BOUTS OF RESPONDING FROM VARIABLE-INTERVAL REINFORCEMENT OF LEVER PRESSING BY RATS

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Four rats obtained food pellets by lever pressing. A variable-interval reinforcement schedule assigned reinforcers on average every 2 min during one block of 20 sessions and on average every 8 min during another block. Also, at each variable-interval duration, a block of sessions was conducted with a schedule that imposed a variable-ratio 4 response requirement after each variable interval (i.e., a tandem variable-time variable-ratio 4 schedule). The total rate of lever pressing increased as a function of the rate of reinforcement and as a result of imposing the variable-ratio requirement. Analysis of log survivor plots of interresponse times indicated that lever pressing occurred in bouts that were separated by pauses. Increasing the rate of reinforcement increased total response rate by increasing the rate of initiating bouts and, less reliably, by lengthening bouts. Imposing the variable-ratio component increased response rate mainly by lengthening bouts. This pattern of results is similar to that reported previously with key poking as the response. Also, response rates within bouts were relatively insensitive to either variable.

  Key words: bouts, response rate, log survivor plot, variable-interval schedule, tandem ratio, lever press, rats

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Operant behavior sometimes appears to be organized into bouts of activity separated by pauses. Such patterns, when they occur, have potentially important implications for calculating response rate and for interpreting changes in response rate (Baum, 2002; Gilbert, 1958; Killeen, Hall, Reilly, & Kettle, 2002; Mechner, 1992; Pear & Rector, 1979; Shull, Gaynor, & Grimes, 2001). If responding is organized into bouts, changes in response rate can arise from changes in the amount of time between bouts, in the length of bouts, in the response rate during bouts, or in combinations of these features. Similar changes in total response rate, then, can result from different patterns of change at the level of bouts. Such differences would be important to take into account if they were related to different classes of controlling variables or if they were predictive of other interesting features of behavior, such as its resistance to attenuation by punishment and other disrupters.

Indeed, differences of this sort have been demonstrated for responding maintained by variable-interval (VI) schedules of reinforcement (Blough, 1963; Mellgren & Elsmore, 1991; Shull et al., 2001). In one study (Shull et al., 2001) rats obtained food pellets by nose poking a lighted key. Several different operations were carried out that produced roughly similar changes in the total rate of key poking. With respect to total response rate, then, those operations were equivalent in their effect. Yet those operations could be differentiated based on how they affected bout-initiation rate and bout length. Varying the rate, size, and percentage of reinforcers that were contingent on key poking changed total key-poking rate primarily by altering the rate of initiating bouts. Each of these variables also had a corresponding, but smaller and less reliable, effect on the length of bouts. In contrast, adding a small variable-ratio (VR) requirement to the end of the VI schedule (technically, changing the VI schedule to a tandem VI VR 9 schedule) increased total rate of key poking primarily by increasing the length of bouts. In fact, there was some tendency for the added VR 9 requirement to decrease the rate of initiating bouts so that the total rate of key poking and the rate of initiating bouts of key poking changed in opposite directions. It is almost as if the additional VR 9 response requirement kept the rat responding in the bout longer than it otherwise would have, making the bouts somewhat less attractive to enter. If so, that may help explain why response rates that are increased by ratio

contingencies are thereby made less resistant to disruption (Lattal, 1989; Nevin, Grace, Holland & McLean, 2001).

This pattern of results for total response rate, bout-initiation rate, and bout length was obtained under a somewhat unusual procedure. With rats as the subjects, the response was nose poking a lighted key (a pigeon key). Also, two different reinforcement schedules and their discriminative stimuli (a blinking or a steadily illuminated keylight) alternated every 50 s during each session. That is, the schedules were presented in a multiple-schedule arrangement.

The question that motivated the present study was whether the differential effects of reinforcement rate and VR requirement on the rate and length of bouts depended on the particular features of the earlier study—particularly on the use of the key-poking response. The question seemed worthwhile considering for at least two reasons. First, the way rats nose poke a lighted key resembles the way they sniff and root when food pellets are hidden in their bedding material. Perhaps this resemblance to foraging behavior makes key poking especially prone to occur in bouts. If so, the pattern of results described above might not be found with responses other than key poking.

Second, key poking in the earlier study (Shull et al., 2001) occurred at high rates during bouts, and this characteristic of responding may be essential for generating interpretable estimates of bout rate and bout length through the technique used by Shull et al. The technique involves constructing a kind of frequency distribution of interresponse times (IRTs) known as a log survivor plot and then fitting a line to a segment of that plot (Machlis, 1977; Shull et al., 2001; Sibley, Nott, & Fletcher, 1990; for some qualifications see Langston, Collett, & Silby, 1995; Tolkamp & Kyriazakis, 1999). As should become clearer when the relevant data are described in the Results section, the technique works best when the average times between responses within a bout are substantially shorter than the average times between bouts so that the frequency distributions of the two types of behavior overlap minimally. That, indeed, was the situation in our prior work with key poking as the response (Shull et al., 2001). The average between-bout times

were typically in the order of 4 s to 20 s, whereas the within-bout IRTs were in the order of 0.20 s to 0.25 s, which translates into a within-bout rate of between 250 and 300 key pokes per minute. The log survivor technique might not work well with responses that have a lower maximum rate.

The purpose of the present study was to determine if the pattern of effects, described above, on aspects of bouts could be demonstrated with a response other than key poking. We chose lever pressing as the response, in part because lever pressing has been far more common than key poking in studies of operant behavior with rats as subjects. Also, our initial impression—based simply on listening to the patterns of performance—was that lever pressing in our experimental chambers seldom if ever occurs at the high rates characteristic of key poking in our chambers. Thus lever pressing seemed a useful response for assessing the generality of the earlier findings regarding bout rate and bout length.

In brief, the study consisted of training rats in consecutive blocks of sessions on each of two different VI schedules of reinforcement for lever pressing. Further, at each VI an additional block of training sessions was arranged with a VR added at the end of the VI period. We were interested to see if the pattern of results obtained previously (Shull et al., 2001) would be observed with a response other than key poking, namely with lever pressing, and under conditions that differed in a number of other respects from those arranged in the earlier study. Specifically, we were interested to see if VI duration would affect total response rate mainly by changing bout-initiation rate and if the added VR requirement would increase total rate of lever pressing mainly by increasing the average length of bouts.

