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BOUTS OF RESPONDING: THE RELATION BETWEEN BOUT RATE AND THE RATE OF VARIABLE-INTERVAL REINFORCEMENT

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By nose poking a lighted key, rats obtained food pellets on either a variable-interval schedule of reinforcement or a schedule that required an average of four additional responses after the end of the variable-interval component (a tandem variable-interval variable-ratio 4 schedule). With both schedule types, the mean variable interval was varied between blocks of sessions from 16 min to 0.25 min. Total rate of key poking increased similarly as a function of the reinforcer rate for the two schedule types, but response rate was higher with than without the four-response requirement. Analysis of log survivor plots of interresponse times showed that key poking occurred in bouts. The rate of initiating bouts increased as a function of reinforcer rate but was either unaffected or was decreased by adding the four-response requirement. Within-bout response rate was insensitive to reinforcer rate and only inconsistently affected by the four-response requirement. For both kinds of schedule, the ratio of bout time to between-bout pause time was approximately a power function of reinforcer rate, with exponents above and below 1.0.

Key words: bouts, log survivor plot, variable-interval schedule, tandem ratio, time allocation, key poke, rats

Responding maintained by variable-interval (VI) schedules of reinforcement sometimes occurs in bouts (Baum, 2002; Baum & Rachlin, 1969; Blough, 1963; Gilbert, 1958; Kirkpatric & Church, 2003; Mechner, 1992; Mellgren & Elsmore, 1991; Nevin & Baum, 1980; Pear & Rector, 1979; Shull, Gaynor, & Grimes, 2001). When responding is organized this way, changes in response rate can arise from changes in the pauses between bouts, from changes in the length of bouts, or from changes in the response rate within bouts. If a given independent variable affects these various aspects of performance differently, then the relation between total response rate and that independent variable will represent a mixture of effects rather than a single one. Such mixtures are unlikely to be as general or fundamental as relations involving single dimensions would be (Blough, 1963; Gilbert, 1958; Mechner, 1992; Pear & Rector, 1979).

When reinforcer rate is varied, for example, the resulting change in total response rate derives mainly from a change in the average time between bouts (or, equivalently, from a change in the rate of initiating bouts) and, to a lesser extent, from a change in the length of bouts (Shull et al., 2001; cf. Hurwitz, 1957 [as cited in Millenson, 1967, p. 91], and Shull, Gaynor, & Grimes, 2002, for evidence of a similar pattern of performance change during extinction). Response rate within bouts, in contrast, appears insensitive to changes in reinforcer rate (Kirkpatric & Church, 2003; Shull et al., 2001; Shull & Grimes, 2003). Thus the relation between total response rate and reinforcer rate is a combination of sensitive and insensitive effects. Perhaps the relation between bout-initiation rate and reinforcer rate is different from, and more general than, that between the composite performance measure (i.e., total response rate) and reinforcer rate (Shull, 1991).

One aim in conducting the present study was to determine whether the relation between bout-initiation rate and reinforcer rate was similar to or different from that between total response rate and reinforcer rate. To this end, we determined (with rats) the relations between these performance measures and reinforcer rate over a range of VI schedules (from VI 16 min to VI 0.25 min).

We also examined these measures of performance over the same range of VI schedules but with the additional requirement that a variable number of responses ($M = 4$) oc-

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cur after the end of each interval to produce the assigned reinforcer. Technically, this arrangement is a tandem VI variable-ratio (VR) 4 schedule of reinforcement. Adding a small VR (or a small fixed ratio) response requirement to a VI schedule causes response rate to increase (Killeen, 1969; Lattal, 1989), and it does so mainly by increasing the length of bouts rather than by increasing the rate of initiating bouts (Shull et al., 2001; Shull & Grimes, 2003). Such results suggest that the relation between bout-initiation rate and reinforcer rate might be similar (and thus general) between the VI and the tandem VI VR series despite differences in total response rate. If the relation were similar across the two schedule types, the idea that bout-initiation rate is primary would be supported.

Results from our previous study (Shull et al., 2001), however, hinted that bout-initiation rate might actually be lower with than without an additional tandem VR requirement, as if the additional response requirement made bouts less attractive to enter. Thus adding a VR requirement might shift total response rate and bout-initiation rate in opposite directions. If so, conclusions about the effect of adding a VR requirement would depend critically on whether the measure of performance was total response rate or bout-initiation rate. The present study confirmed this decremental effect of the VR requirement on bout-initiation rate.

METHOD

Subjects

The subjects were 4 male Long Evans Hooded rats, about a year old at the start of the experiment. Obtained as babies (about 150 g), they were gradually (over several months) brought to a weight of 335 g (± 15 g) and maintained at that level by free access to food blocks in their home cages for 1 to 1.5 hr after each session. (Ator, 1991, provides a rationale for this method of food deprivation for rats. As discussed by Ator, percentage free-feeding body weight usually is not a meaningful measure of a rat's deprivation level because rats given free access to food will grow continuously.)

The rats were housed in individual plastic cages, covered with metal grate tops, with free access to water. The home cages were kept in a room that maintained a temperature of about 22 °C. The overhead lights in the room were on from about 6:00 a.m. until 6:00 p.m. each day; the experimental sessions were conducted during the lights-on periods. The rats had previously served as subjects in an undergraduate laboratory course to demonstrate basic behavioral phenomena such as shaping, discrimination, and behavioral chains.

Apparatus

Each rat was assigned to one of four similar experimental chambers for the duration of the experiment. These chambers, located in a separate room from the home cages, were 300 mm wide by 320 mm deep by 300 mm high. They were constructed of sheet metal (top and three sides), clear plastic (rear door), and stainless steel rods (7 mm diameter) spaced 10 mm apart (floor). Food pellets (45-mg Noyes, Formula A, obtained from Research Diets, Inc.) were delivered into a small metal food tray located behind a square opening (44 by 44 mm) in the middle of the front panel, 43 mm above the floor. The operation of the pellet dispenser made a click, and the pellet landing in the tray made a plinking sound a fraction of a second later.

The operandum was a translucent plastic key (a Lehigh Valley Electronics pigeon key), mounted behind a 19 mm diameter round hole through the left wall. The center of the key was 51 mm toward the rear of the chamber from the front wall and 62 mm above the floor. For a response to be recorded, the key had to be pushed a distance of about 1.5 mm (measured at the center) with a force of at least 0.18 N (three of the four chambers) or 0.3 N (the fourth chamber; Rat C3). A recordable response produced a brief click from a small snap-action switch connected to the key. Each rat was observed to poke its key mostly with its nose but occasionally with its paw. At the start of each session the key was transilluminated with a white light; the light remained on until the end of the session.

A metal drinking spout extended into the chamber through a small hole in the left wall near the back left corner (approximately 240 mm from the front wall and 25 mm above the floor). The spout was attached to a water bottle suspended outside the chamber and provided continuous access to water.

The four chambers were placed on a cart, two to a shelf. No attempt was made to shield any of the chambers from sounds made in the others; it was apparent that each rat quickly learned to go to its food tray only when its own feeder operated. The four chambers operated concurrently, although out of phase.

The experimental sessions were conducted with the room darkened except for low-level light that entered from the corridor through a translucent window. The keylight provided the only other source of illumination in the chamber (i.e., there was no houselight or feeder light).

Four special-purpose computers (Walter & Palya, 1984), one for each chamber, controlled the experimental events and recorded the data. These computers were connected to a desktop computer for uploading programs and downloading data.

Procedure

Key poking was established by reinforcing successively closer approximations (shaping) with food pellets. Following shaping, the rats were given a few days' training on progressively longer VI schedules until the value reached was a VI 1-min schedule, which was the first condition of the experiment.

Throughout the experiment, sessions were conducted daily. Each session lasted for 2 hr or until 101 food pellets (at one food pellet per reinforcer) had been delivered, whichever occurred first. A condition consisted of a block of 20 consecutive sessions during which a particular schedule of reinforcement was in effect. Based on visual inspection, total response rate typically appeared to stabilize before the 15th session (with two exceptions, Conditions 7 and 14, as noted below).

For one set of conditions, reinforcement of key poking was arranged by VI schedules of reinforcement. That is, throughout each session the first key poke that occurred after a variable interval of time elapsed produced a food pellet. The first interval in a session was timed from the start of the session; all subsequent intervals were timed from the previous pellet delivery. The intervals in a session were drawn randomly (with replacement) from a list of 16 that was constructed to provide a roughly constant probability of reinforcement in time since the last reinforcer (Fleshler & Hoffman, 1962; Hantula, 1991) except that the shortest interval in the list was never longer than 4 s regardless of the mean VI. The mean VI duration differed among conditions.

For another set of conditions, the schedule operated exactly like a VI schedule except that after the end of the interval some unpredictable number of responses, from 2 through 8 ($M = 5$), was required to obtain the assigned reinforcer. (This arrangement required the one response specified by the VI component plus an average of four additional responses.) Each whole number from 2 through 8 had an equal likelihood of being selected. Because there was no stimulus change to indicate the end of the interval, this schedule is referred to as a tandem VI VR 4 schedule. Table 1 lists the training schedules (VI and tandem VI VR 4 schedules) in the order that they occurred.

