift* in some parameter of a recent operant (see Mechner, 1992, pp. 57-61 for a discussion of this and other possible reinforcement mechanisms.) Various molecular-level hypotheses of the mechanisms of reinforcement could be investigated readily in human subjects with the preparation described in this paper.

It is also possible to restrict the allowable rO topography to either simplify the response patterns or to make them more complex. For example, one could ignore the rhythm aspect of keypresses in the pattern identification and reinforce rOs with only one of several keypress orders to generate very simple patterns. Alternatively, one could require a certain order of keypresses and rhythms at the beginning and end of an rO while leaving the topography of the middle portion free to vary in order to create more complicated rOs. We are currently using these variants to investigate the issue of extinction-induced variability in more depth.

In conclusion, the rO technique can yield a wealth of data regarding the structure and dynamic properties of operant responses, both at the level of the individual response and at more molar levels when these measures are examined in the aggregate across sessions. Figures 2 and 3 suggest that with rO measures, changes can still be observed after thousands of occurrences. The implication of this observation is that when the internal structure of an operant is examined, and when sufficiently sensitive measures are used, long-term changes and drifts can be observed far longer than when only response rates or IRTs are recorded. The rO technique may thus permit the study of functional relations not previously observed with more conventional techniques.

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