METHOD

Subjects

The subjects were 4 male Long-Evans Hooded rats, about 1 year old at the start of the experiment. They previously had been used in an undergraduate laboratory class to demonstrate some basic behavioral processes such as shaping, discrimination training, and chaining. Except during the experimental

sessions, the rats were housed in individual clear-plastic cages, covered with metal grate tops, with free access to water. The home cages were kept in a room that maintained a 12: 12 hr light/dark cycle, with dark beginning about 6:00 p.m. Experimental sessions were conducted during the light period. Throughout the experiment, the rats were maintained at a weight of 335 g ($\pm$ 15 g) by giving them access to food in their home cages for between 1 and 1.5 hr after their experimental sessions (Ator, 1991).

Apparatus

The experimental sessions were carried out in four identical operant conditioning chambers (Colbourn Instruments), each measuring 29 cm high by 29 cm wide by 25.5 cm deep. The chambers were placed, unshielded, on tables in a room that was darkened during sessions except for low-level ambient light that entered the room through a translucent window. Each chamber was constructed of two clear plastic sidewalls and two walls of sheet-metal panels. The rear (metal) wall contained an opening, 7 cm above the floor, through which the spout of a water bottle protruded 0.5 cm into the chamber. The rats had continuous access to water during all experimental sessions.

On the front wall were two identical response levers located 6 cm above the grid floor, one 5.5 cm to the left of center and the other 5.5 cm to the right of center. Only the left lever was operative for this project. The lever was 3.5 cm wide and extended 2 cm into the chamber. A downward force on the lever of at least 0.3 N operated a switch that was connected to the lever and thereby generated a recordable response. Located 2.5 cm above each lever were three small (5 mm diameter) light bulbs (one each of yellow, red, and green), arranged in a horizontal row, 1.5 cm apart center to center. There was no houselight.

Centered on the front wall, 2 cm above the floor, was a rectangular opening (4 cm high and 3.5 cm wide) behind which was a small metal box with a hole at the top through which food pellets (45 mg Noyes pellets, Formula A, from Research Diets) were delivered from an electrically operated dispenser. A distinctive click occurred whenever a pellet was delivered.

A computer running software and interface modules supplied by Colbourn Instruments (LabLinc®) controlled all experimental events and data recording. The times of each left-lever response were recorded to the nearest 10th of a second.

Procedure

Because the rats had experience obtaining food pellets by pressing the left lever, they needed no preliminary training. The project consisted of four conditions, each of which was in effect for 20 consecutive daily 2-hr sessions. At the start of each session, the three small bulbs above the left lever were illuminated; at the end of the session, those bulbs were darkened. Performance appeared to stabilize in each condition well before 20 sessions had been conducted.

The first condition was a VI 2-min schedule of reinforcement. That is, the first left-lever press that occurred after an interval of time had elapsed operated the pellet dispenser, delivering a pellet. The intervals varied unpredictably from one reinforcer to the next, but their average duration was 2 min. The first interval was timed from the start of the session; all others were timed from the previous pellet delivery. The frequency distribution of intervals comprising the VI approximated a geometric distribution, with a minimum interval of 6 s. This distribution was generated by arranging a constant probability ($p = .05$) of assigning reinforcement at the end of each consecutive 6-s interval until an assignment occurred.

The second condition was exactly like the first except that four responses had to occur, on average, instead of only one, to obtain the pellet. That is, after the interval arranged by the VI schedule had elapsed, each subsequent response had a .25 probability of producing the assigned pellet until the pellet was obtained. No stimulus change indicated either the end of the interval or the number of responses needed to obtain the pellet. Thus, in technical terms, the schedule was a tandem variable time (VT) 2-min VR 4 schedule of reinforcement. (This schedule differs from the tandem VI VR used by Shull et al., 2001, in that the latter always required at least two responses after the end of the interval— one required by the VI component and the other being the minimum required by the VR
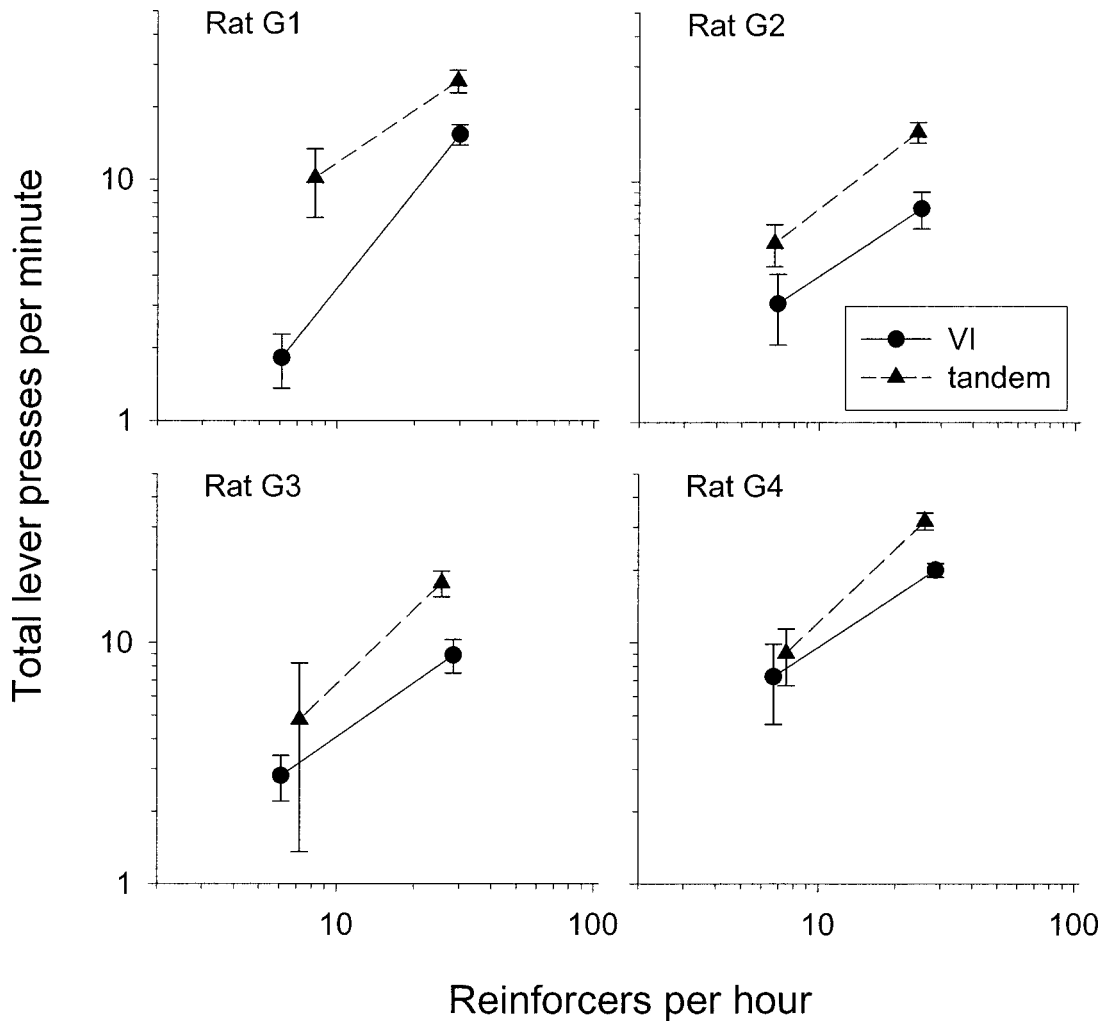
Fig. 1. Total rate of lever pressing (means of the daily response rates over the last five training sessions) plotted as a function of the mean (over five sessions) obtained rate of reinforcement. The schedule of reinforcement was either a VI or a tandem schedule that imposed a VR 4 schedule at the end of the variable time interval (i.e., a tandem VT VR 4). The points at the left in each panel are from the 8-min schedules; those at the right are from the 2-min schedules. The axes are scaled logarithmically. The error bars indicate one standard deviation unit (based on each day's rate over the last five sessions) above and below the mean. Because of the logarithmic scaling, one standard-deviation unit below the mean appears as a larger deviation than one standard deviation above the mean.