During the last five sessions of each condition, the computer recorded the time of occurrence of every response and reinforcer. Interresponse time (IRT) distributions were derived from these times. The times were recorded in units of 0.01 s, but as best we could determine, our system actually resolved time intervals to about the nearest 0.1 s.

After the end of each condition, the rats were given a single 2-hr session of extinction.

Table 1

The sequence of conditions.

Order	Schedule
1	VI 1 min
2	VI 2 min
3	VI 4 min
4	VI 8 min
5	VI 0.5 min
6	VI 0.25 min
7	VI 1 min (replication)
8	VI 4 min (replication)
9	tandem VI 4-min VR 4
10	tandem VI 8-min VR 4
11	tandem VI 2-min VR 4
12	tandem VI 1-min VR 4
13	tandem VI 16-min VR 4
14	VI 16 min
15	tandem VI 0.5-min VR 4
16	tandem VI 0.25-min VR 4

Note. Rat C3 died after completing Condition 6.

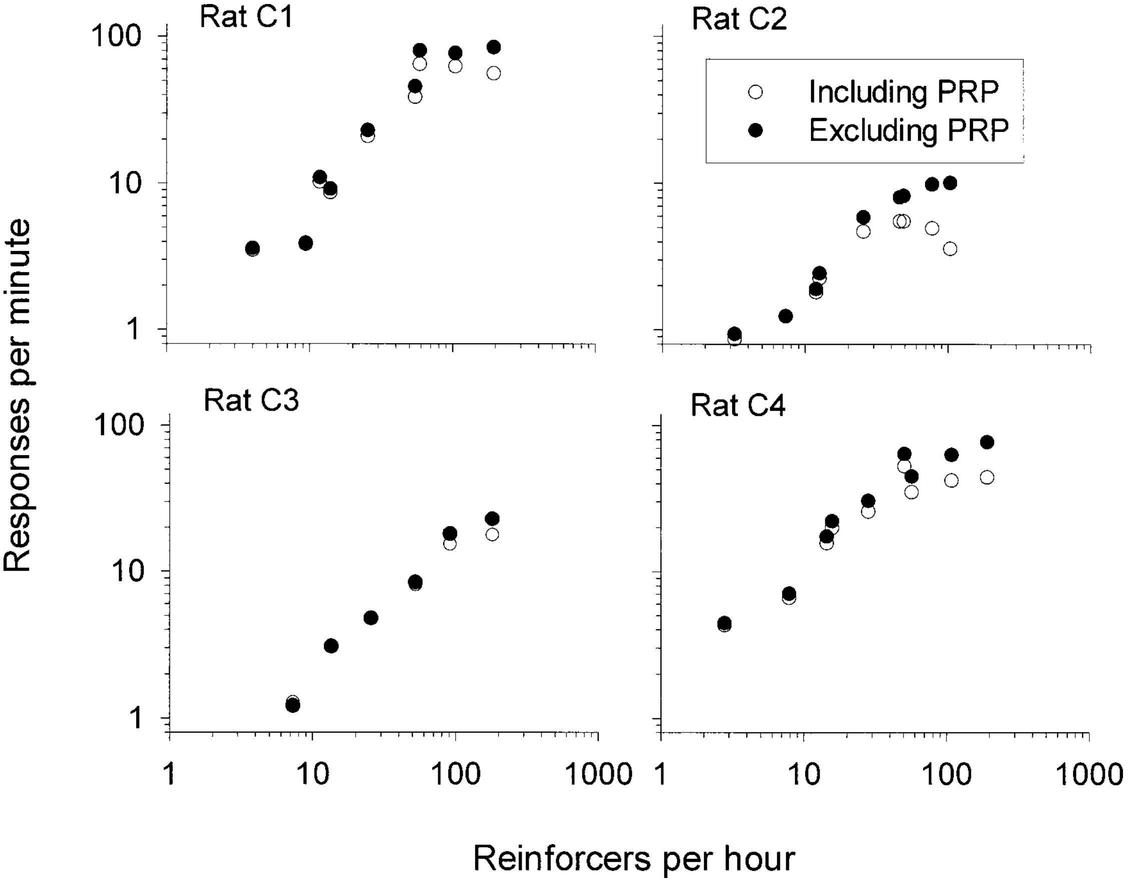

Fig. 1. The total rate of key poking (with and without the postreinforcer pauses and the responses that ended them) plotted as a function of obtained reinforcer rate from the VI schedules. Each panel shows data for 1 of the rats. The values are the means calculated over the last five sessions of each condition. Both axes are scaled logarithmically.

The results from these extinction sessions are not reported here.

RESULTS

Figure 1 shows how total response rate varied as a function of reinforcer rate obtained from the VI schedules. Total response rate is shown calculated two different ways—with the postreinforcer pauses, and the responses that ended them, either included or excluded. Baum (1993) demonstrated that the set of variables controlling the postreinforcer response is at least partly different from the set controlling the other responses, and he argued that the postreinforcer responses (and their pause times) should, therefore, be excluded in calculating response rate. In Figure 1, the two response-rate functions increasingly diverge as reinforcer rate increases, presumably because the higher the reinforcer rate, the more of the session time was taken up with postreinforcer activities. For 2 rats (C1 and C2), including the postreinforcer pauses and their responses resulted in bitonic response rate functions. Excluding the postreinforcer pauses and their responses eliminated the downturn of those functions at the highest reinforcer rates, an effect also reported by Baum (1993). Because postreinforcer pause time seemed to indicate special constraints on responding, following Baum (1993) we excluded the postreinforcer pauses and their responses from the following analyses of response rate and IRT distributions.

For Rats C1 and C4, the replication of the VI 1-min schedule (Condition 7) produced response rates that were noticeably higher than were produced by the initial exposure to the VI 1-min schedule. The replication condition came after exposure to the VI 0.25-min schedule, and it appears that the effects of that rich schedule may have persisted through 20 sessions with the VI 1-min schedule.

A major purpose of this study was to determine the relation between bout-initiation rate and reinforcer rate, and for that it is necessary to measure bout-initiation rate. One way to assess characteristics of bouts is to plot the frequency distribution of IRTs as a log survivor plot (Fagen & Young, 1978; Machlis, 1977; Shull et al., 2001; Sibley, Nott, & Fletcher, 1990). This is a semilogarithmic plot of the proportion of IRTs that are longer than any particular duration, *t*. Figure 2 shows illustrative log survivor plots of IRTs (with the postreinforcement pauses excluded) from Rat C1. The top panel shows the plots from each of the last five sessions of the schedule listed; these plots provide some indication of the typical day-to-day variability. The bottom panel presents a single plot for each of the three listed VI schedules. These plots were derived from combining the IRTs over the last five sessions of exposure to the schedule into a single frequency distribution.

Each plot appears to consist of two limbs, a steeply declining limb at the left and a more gradually declining limb extending toward the right. Such "broken stick" patterns (Clifton, 1987) are what would be expected if responding were organized into bouts. A bout-like organization implies that the IRT distribution as a whole is a combination of two separate distributions: one for within-bout IRTs that are mostly short, and the other for between-bout intervals that can also be short but that are on average relatively long. From this conception, the left-hand (steeper) limb of the log survivor plot is dominated by the short within-bout response times and the right-hand limb consists mainly of between-bout times.

That the two limbs do, in fact, represent distributions of functionally different response times is supported by the differential effect of VI duration on the slopes of the two limbs. Increasing the reinforcer rate (i.e., decreasing the VI duration) steepened the slope of the right-hand (between-bout) limb but had no apparent effect on the slope of the left-hand (within-bout) limb. A steepening of the right-hand limb implies a shift in the frequency of between-bout intervals toward shorter durations. Hence increasing the reinforcer rate appears to shorten the average between-bout interval (or, equivalently, to increase the rate of initiating bouts) but seems not to change the rate of within-bout responding. It is evident also that increasing the reinforcer rate causes the left-hand limb to lengthen, which implies that relatively more of the IRTs are within-bout IRTs. That is, in this data set the average number of responses per bout increased as a function of reinforcer rate.