component. With the tandem VT VR 4 schedule, approximately one fourth of the assigned reinforcers could be obtained with only a single response.)

The last two conditions were exactly like the first two except that the VI schedule (or the VT component of the tandem schedule) averaged 8 min instead of 2 min. Specifically, the third condition was a tandem VT 8-min VR 4 schedule, and the fourth condition was a VI 8-min schedule.

RESULTS

Figure 1 shows that the total rate of lever pressing was higher when reinforcers were scheduled every 2 min on average than when they were scheduled every 8 min on average. The rate of lever pressing also was higher when the additional VR schedule was imposed than when it was not. The effect of the additional VR was more consistently evident with the richer than with the leaner VI durations.
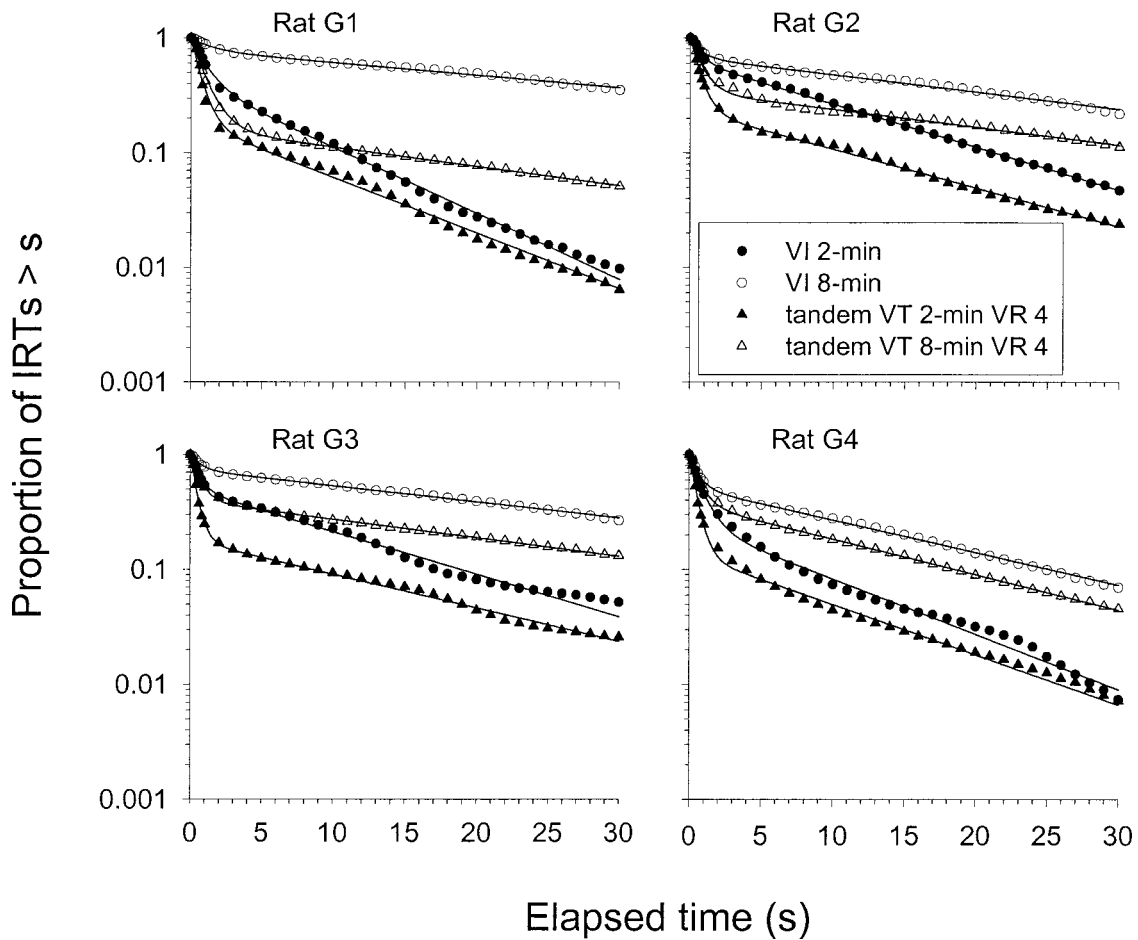
Fig. 2. Log survivor plots of IRTs (semilog plots of the proportion of IRTs longer than *t* s) from each condition. Proportions are plotted every 0.2 s for the first second and every 1 s thereafter. The smooth lines show the best fitting sum of two exponential decay functions. The proportions are based on all the response times generated during the last five sessions of a condition.