It is possible to generate serviceable quantitative estimates of bout-initiation rate, the average number of responses per bout, and the rate of responding within bouts based on some simplifying assumptions about bout initiations and responding within bouts (cf., Killeen, Hall, Reilly, & Kettle, 2002; Shull, et al., 2001; Shull & Grimes, 2003). The assumptions are that responses within bouts and bout initiations occur at random but at different rates. This kind of two-process (pause-bout) conception implies that the survivor plots can be described as the sum of two exponential decay processes (cf., Killeen et al., 2002), which may be written:

$$F_{(\mathrm{IRT}>t)} = (1 - p)e^{-Wt} + pe^{-Bt}, \qquad (1)$$

where $F_{(\mathrm{IRT}>t)}$ is the proportion of IRTs longer than any given duration, *t,* and where, in our interpretation, the first term to the right of the equality sign, $(1 - p)e^{-Wt}$, represents the component of the plot contributed by within-bout responding. The second term, pe^{-Bt}, represents the component due to between-bout times. For the first term, $1 - p$ is an estimate of the proportion of IRTs that occur within bouts, e is the base of the natural logarithms, W is the rate of responding within bouts, and t is elapsed time in units of the x-axis. For the second term, p is the proportion of IRTs that are bout-initiations, and B is the *rate of initiating bouts.* It might help to note that p is also the y-intercept of an imaginary straight line drawn to represent the right-hand limb and extended left to the y-axis. The reciprocal of p (i.e., $1/p$) is an estimate of the average number of responses per bout (including the bout-initiation response); that is, it is an estimate of average *bout length.* Thus

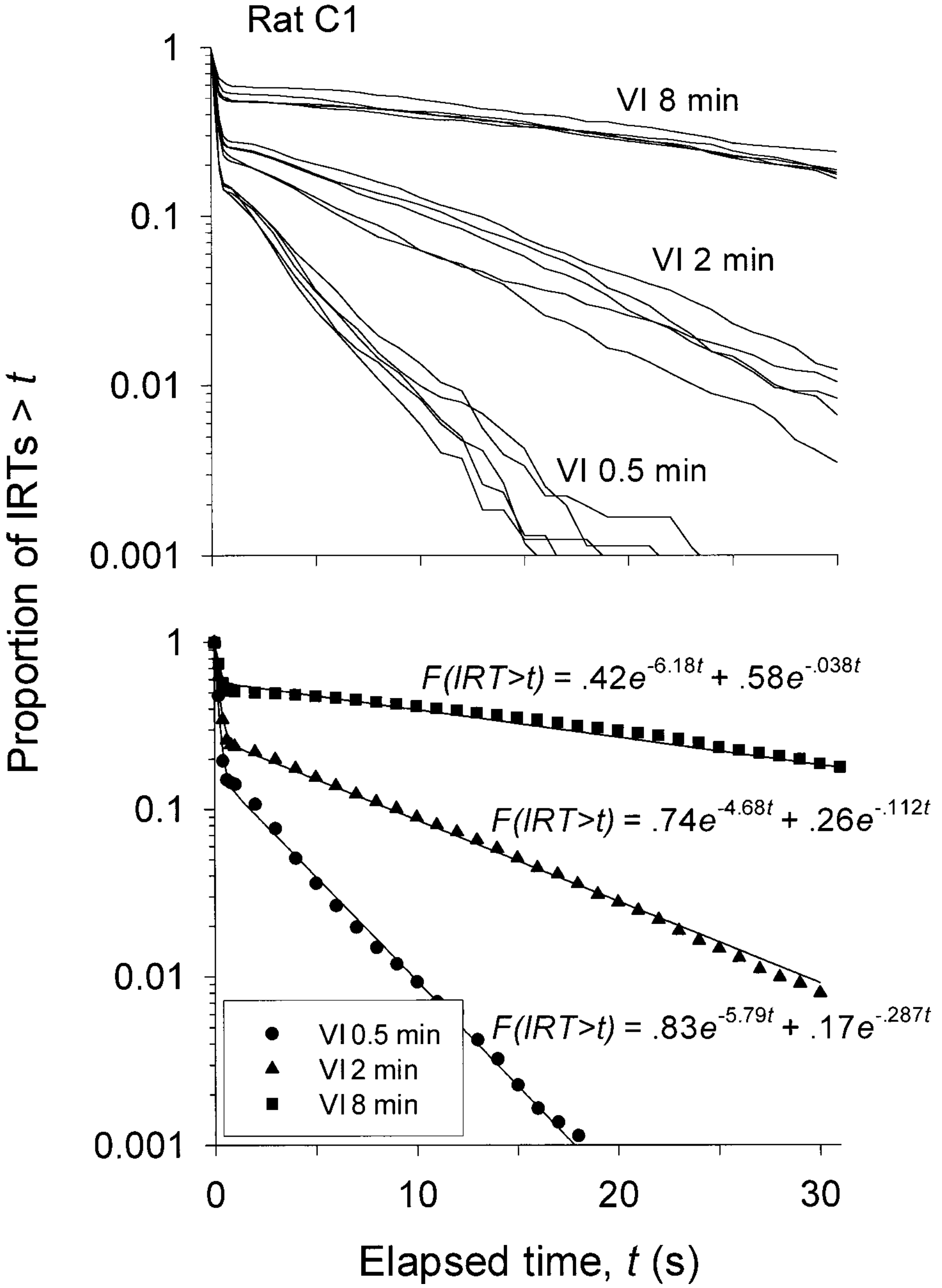

Fig. 2. Illustrative log survivor plots of IRTs from the VI schedules indicated for Rat C1. The top panel shows the plots from each of the last five sessions of the schedule indicated. The bottom panel shows a single plot for each schedule derived from the IRTs combined over the same five sessions. The fitted smooth lines (bottom panel) are the best-fitting sum of two exponentials (Equation 1); the corresponding equations are shown next to the plot.

the lower the *y*-intercept of the right-hand limb, the longer the average bout is.

The smooth lines through each plot in the lower panel of Figure 2 represent the best-fitting sum of two exponentials (Equation 1) to the survivor plots. For each fit, the sample included all the IRTs during the last five sessions of the condition (excluding the postreinforcer pauses) that were 30 s or less plus any longer IRTs needed to ensure that the sample contained all but the longest 1% of the distribution. The fits were carried out with a routine provided by SigmaPlot® 8, a graphing program (''Exponential decay, double exponential, 4 parameters, reciprocal-y weighting''), that uses an iterative process (100 iterations) to find values of the parameters that minimize the squared deviations from the function. For these fits, the coefficients, $1 - p$ and p, were constrained to sum to 1.0 since those terms represent the proportions of the two kinds of response that are assumed to comprise the distribution. (The ''reciprocal-y weighting'' gives greater weight to deviations at low survivorship values than would be given without such weighting. For most survivor plots, the parameters were very similar whether or not the reciprocal-y weighting was used; but occasionally in our full set of data from all 4 rats, the weighting generated fitted functions that appeared by eye to represent the slope of the right-hand limb better.) The equations of the three, best-fitting functions are shown in Figure 2. The values for bout-initiation rate (B) and the average number of responses per bout ($1/p$) confirm what was apparent from visual inspection: that increasing the reinforcer rate led to an increase in bout-initiation rate (B) and in the average number of responses per bout ($1/p$).

By the method just described, we fitted Equation 1 to the IRT survivorship distributions from all the conditions in the experiment so as to obtain estimates of bout-initiation rate, the average number of responses per bout, and within-bout response rate.[1] Figures 3 through 5 show the majority of these log survivor plots over the range of VI durations, along with lines representing the best-fitting sum of two exponentials. Note that the *x*-axis is extended beyond 30 s to 100 s (Figure 3) and 250 s (Figure 4) so as to display the distributions fully (or nearly so).

A few features of these plots should be noted. First, for both the VI schedules and the tandem VI VR 4 schedules, increasing the reinforcer rate steepened the right-hand limb of the plots, implying an increase in bout-initiation rate. Second, adding the VR 4 requirement to a given VI schedule tended to lower the *y*-axis intercept of the right-hand limb; that is, it increased the average number of responses per bout. Sometimes adding the VR 4 also made the slope of the right limb less steep (e.g., Rat C1 in Figure 4), indicating a lower bout-initiation rate. (These effects of reinforcer rate and added VR requirement are consistent with those reported by Shull et al., 2001.) Third, the best-fitting sum of two exponentials provided a good description of the large-scale features of most of the plots. The consistencies are striking given the range of differences in VI duration and IRT duration (i.e., *x*-axis scaling).

Systematic deviations from the best-fitting lines occurred sometimes, however. With the shortest VI schedules, for example, the right-hand limbs (the bout-initiation limbs) do not decline linearly but instead decline at a low rate for some seconds after a bout and then steepen (see especially the VI 0.5-min plots for Rat C4 in Figure 3 and the VI 0.25-min plots for all the rats in Figure 5). What this pattern means is that the likelihood of reinitiating a bout is low for a while after a bout and then rises. An analogous pattern of increasing likelihood of reinitiating a bout as time elapses is evident for Rat C2 (and, perhaps C3) with the longer VI schedules (Figures 3 and 4). To the extent that the plots display such patterns, the values of bout-initiation rate, B, given by the fits of Equation 1 will overestimate the true bout-initiation rate. Evidence presented in the Appendix suggests to us, however, that the magnitude of these errors of estimating bout-initiation rate is relatively small for this data set.

Figure 6 shows that bout-initiation rate (B from fits of Equation 1 times 60) and total key-poking rate are similar increasing, negatively accelerated functions of obtained reinforcer rate (in logarithmic coordinates). It

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[1] We also estimated the slope and intercept of the right-hand limb of each log survivor plot by fitting a straight line to the log survivorship values from 1 s through at least 30 s plus whatever longer IRTs were needed to ensure that all but the longest 1% of the distribution was included in the sample. For this we used the exponential fit provided by Microsoft® Excel (see Shull et al., 2001). The bout-initiation rates estimated this way correlated highly with the estimates obtained with the SigmaPlot® fits to the sum of two exponentials—the r^2 values of the correlations of the logarithms of the two estimates of bout-initiation rate were all at least .99. The fits of the sum of two exponentials have the advantage of providing estimates of within-bout response rate.

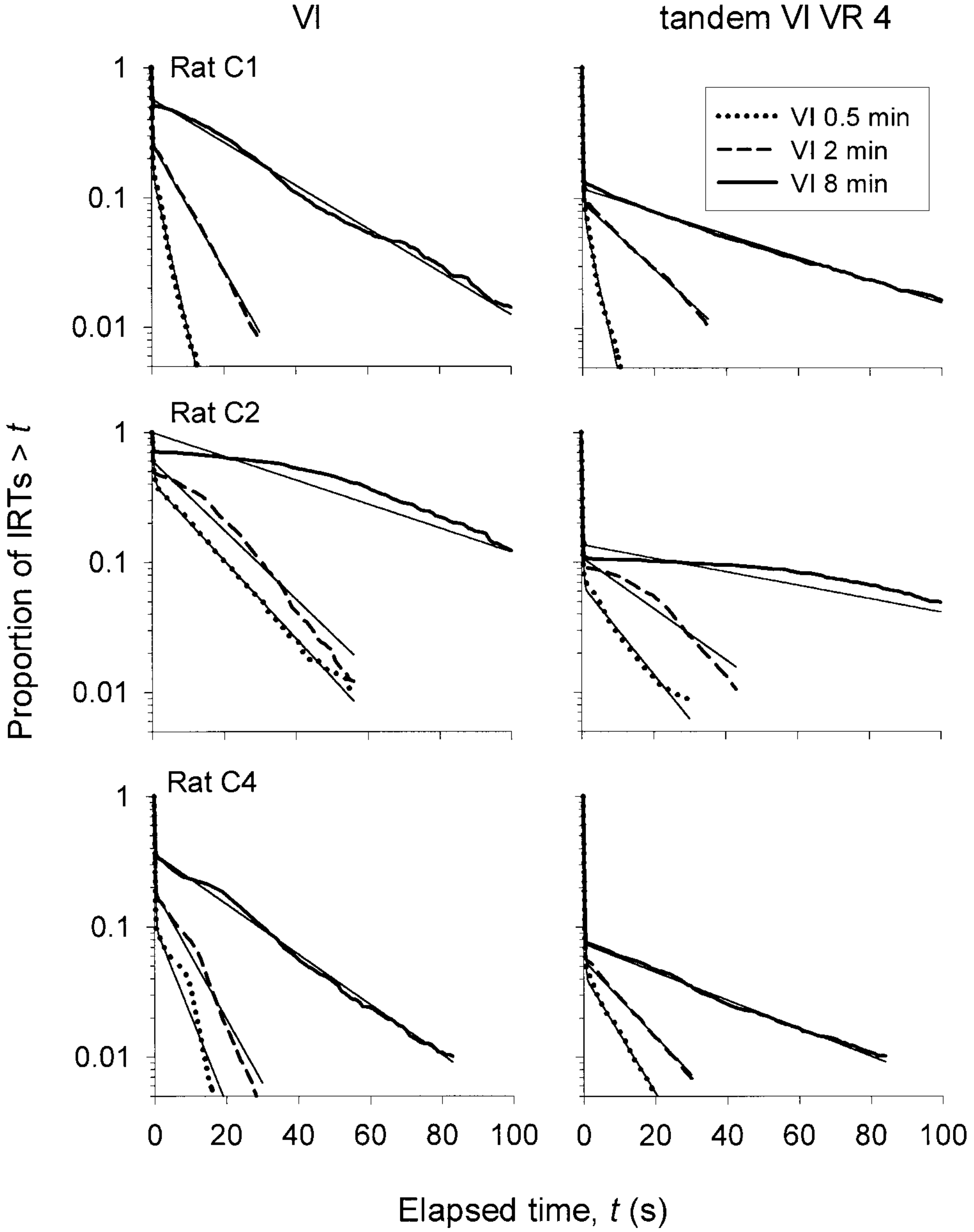

Fig. 3. Log survivor plots of IRTs from selected conditions in the VI (left column) and tandem VI VR 4 (right column) series for the 3 rats that received both series. The fitted smooth lines are the best-fitting sum of two exponentials.

shows also that imposing the VR 4 requirement, in contrast, affected total response rate and bout-initiation rate differently. For a given reinforcer rate, total response rate was higher but bout-initiation rate tended to be the same or lower with than without the VR 4 requirement.

Figure 6 shows that within-bout response rate (*W* from fits of Equation 1 times 60) was unrelated to reinforcer rate and was inconsistently affected by the VR 4 requirement. The VR 4 requirement increased within-bout response rate for Rat C2 but not for Rats C1 and C4.

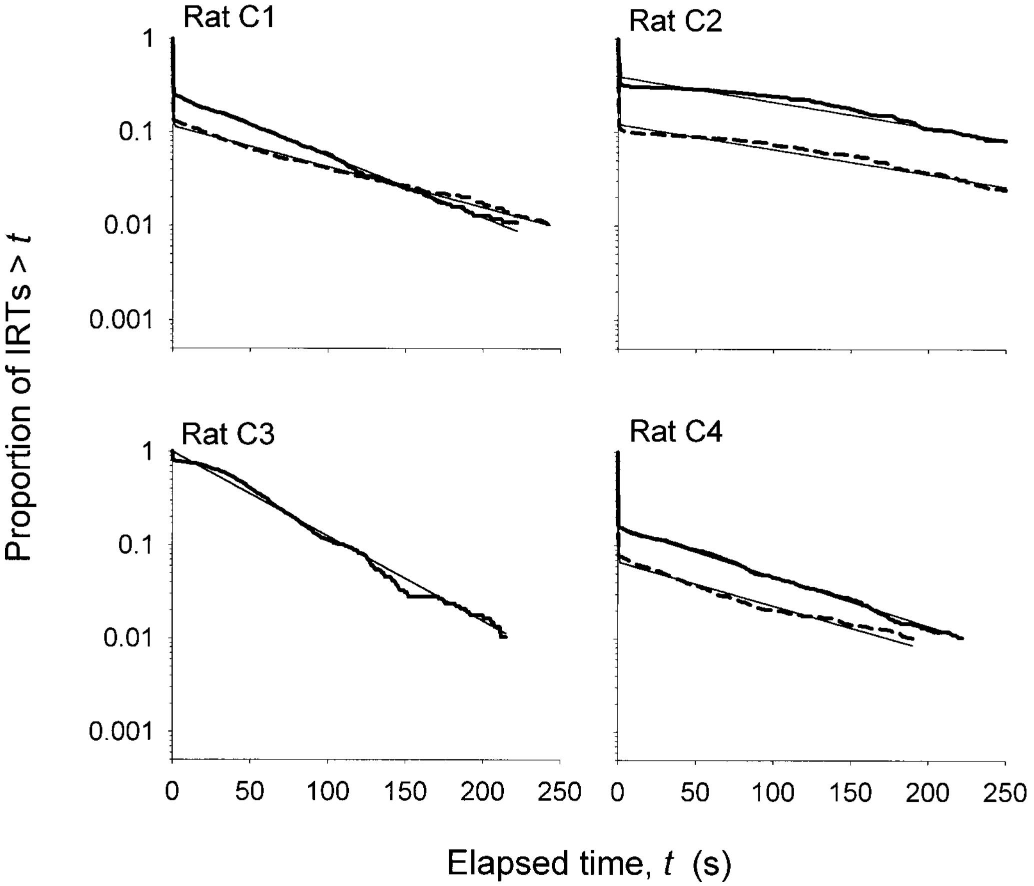

Fig. 4. Log survivor plots of IRTs from the longest VI schedule (VI 16 min for Rats C1, C2, and C4; VI 8 min for Rat C3; solid curves) and from the tandem VI 16 min VR 4 (Rats C1, C2, and C4; dashed curves). The fitted smooth lines are the best-fitting sum of two exponentials.

There is reason to question the validity of the estimates of within-bout response rate shown in Figure 6. These estimates were based on assuming an exponential distribution of within-bout IRTs (i.e., the first exponential term in Equation 1). Yet such a distribution seems highly implausible. The simple mechanics of the rat's having to move its head to make another response virtually guarantees that there will be some lower limit on how brief an IRT can be (Killeen et al., 2002; Palya, 1992). Thus the fits to Equation 1 most likely yield a high estimate of the mean within-bout response rate. To estimate within-bout response rate a different way, we determined the median IRT values from the tandem VI VR 4 series. For these conditions the median values fell clearly within the steep left-hand limb (see Figures 3 and 4) and so provided estimates of the typical within-bout IRT for the tandem series. The within-bout response rate estimated this way is the reciprocal of the median IRT. Because the median is based on the full IRT distribution, it will be longer (and so the estimated within-bout response rate will be somewhat lower) than it would be if it were based solely on the within-bout distribution.