The question of primary interest was whether these changes in total response rate emerged from similar or dissimilar patterns of change in the rate and length of bouts. That, in turn, raises the question of how best to assess these features of bouts. Log survivor plots of IRTs provide one method for such assessment (Fagen & Young, 1978; Shull et al., 2001; Sibley et al., 1990; Staddon & Zanutto, 1997). These are semilogarithmic plots that show the proportion of IRTs in a sample that are longer than any particular duration, *t*. If responding occurs in bouts, the plots will often show a sharp inflection, falling steeply at first and then more gradually. The two limbs are suggestive of two response states, one in which responses occur at a high rate

and the other in which responses occur at a lower rate. In terms of bouts, the initial limb of the log survivor plot is interpreted as comprised of a mixture of within-bout IRTs and short between-bout IRTs. The second limb is interpreted as comprised largely of between-bout IRTs (i.e., of times from the end of one bout to the start of the next).

Figure 2 shows four different log survivor plots for each rat—one for each condition. (Ignore, for the moment, the smooth lineplots; these are fitted functions and will be described shortly.) Each plot is derived from a single frequency distribution of IRTs consisting of all the IRTs from the last five sessions of the condition. (These response-time totals are listed in the appendix.) Several fea-

tures of these plots are notable. First, the plots appear to be composed of two limbs, suggestive of bouts and between-bout pausing. Second, the transition between the two limbs is gradual rather than abrupt. Third, the limbs seem to be affected differently by the different independent variables. The slope of the right-hand limb was affected by the average frequency of reinforcement but not by the presence or absence of the VR 4 requirement. The length of the left-hand limb, in contrast, was affected by the VR requirement. As discussed at length in the paper by Shull et al. (2001), the slope of the right-hand limb is interpretable as indicating the rate of initiating bouts: the steeper the slope, the higher the bout-initiation rate. The intercept of the right-hand limb—the point where the limb would intersect the *y*-axis if it were extended back that far—is interpretable as indicating the proportion of responses that are bout initiations. The inverse of that intercept is the average number of responses per bout (including the bout-initiating response). The log survivor plots, then, do indeed indicate that the changes in total response rate shown in Figure 1 derive from different patterns of change in bout-initiation rate and bout length. Bout-initiation rate was an increasing function of reinforcement rate but was little affected by the presence or absence of the VR 4 requirement. The presence or absence of the VR 4 requirement affected mainly the length of bouts.

Although mere inspection of the log survivor plots is sufficient to answer the primary question about the pattern of change in bout-initiation rate and bout length, there may be value in measuring these features of bouts more precisely. The log survivor plots permit such measurement under certain conditions. If it can be assumed that the limb representing bout-initiation times is approximately linear (in semilogarithmic coordinates), the numerical values of the slope and intercept of the best fitting straight line to that limb can be used to estimate bout-initiation rate and responses per bout. The main practical task, then, is to choose a segment of the log survivor plot that represents mainly bout-initiation times so that a line can be fit to that segment. The segment needs to be sufficiently to the right of the intersection of the two

limbs so that it includes relatively few within-bout IRTs.

In our previous work, with key poking as the response, the log survivor plots showed a sharp break at the point where the two limbs intersected, and that intersection point occurred well to the left of 1 s. Thus it worked well to fit a line to the segment spanning the interval from 1 s through 12 s (Shull et al., 2001). The 1- through 12-s segment, however, clearly will not work well with the log survivor plots in Figure 2, obtained with lever pressing as the response. The intersection of the two limbs appears as a bend in the plot that extends well to the right of 1 s. Data points within the bend will contain substantial frequencies of within-bout IRTs, and a linear fit that includes those points will overestimate bout-initiation rate and underestimate bout length.

We determined the slope and intercept of the bout-initiation limb two ways. One way was to fit a straight line to the segment from 5 s through 30 s, the rationale being that 5 s was sufficiently to the right of the intersection of the two limbs so as to include mainly bout-initiation times. The straight line on semilogarithmic coordinates is an exponential function of the form

$$r(t) = pe^{-bt}, \qquad (1)$$

where, on semilogarithmic coordinates, $r(t)$ represents the proportion of response times (IRTs) longer than any particular duration, p is the intercept, b is the slope, t is elapsed time in units of the x axis, and e is the base of natural logarithms. The value of b, then, provides an estimate of the bout-initiation rate (bout initiations per second because the x-axis is in units of seconds); p is an estimate of the proportion of responses that are bout initiations so that $1/p$ provides an estimate of the average number of responses per bout (including the bout-initiating response). These fits were carried out with the exponential-fit routine provided by Microsoft®Excel that, in essence, provides a least-squares fit of a straight line to the logarithms of the survivors.