Figure 7 shows these two estimates of within-bout response rate for the tandem VI VR 4 series (i.e., one based on fits to Equation 1 and the other based on median IRT) plotted as functions of reinforcer rate. Although the estimates based on the median IRT were, on average, lower (by 15% to 20%) than the estimates derived from the fits of Equation 1,

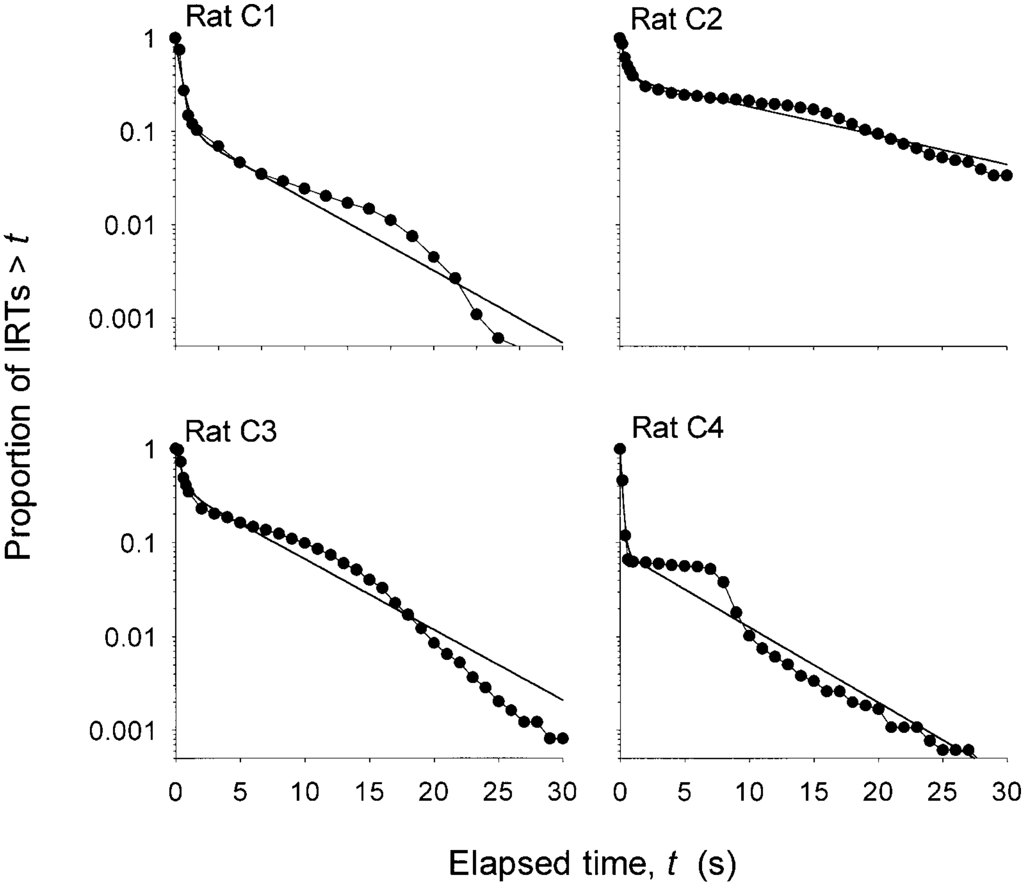

Fig. 5. Log survivor plots of IRTs from the shortest VI schedule (VI 0.25 min). The fitted smooth lines are the best-fitting sum of two exponentials.

conclusions would be similar regardless of which estimate was used. With either kind of estimate, within-bout response rate appears unrelated to reinforcer rate. Also, the mean values of these two estimates of within-bout response rate were all above 250 responses per minute. For the individual rats, the means were 331 (Equation 1) and 280 (med) for Rat C1; 356 (Equation 1) and 280 (med) for Rat C2; and 351 (Equation 1) and 288 (med) for Rat C4.

The other feature of bouts that is known to be affected by the imposition of a VR 4 requirement is their length (i.e., the average number of responses per bout). Figure 8 shows (consistent with the data reported by Shull et al., 2001; Shull & Grimes, 2003) that bouts were longer with than without the VR 4 requirement. Also, with both kinds of schedule, bouts tended to become longer as reinforcer rate increased. There is, however, an anomaly with respect to this trend in the plots for the 3 rats that received the VI 16-min schedule (Condition 14 for Rats C1, C2, and C4). Bout length for this condition (the filled point at the far left in each plot) appears to lie well above the trend of the other data points from the VI series. This anomaly probably represents a carryover effect from the previous condition—a tandem VI 16-min VR 4 schedule. Most likely 20 sessions of exposure to the VI 16-min schedule was insufficient to eliminate the effect of the prior VR 4 requirement on bout length, especially given the small number of reinforcers per session with the VI 16-min schedule (typically fewer than 8). An implication is that the total response rates for the VI 16-min schedule are probably above their stable level.

It appears, then, that the VR 4 requirement

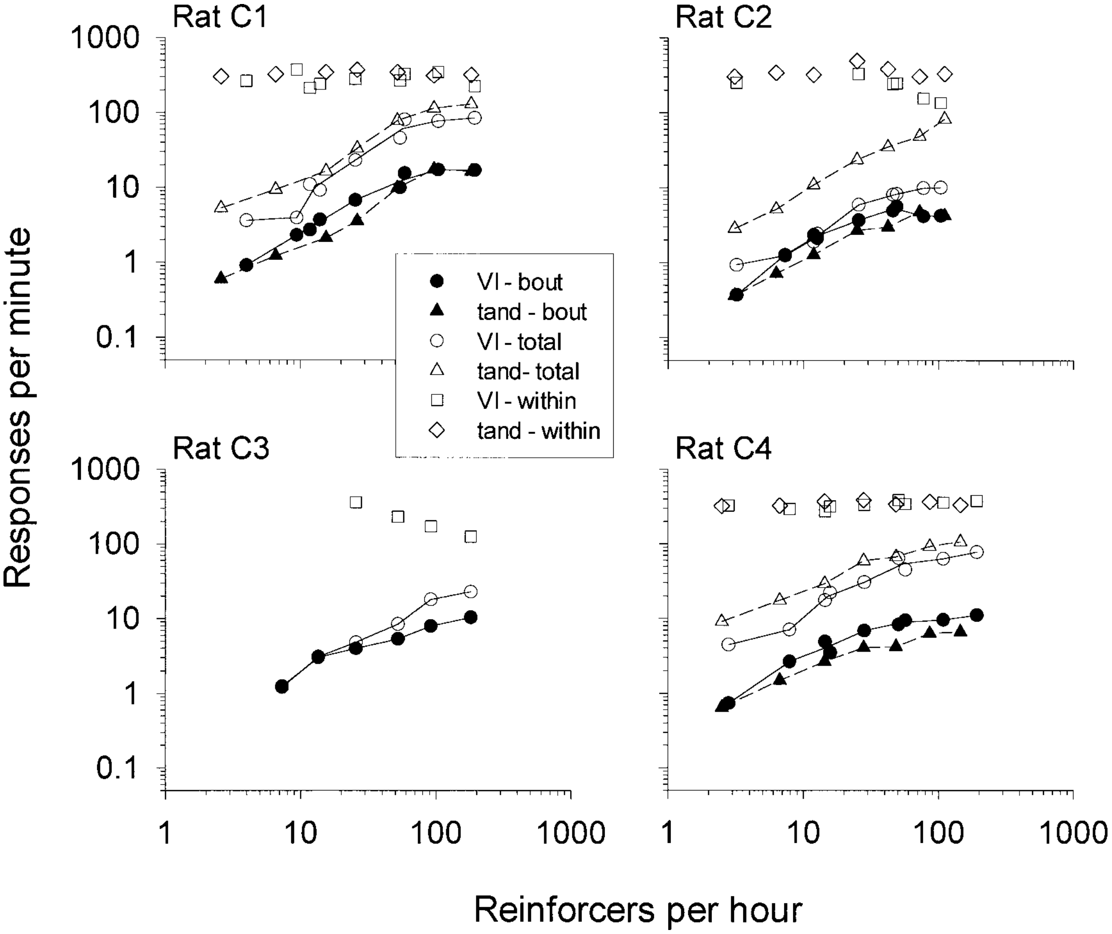

Fig. 6. Three different kinds of response rate (total key-poke rate, bout-initiation rate, and within-bout response rate) plotted as functions of obtained reinforcer rate. For each kind of response rate, one plot shows data from the VI series, and the other plot shows data from the tandem VI VR 4 series. The axes are scaled logarithmically. For the VI-1 min and VI-4 min schedules, the lines connect the geometric mean of the two determinations. For three of Rat C2's VI conditions and two of Rat C3's, only one response occurred per bout, so meaningful within-bout response rate could not be calculated for those conditions.

increased total response rate through a combination of sometimes-conflicting effects on bouts. Figure 9 summarizes these effects. For these summaries, we calculated the ratio of the performance measure (tandem/VI) at each VI value and then averaged these ratios (geometric means). (Visually, these ratios correspond to the average vertical distance between the pair of plots for a particular type of performance measure in Figures 6 and 8.) Figure 9 shows that, as already described, the imposition of the VR 4 requirement increased total response rate but decreased bout-initiation rate. Also, as already noted in relation to the data in Figure 6, adding the VR 4 requirement sometimes increased within-bout response rate, but never to the degree required to account fully for the effect on total response rate. The primary contributor to the increase in total response rate appears to be the increase in bout length (the set of bars farthest to the right). Finally, the left-most set of bars in Figure 9 indicates that adding the VR 4 requirement had only a small decremental effect on the obtained reinforcer rate. The procedure, then, appears to be an effective way to increase total response rate without substantially altering reinforcer rate.

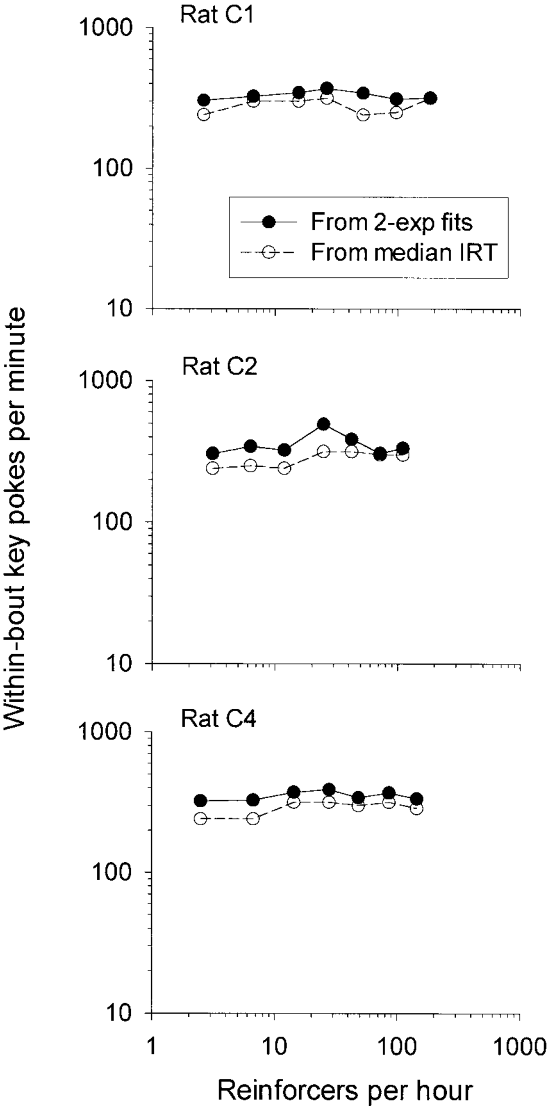

Fig. 7. Two different estimates of within-bout response rate for the tandem VI VR 4 schedules plotted as functions of obtained reinforcer rate. One estimate is *W* from fits of Equation 1 (multiplied by 60 to convert from responses per second to responses per minute). The other estimate is the reciprocal of the median IRT.

DISCUSSION

The Sensitivity of Response Rate to Reinforcer Rate

The sensitivity of response rate to reinforcer rate can be defined as the proportional change in response rate due to a given proportional change in reinforcer rate—that is, as the slope of the function relating response and reinforcer rates when both axes are scaled logarithmically (cf. Baum, 1974, 1993). We suspected prior to conducting the study that bout-initiation rate might be more sensitive than total response rate to reinforcer rate. Our reasoning was that a component of total response rate is within-bout response rate which, as demonstrated in Figures 6 and 7, is insensitive to reinforcer rate. It turned out, however, that total response rate was at least as sensitive to reinforcer rate as bout-initiation rate was (Figure 6). Indeed, the slopes (in logarithmic coordinates) of the total response rate and bout-initiation rate plots were similar over the range of reinforcer rates, including becoming less steep as reinforcer rate increased—a pattern consistent with a hyperbolic relation between response and reinforcer rates (Davison & McCarthy, 1988; Herrnstein, 1970; Williams, 1988).

In our previous work (Shull et al., 2001) the data were suggestive but not definitive that the average number of responses per bout increased as a function of reinforcer rate on VI schedules. As discussed by Shull et al., such a relation might be expected on theoretical grounds (Nevin & Baum, 1980) but might be difficult to demonstrate because of contingencies inherent in VI schedules that favor uniformly short bouts (i.e., one response per bout). In that earlier study only two VI schedules were used (VI 4 min and VI 1 min). The present study arranged a wider range of VI durations, and the evidence for a positive relation between responses per bout and reinforcer rate is unmistakable (Figure 8). An implication of this relation is that the sensitivity of total response rate to reinforcer rate comes from at least two sources: the effect of reinforcer rate on bout-initiation rate and the effect on bout length.

The Bout as a Unit of Operant Behavior

It is possible to increase the rate of a response either by increasing the rate of contingent reinforcement or by adding a small response requirement (here, a VR 4) to the end of a VI schedule. These two methods are not equivalent in their effect, however. For example, when total response rate is increased by increasing the reinforcer rate, the response is strengthened in the sense that its rate is made more resistant to disruption (Nevin & Grace, 2000; Smith, 1974). In contrast, when response

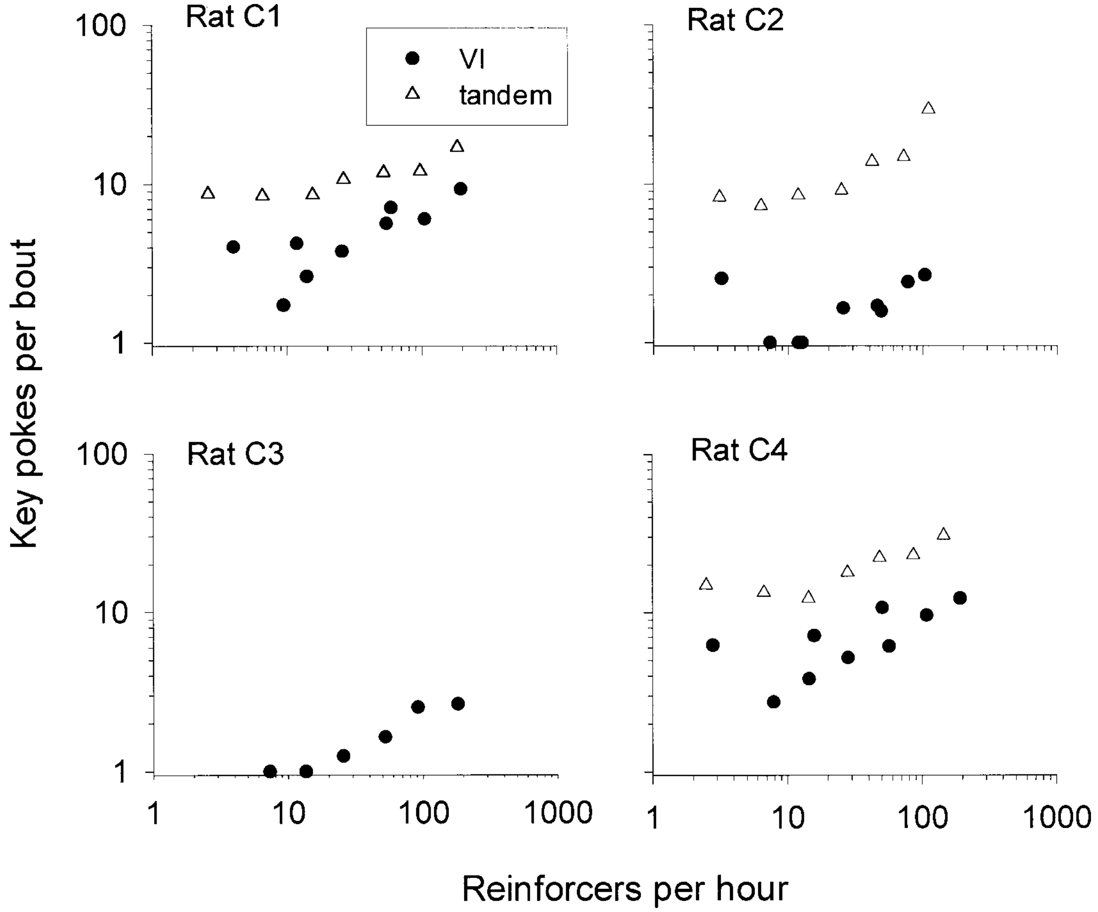

Fig. 8. The average number of key pokes per bout (i.e., bout length) plotted as a function of obtained reinforcer rate from the VI schedules (solid circles) and the tandem VI VR 4 schedules (open triangles).

rate is increased by adding a ratio (or related) contingency, the response rate is made more "fragile" (Catania, 1998, p. 122) in the sense of becoming less resistant to disruption (Lattal, 1989; Nevin, Grace, Holland, & McLean, 2001; Powell, 1970). The analysis of bouts suggests one possible way to understand such apparent inconsistencies.