The second way we estimated these values was to fit an equation representing the sum of two exponentials (cf., Killeen et al., 2002) to the survivor plot over its full range (0 to 30 s). That equation can be written as

$$r(t) = (1 - p)e^{-wt} + pe^{-bt}, \qquad (2)$$

where, again, $r(t)$ represents the proportion of response times (IRTs) longer than any particular duration. The term at the far right (pe^{-bt}) is the same as the term on the right in Equation 1; recall that it is interpreted as representing bout-initiation times so that (as in Equation 1) p represents the proportion of responses that are bout initiations, and b represents the bout-initiation rate (bout initiations per second). The term just to the right of the equality sign $[(1 - p)e^{-wt}]$ is interpreted as representing within-bout response times so that 1-p represents the proportion of responses that are within-bout responses, and w is an estimate of the rate of those within-bout responses (responses per second). Again, e is the base of the natural logarithms, and t represents elapsed time. We carried out these fits with a curve-fitting routine supplied by SigmaPlot® 8.0, a graphing program (the "double-exponential fit with four parameters, reciprocal-y weighting"). This routine determines the best fitting parameters through an iterative process that minimizes the squared deviations. For these fits, $p + (1 - p)$ was constrained to equal 1.0. (The reciprocal-y weighting gives greater weight to deviations at small survivor values than would be the case with no weighting. For the most part, the parameter estimates were similar whether or not the weighting was used. But occasionally the reciprocal-y weighting produced fits that appeared by eye to better represent the slope of the right-hand limb, probably because such weighting is essentially what the logarithmic scaling does.)

The two methods for estimating the slope (b) and intercept (p) of the bout-initiation (right-hand) limb of the four plots in Figure 2—that is, fitting a line to the 5- through 30-s segment and fitting the double-exponential function—produced similar values. Indeed, the slope values correlated (Pearson r) at least .98 for each of the 4 rats (at least .99 for 3 of the 4 rats) and the intercept values correlated at least .99. Thus one method worked as well as the other for estimating bout-initiation rate and bout length. The double-exponential fit has the advantage of providing an estimate of the within-bout response rate (w). Also, because the double-exponential fit uses the full set of survivor data, it eliminates

the need to select a particular segment of the log survivor plot for the fits. Given these advantages, the results of the double-exponential fits will be reported here. The smooth line-plots in Figure 2 (four for each rat) show the best fitting double-exponential equations.

From these estimates, then, it is possible to see how the rate of initiating bouts and the rate of responding within bouts varied as functions of rate of reinforcement and the presence of the VR response requirement. Figure 3 shows these responses rates, and it also includes the total rates of lever pressing, given previously in Figure 1, for comparison. The axes are scaled logarithmically, in part to facilitate comparison of response rates that differ greatly in magnitude and in part because the slope of a plot in logarithmic coordinates indicates the sensitivity of the indicated response rate to changes in reinforcement rate. The results of the numerical estimates of bout-initiation rate are entirely in accord with the conclusions derived from merely inspecting the log survivor plots. The rate of initiating bouts increased as a function of rate of reinforcement but was little affected by the presence or absence of the VR 4 requirement.

Rate of responding within bouts, as estimated from the double-exponential fits, was substantially higher than the total response rate. Across the 4 rats and four conditions, the average within-bout response rate was 82 responses per minute ($Mdn = 81$; range, 42 to 130). This value corresponds to a mean within-bout IRT of 0.73 s. Within-bout response rate was much less sensitive than either bout-initiation rate or total response rate to rate of reinforcement. Also, within-bout response rate was only inconsistently affected by the presence or absence of the VR 4 requirement. The VR requirement increased the within-bout response rate for Rats G1 and G3, but it did not do so consistently for the other 2 rats. Thus it seems fair to say that within-bout response rate was rather insensitive to rate of reinforcement and to the presence or absence of the VR 4 requirement. Consequently, changes in within-bout response rate do not appear to contribute much to the systematic changes in total response rate shown in Figure 1.

If the relation between total response rate and reinforcement rate resulted entirely from
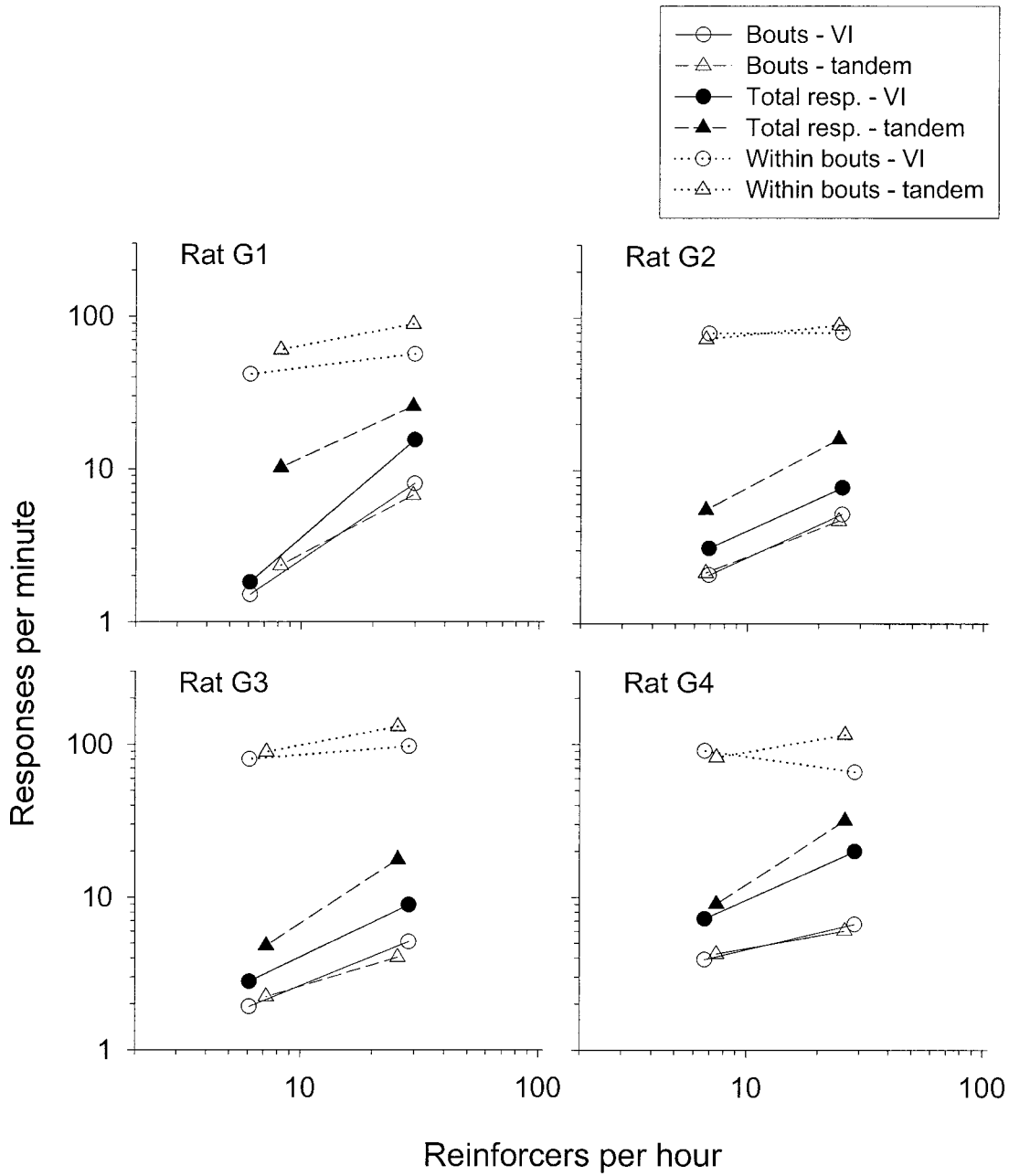
Fig. 3. Three different kinds of response rate plotted as functions of obtained rate of reinforcement. Total response rates (Total resp.; solid points) were calculated from daily response and time totals and were shown in Figure 1. Bout-initiation rate (Bouts; the lower pair of open points) and within-bout response rate (Within bouts; the upper pair of open points) were calculated from the double-exponential fits to the log survivor plots (in Figure 2)—from Equation 2, $b \times 60$ for bout initiations per minute and $w \times 60$ for within-bout responses per minute. As indicated in the legend, the schedule of reinforcement was either a VI schedule or a tandem VT VR 4 schedule. Note that the axes are scaled logarithmically.

changes in bout-initiation rate, bout-initiation rate would be at least as sensitive as total response rate to rate of reinforcement. Indeed, the sensitivities of the two kinds of response rate (i.e., the slopes of the plots in Figure 3) were similar. But for Rats G1, G4, and, perhaps, G3, bout-initiation rate was less sensitive than total response rate to reinforcement rate, indicating that changes in bout length probably also contributed to the relation between total response rate and reinforcement rate.

Figure 4 shows that, for the simple VI schedule, bout length (i.e., the average number of responses per bout) did, indeed, increase as a function of reinforcement rate for Rats G1, G3, and G4. Likewise, with the tandem VT VR 4 schedules, bout length increased as a function of reinforcement rate for Rats G2, G3, and G4. Thus, although the effect was not entirely consistent, higher reinforcement rates tended to produce longer bouts. The effect of the VR 4 requirement on bout length, however, was entirely consistent. For all 4 rats, bout length was higher when the VR 4 requirement was imposed than when it was not.

DISCUSSION

The pattern of results reported here with lever pressing as the response is similar to that reported previously with key poking as the response (Shull et al., 2001). That is, with both forms of response, VI reinforcement generated responding that appeared organized into bouts. Variables that had a similar effect on total response rate had different effects on performance at the level of bouts. With either lever pressing or key poking, increasing the reinforcement rate increased total response rate mainly by shortening the pauses between bouts (or, equivalently, by increasing the bout-initiation rate) and, less reliably, by lengthening bouts. Imposing a VR 4 requirement at the end of the interval increased total response rate mainly by lengthening bouts. This pattern of results, then, is not restricted to responses, like key poking, that may resemble components of naturally occurring foraging behavior. Given that there were numerous procedural differences between our earlier study and the present one (e.g., the single-schedule arrangement in the

present study versus the multiple-schedule arrangement in the Shull et al. study), the differential effect on bout rate and bout length appears to be a fairly general outcome.

A difference between the present data set and our previous one (Shull et al., 2001) is apparent, however, in the region of the log survivor plots where the two limbs intersect. With key poking as the response, the log survivor plots showed a sharp break where the two limbs met (cf., Figures 5 and 6 in Shull et al.), whereas with lever pressing as the response, the plots show more of a gradual curve in that region (Figure 2). Although the bout-like pattern is unmistakable when the intersection is sharply localized, either pattern is consistent with a pause-bout organization of responding. The more the distribution of within-bout IRTs overlaps the distribution of between-bout times, the more curved the log survivor plot will be in the region where the two limbs intersect—an implication that can be readily confirmed with simulations based on the sum of two exponentials (Equation 2). Thus the curved versus sharp-break appearance of the log survivor plots would be expected given that the within-bout IRTs were longer in the present data set ($M = 0.73$ s), with lever pressing as the response, than in the earlier data set (*Mdns* in the range of 0.20 to 0.25 s), with key poking as the response. Because of the many procedural differences between the two studies, it is not known what these differences in within-bout IRTs are due to, but any of a variety of specific factors related to topography and the physical properties of the operanda seem likely candidates. Such factors include the force required to operate the key or lever, the distance the operandum must be moved to count as a response, the distance between the operandum and the food tray, and so forth.