When responding is organized into bouts, there is a choice about what to count as a unit of operant behavior—whether the individual response (e.g., key poke) or the bout. Sometimes it will not matter which kind of unit is counted. For example, regardless of whether the unit is the individual response or the bout, the relation between response rate and reinforcer rate is similar except for absolute level (Figure 6). But sometimes it does matter which unit is counted. If individual responses are counted, adding a VR requirement causes response rate to increase; if bouts are counted, adding a VR requirement causes response rate to decrease (or to remain unchanged). If the bout is the unit, adding the VR requirement increases total response rate by making the units larger, not by making them more frequent.

The question of whether to count individual responses or bouts is an old one (Arbuckle & Lattal, 1988; Baum, 2002; Killeen, 1988 [pp. 326–327], 1994; Machlis, 1977; Mowrer & Jones, 1945; Skinner, 1938, p. 300; cf. also, Marr, 1979; Morse, 1966; Reid, Chadwick, Dunham, & Miller, 2001; Shimp, 1984). Skinner's (1938, pp. 33–41) approach was to view the unit as something to be discovered rather than asserted—discovered on the basis of which specification generated the more or-

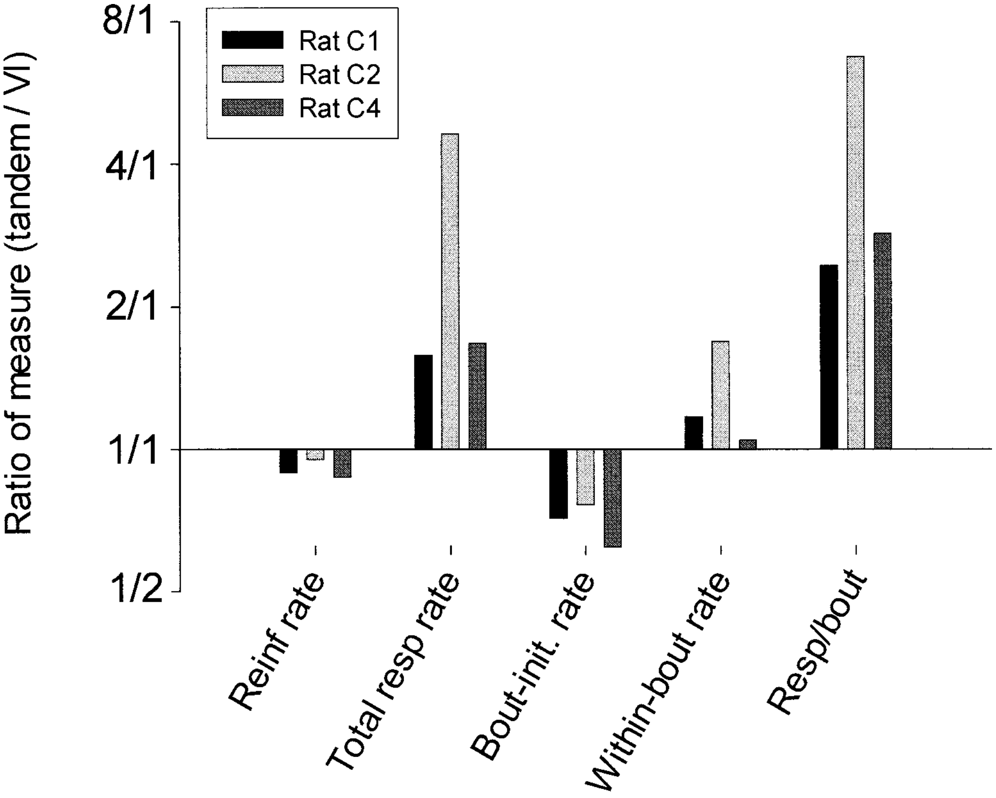

Fig. 9. A summary of the effects of imposing the VR 4 requirement on several measures for the 3 rats that received the tandem VI VR 4 series. Each group of bars shows the effect on a particular measure; each bar represents the effect for a particular rat. The effect is expressed as a ratio—the measure obtained with the tandem VI VR 4 schedule relative to the measure obtained with the simple VI schedule. A ratio was obtained at each VI (using the geometric means of the two determinations for the VI 1 min and VI 4 min), and the heights of the bars represent the geometric means of those ratios. The *y*-axis is scaled logarithmically.

derly, simple, and integrative relations. Such criteria would seem to favor the bout as the unit of choice because the relation between response rate and reinforcement appears to be more broadly consistent for bout-initiation rate than for total response rate. It is reasonable to suppose that generating longer bouts by adding the VR requirement diminishes the reinforcement associated with engaging in bouts—either because of greater effort expended in longer bouts or because of the longer delays between bout-initiations and pellet deliveries. The decline in bout-initiation rate due to adding the VR 4 requirement could reflect such a decline in reinforcement. Moreover, a decline in reinforcement due to the VR 4 requirement might help explain why response rates that are increased by ratio contingencies are thereby made more susceptible to disruption (Lattal, 1989; Nevin et al., 2001; Powell, 1970).

Activity Bouts and Time Allocation

This view of bouts as a unit of behavior is similar in many respects to Baum's (2002) concept of *activity*. From Baum's perspective, within-bout responses would be part of a continuous, ongoing activity despite the fact that those responses are measured as discrete switch closures. Between-bout intervals (but not within-bout IRTs) would represent breaks from that activity. There is considerable precedent and support for such a view (e.g., Premack, 1965; Steller & Hill, 1952).

An implication of this view is that time allocation between bouts and pauses might be a useful measure of performance on so-called single-response VI schedules of reinforce-

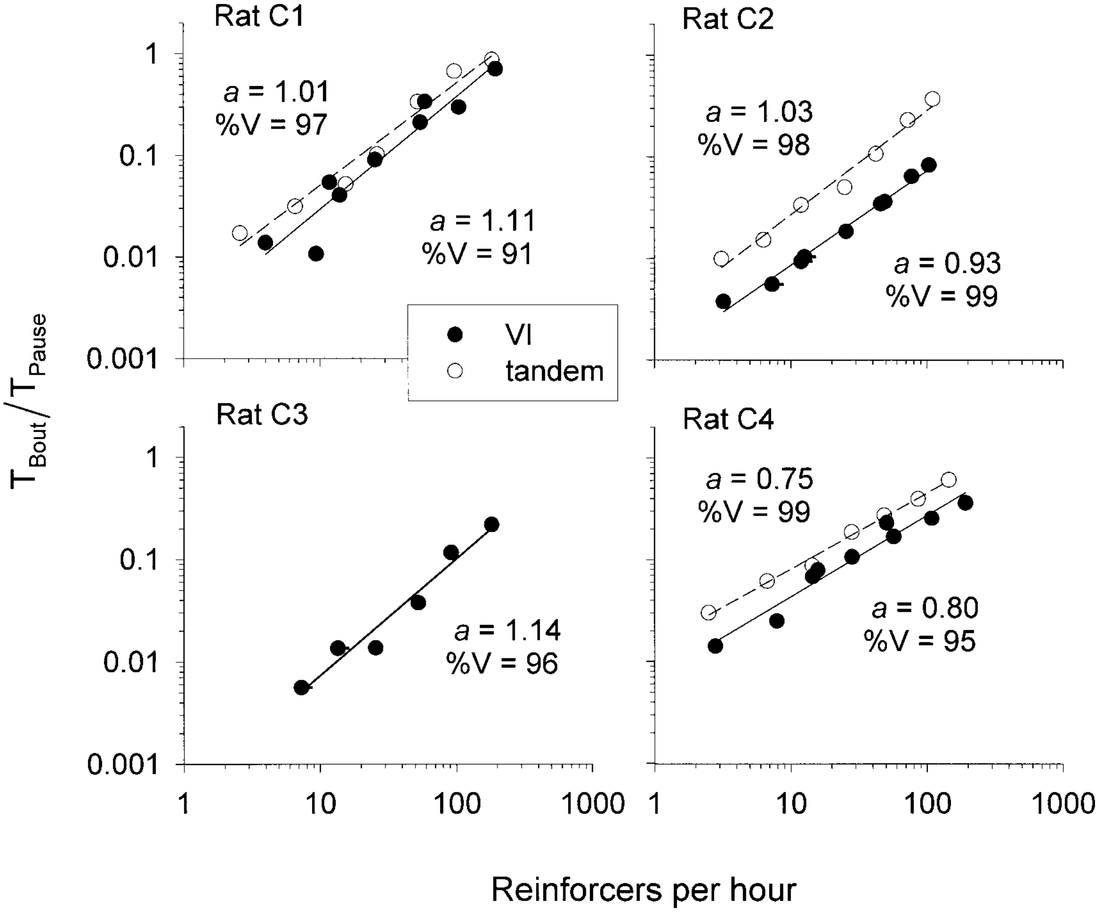

Fig. 10. The ratio of bout time to pause time plotted as a function of obtained reinforcer rate for the VI series and the tandem VI VR 4 series. The straight lines (solid for the VI series and dashed for the tandem series) show the best fits of Equation 4 (based on linear fits [Pearson method] to the logarithms of the time ratios and reinforcer rates). The slope of the line in logarithmic coordinates (*a*) and the percentage variance-accounted-for (%V, i.e., r^2 times 100) appear in the lower right of each panel for the VI series and in the upper left for the tandem series. For three of Rat C2's VI conditions and two of Rat C3's, only one response occurred per bout, so the within-bout IRT was undefined. For those conditions (noted by short horizontal lines attached to the relevant symbols) the within-bout IRT was set equal to the mean within-bout IRT for the other VI conditions for that rat.