One consequence of the gradually bending intersection in the log survivor plots is that the specific method used by Shull et al. (2001) to estimate the slope and intercept of the bout-initiation limb—namely, fitting a line to the 1- through 12-s segment—did not work for the plots obtained in the present study. It was possible, however, to modify that specific method in a way that remained consistent with the aim of characterizing the segment of the log survivor plot that represents bout-initiation times. One way was to choose
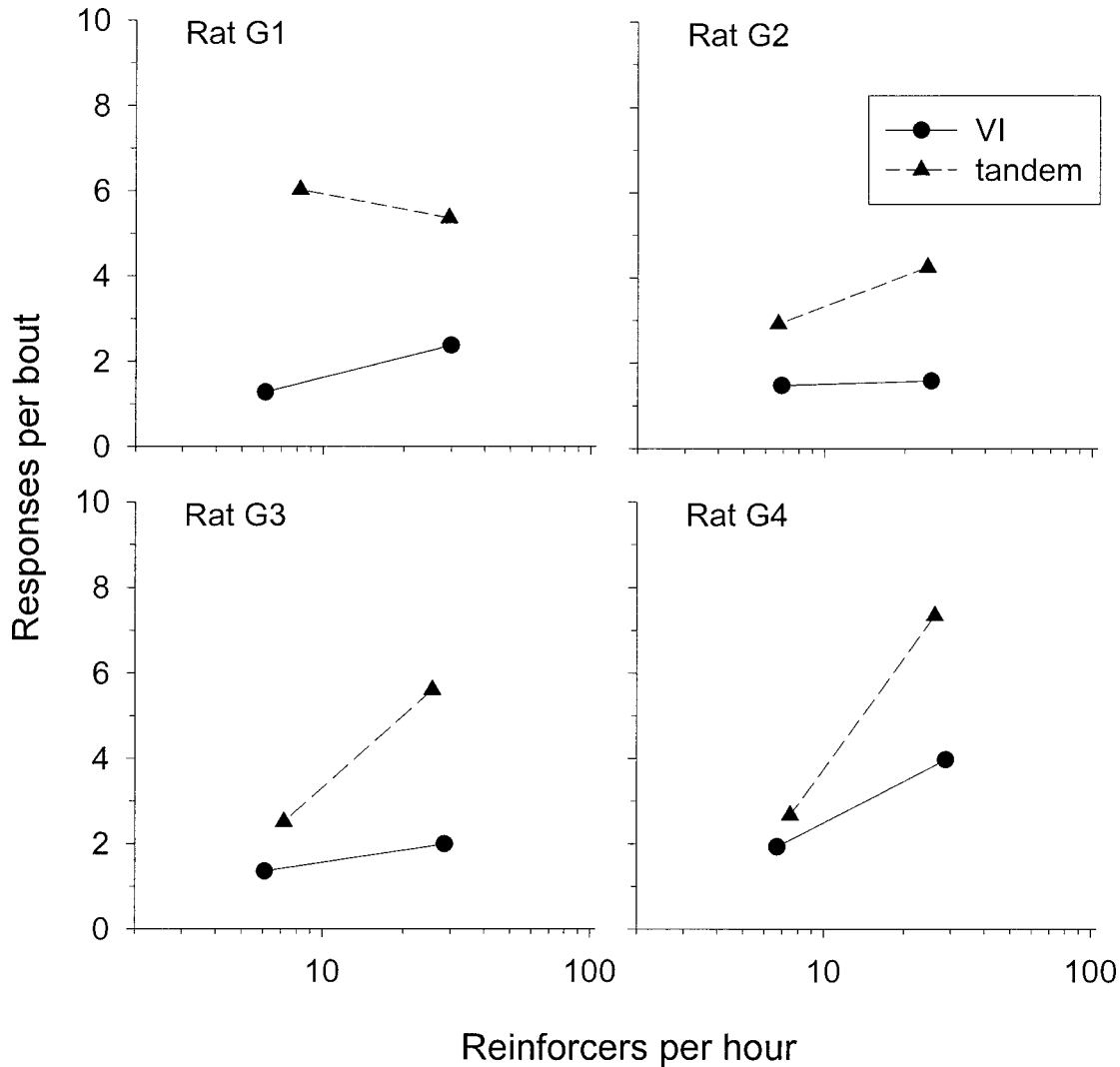
Fig. 4.   The average number of lever presses per bout, as estimated from the double-exponential fits to the log survivor plots in Figure 2 (responses per bout = $1/p$). As indicated in the legend, the schedule of reinforcement was either a VI schedule or a tandem VT VR 4 schedule.

a segment farther to the right (i.e., the segment from 5 s through 30 s) and fit a line to that segment. Another way was to fit an equation representing the sum of two exponential response-generating processes. These two methods produced similar values for the slope and intercept of the bout-initiation limb. The double-exponential fits appeared to describe the log survivor plots well (Figure 2) and had an additional advantage of providing an estimate of the within-bout response rate.

As estimated from the double-exponential fits, within-bout response rate was rather insensitive to either of the two variables that we manipulated to change total response rate. Such insensitivity appears to be broadly characteristic of within-bout responding, of operant behavior as well as consumatory behavior; changes in total response rate result mainly from changes in bout-initiation rate or bout length (Allison, & Castellan, 1970; Cotton, 1953; Davis & Smith, 1992; Gilbert, 1958; Kirkpatrick, 2002; Machlis, 1977; Mechner, 1992; Premack, 1965; Rodnick, Reaven, Haskell, Sims, & Mondon, 1989; Steller & Hill,

1952). With operant behavior, for example, it has long been known that responding generated by fixed-ratio schedules occurs in bouts of high-rate responding separated by pauses—the so-called postreinforcement pause (Felton & Lyon, 1966). Changes in deprivation level (Ferster & Skinner, 1957, Figures 52 & 53; Sidman & Stebbins, 1954), size of the reinforcer (Morse, 1966, p. 80–81; Perone & Courtney, 1992; Powell, 1969), the availability of alternative reinforcers (Derenne & Baron, 2002), and even shock-punishment (Azrin, 1959) affect the duration of the between-bout pauses (or, equivalently, bout-initiation rate) but have little effect on response rate within bouts (i.e., on the so-called running rate). The present data (along with those reported by Blough, 1963) indicate that a similar pattern of differential sensitivity holds as well for performance under VI schedules.

Bout-initiation rate was a similar function of reinforcement rate regardless of whether or not the VR 4 requirement was imposed (i.e., the two bout-initiation rate plots in each panel of Figure 3 were nearly superimposed). Total response rate was, of course, higher with than without the VR 4 requirement. It appears, then, that relations between measures of performance and parameters of reinforcement (such as rate or amount of reinforcement) might prove to be more general with bout-initiation rate than with total response rate as the measure of performance.

REFERENCES

Allison, J., & Castellan, J. (1970). Temporal characteristics of nutritive drinking in rats and humans. Journal of Comparative and Physiological Psychology, 70, 116–125.

Ator, N. A. (1991). Subjects and instrumentation. In I. H. Iversen & K. A. Lattal (Eds.), *Techniques in the behavioral and neural sciences: Vol. 6. Experimental analysis of behavior.* (Part 1, pp. 1–62). Amsterdam: Elsevier.

Azrin, N. H. (1959). Punishment and recovery during fixed-ratio performance. *Journal of the Experimental Analysis of Behavior, 2,* 301–305.