ment (Baum, 2002; Baum & Rachlin, 1969; Pear & Rector, 1979). With concurrent VI VI schedules, the ratio of time spent in each of two activities (T_1/T_2) is an approximate power function of the ratio of reinforcers (R_1/R_2) obtained from those activities (Baum, 1974; Davison & McCarthy, 1988). That is,

$$(T_1/T_2) = c(R_1/R_2)^a \qquad (2)$$

where the curve-fitting constant, *c*, is interpreted as a constant bias (due, perhaps, to reinforcers inherent in the activity or to constraints on the minimum duration of a visit to an alternative) and *a* is interpreted as the sensitivity of time allocation to reinforcer allocation because *a* is the slope of the logarithmic version of Equation 2 [i.e., $\log(T_1/T_2) = \log(c) + a \log(R_1/R_2)$].

A version of Equation 2 might also describe the allocation of time on single VI schedules between bouts and pauses (as implied by comments in Baum, 2002):

$$(T_{\text{Bout}}/T_{\text{Pause}}) = c(R_{\text{VI}}/R_{\text{Pause}})^a \qquad (3)$$

where ($T_{\text{Bout}}/T_{\text{Pause}}$) represents the ratio of time spent in bouts of the schedule-relevant activity to time spent in other activities that occur between bouts, ($R_{\text{VI}}/R_{\text{Pause}}$) represents the ratio of reinforcers provided by the VI schedule to reinforcers obtained from those other activities, and c and a are, again, curve-fitting constants representing bias (c) and the sensitivity of the time ratio to the reinforcer ratio (a).

To assess the applicability of Equation 3, we obtained for each rat and condition estimates of T_{Bout} and T_{Pause}. T_{Pause} is the reciprocal of the bout-initiation rate (Figure 6); T_{Bout} is the average number of responses per bout (Figure 8) multiplied by the mean within-bout IRT (where the mean within-bout IRT equals the reciprocal of the within-bout response rate, W; Figure 6). There is no obvious way to distinguish the effect represented by c from that represented by R_{Pause}. But if R_{Pause} is assumed to be constant over the different schedules, R_{Pause} and c can be combined to form a new constant, c', generating a variant of Equation 3:

$$(T_{\mathrm{Bout}}/T_{\mathrm{Pause}}) = c'(R_{\mathrm{VI}})^{a} \qquad (4)$$

which describes time allocation between bouts and pauses as a power function of reinforcer rate.

Figure 10 shows that Equation 4 provides a good description of the time-allocation data from both the VI and the tandem VI VR 4 series. The percentage variance-accounted-for values are all above 91% ($M = 96\%$), and the deviations from the best-fitting lines do not appear to be systematic. That the function for the tandem series is above that for the VI series is likely due to the VR 4 requirement effectively putting a lower limit on the minimum bout (or visit) duration. The values of a, the index of sensitivity, range from 0.75 to 1.14. These values are consistent with those found for time allocation with concurrent VI VI schedules (Baum, 1979; Wearden & Burgess, 1982). Thus, granting the validity of the bout and pause time estimates, the principle that describes the relation between time allocation and reinforcer distribution on concurrent VI VI schedules appears to apply also to the allocation of time between bouts and pauses on single-response VI schedules.

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APPENDIX

VALIDITY OF THE QUANTITATIVE ANALYSIS OF BOUTS

The technique that we used to quantify bout-initiation rate, average number of responses per bout, and response rate within bouts is based on some simplifying assumptions about the response-generating process—namely, that it can be characterized as

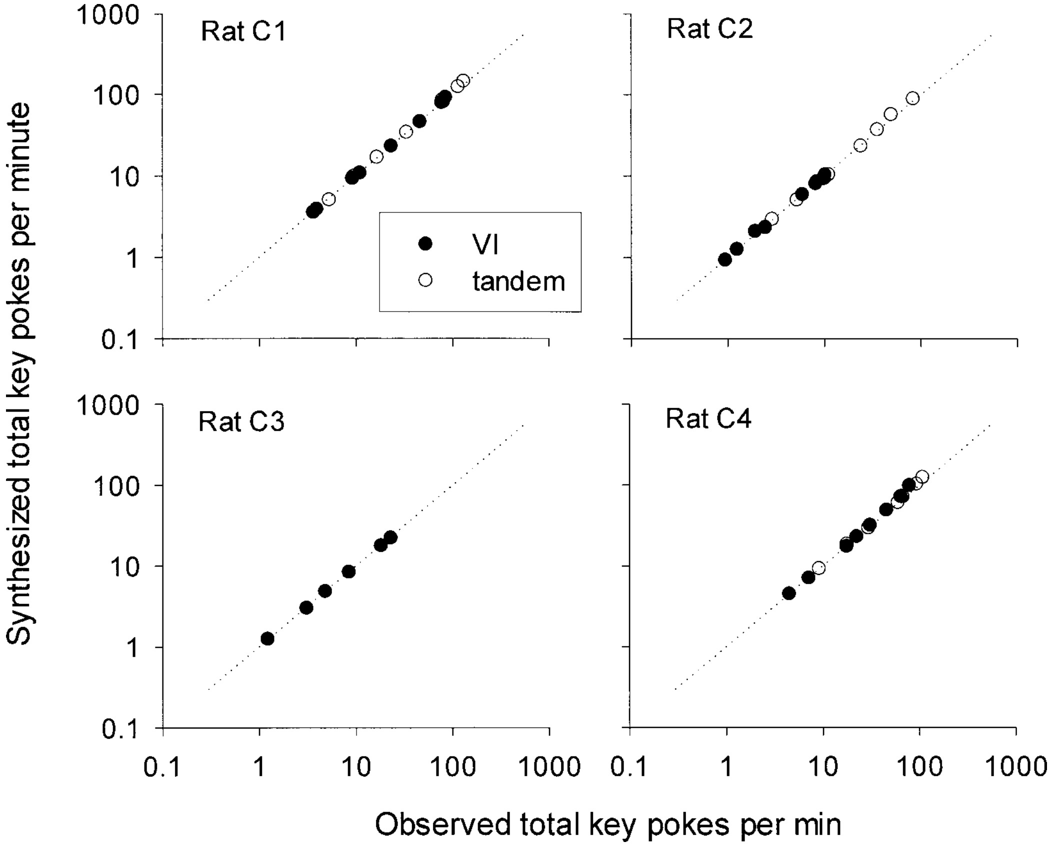

Fig. A1. Total rates of key poking synthesized from components plotted as a function of the total rate of key poking obtained from response and time totals. The dashed diagonal line indicates perfect correspondence.

two alternating states during which responses occur at random but at different rates (cf., Fagan & Young, 1978; Killeen et al., 2002; Shull et al., 2001). Sometimes the log survivor plots were closely consistent with such a simple characterization, but sometimes they were not (cf. Figures 2 through 5). Clearly, Equation 1 cannot be regarded as a generally complete and accurate model of response rate. (For discussion of other limitations on the generality of a 2-exponential model see, for example, Berdoy, 1993; Killeen et al., 2002; Langston, Collett, & Silby, 1995; Mori, Yoda, & Sato, 2001; Slater, 1974; Tolkamp & Kyriazakis, 1999.)

For our purpose, however, the salient question is whether the deviations from Equation 1 are large and systematic enough to compromise conclusions that are based on estimates derived from the fits of Equation 1. One kind of answer to this question is to point to the orderly relations based on such estimates, such as shown in Figures 6 and 10. A second kind of answer can come from taking the components that were generated by the fits of Equation 1 to the log survivor plots and combining them so as to produce a synthesized total response rate. If response rates synthesized this way correspond well with response rates calculated in the usual way (i.e., from response and time totals), then it seems reasonable to conclude that the estimates are valid (even though imperfect) approximations of the key constituents of total response rate.

For each rat and condition we computed a synthesized response rate by combining the components according to the following equation:

$$P_{\text{synthesized}} = N/\{[1/B] + [N(1/W)]\} \quad \text{(A1)}$$

where $P_{\text{synthesized}}$ is the synthesized total response rate, N is the average number of responses per bout, B is the bout-initiation rate, and $1/W$ is the within-bout IRT (see also Equation 2 in Shull et al., 2001). Figure A1 shows that the response rates synthesized this way correspond closely to the response rates calculated from response and time totals. We conclude from this correspondence that the fits of Equation 1 provide adequate estimates of bout-initiation rate, bout length, and within-bout response rate.