Baum, W. M. (2002). From molecular to molar: A paradigm shift in behavior analysis. *Journal of the Experimental Analysis of Behavior, 78,* 95–116.

Blough, D. S. (1963). Interresponse time as a function of continuous variables: A new method and some data. *Journal of the Experimental Analysis of Behavior, 6,* 237–246.

Cotton, J. W. (1953). Running time as a function of amount of food deprivation. *Journal of Experimental Psychology, 46,* 188–198.

Davis, J. D., & Smith, G. P. (1992). Analysis of the microstructure of the rhythmic tongue movements of rats ingesting maltose and sucrose solutions. *Behavioral Neuroscience, 106,* 217–228.

Derenne, A., & Baron, A. (2002). Preratio pausing: Effects of an alternative reinforcer on fixed- and variable-ratio responding. *Journal of the Experimental Analysis of Behavior, 77,* 273–282.

Fagen, R. M., & Young, D. Y. (1978). Temporal patterns of behaviors: Durtions, intervals, latencies, and sequences. In P. W. Colgan (Ed.), *Quantitative ethology* (pp. 79–114). New York: Wiley.

Felton, M., & Lyon, D. O. (1966). The post-reinforcement pause. *Journal of the Experimental Analysis of Behavior, 9,* 131–134.

Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement.* New York: Appleton-Century-Crofts.

Gilbert, T. F. (1958). Fundamental dimensional properties of the operant. *Psychological Review, 65,* 272–282.

Killeen, P. R., Hall, S. S., Reilly, M. P., & Kettle, L. C. (2002). Molecular analyses of the principal components of response strength. *Journal of the Experimental Analysis of Behavior, 78,* 127–160.

Kirkpatrick, K. (2002). Packet theory of conditioning and timing. *Behavioural Processes, 57,* 89–106.

Langston, S. D., Collett, D., & Silby, R. M. (1995). Splitting behaviour into bouts; a maximum likelihood approach. *Behaviour, 132,* 781–799.

Lattal, K. A. (1989). Contingencies on response rate and resistance to change. *Learning and Motivation, 20,* 191–203.

Machlis, L. (1977). An analysis of the temporal patterning of pecking in chicks. *Behaviour, 63,* 1–70.

Mechner, F. (1992). *The revealed operant: A way to study the characteristics of individual occurrences of operant responses.* Cambridge, MA: Cambridge Center for Behavioral Studies.

Mellgren, R. L., & Elsmore, T. F. (1991). Extinction of operant behavior: An analysis based of foraging considerations. *Animal Learning & Behavior, 19,* 317–325.

Morse, W. H. (1966). Intermittent reinforcement. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application* (pp. 52–108). New York: Appleton-Century-Crofts.

Nevin, J. A., Grace, R. C., Holland, S., & McLean, A. P. (2001). Variable-ratio versus variable-interval schedules: Response rate, resistance to change, and preference. *Journal of the Experimental Analysis of Behavior, 76,* 43–74.

Pear, J. J., & Rector, B. L. (1979). Constituents of response rate. *Journal of the Experimental Analysis of Behavior, 32,* 341–362.

Perone, M., & Courtney, K. (1992). Fixed-ratio pausing: Joint effects of past reinforcer magnitude and stimuli correlated with upcoming magnitude. *Journal of the Experimental Analysis of Behavior, 57,* 33–46.

Powell, R. W. (1969). The effect of reinforcement magnitude upon responding under fixed-ratio schedules. *Journal of the Experimental Analysis of Behavior, 12,* 605–608.

Premack, D. (1965). Reinforcement theory. In D. Levine (Ed.), *Nebraska symposium on motivation, 1965* (pp. 123–180). Lincoln, NE: University of Nebraska Press.

Rodnick, K. J., Reaven, G. M., Haskell, W. L., Sims, C. R., & Mondon, C. E. (1989). Variations in running activ-

ity and enzymatic adaptations in voluntary running in rats. *Journal of Applied Physiology, 66,* 1250–1257.

Shull, R. L., Gaynor, S. T., & Grimes, J. A. (2001). Response rate viewed as engagement bouts: Effects of relative reinforcement and schedule type. *Journal of the Experimental Analysis of Behavior, 75,* 247–274.

Sibley, R. M., Nott, H. M. R., & Fletcher, D. J. (1990). Splitting behaviour into bouts. *Animal Behaviour, 39,* 63–69.

Sidman, M., & Stebbins, W. C. (1954). Satiation effects under fixed-ratio schedules of reinforcement. *Journal of Comparative and Physiological Psychology, 47,* 114–116.

Staddon, J. E. R., & Zanutto, B. S. (1997). Feeding dynamics: Why rats eat in meals and what this means for foraging and feeding regulation. In M. E. Bouton & M. S. Fanselow (Eds.), *Learning, motivation, and cognition: The functional behaviorism of Robert C. Bolles* (pp. 131–162). Washington, DC: The American Psychological Association.

Steller, E., & Hill. J. H. (1952). The rat's rate of drinking as a function of water deprivation. *Journal of Comparative and Physiological Psychology, 45,* 96–102.

Tolkamp, B. J., & Kyriazakis, I. (1999). To split behaviour into bouts, log-transform the intervals. *Animal Behaviour, 57,* 807–817.

APPENDIX

Total frequencies of response times that were longer than the duration (elapsed time) indicated at the left. The totals are sums over the last five sessions of the schedule indicated.

Rat	Elapsed time (s)	VI 2 min	VI 8 min	Tandem VT 2 min VR4	Tandem VT 8 min VR4
G1	0.0	9,066	1,091	15,392	6,110
	0.2	8,512	1,073	14,778	5,885
	0.4	7,726	1,045	12,308	5,017
	0.6	6,902	1,014	8,842	4,014
	0.8	6,037	988	5,980	3,173
	1.0	5,290	962	4,301	2,577
	2.0	3,324	864	2,487	1,498
	3.0	2,764	804	2,179	1,142
	4.0	2,380	778	1,922	988
	5.0	2,059	753	1,709	903
	6.0	1,794	732	1,553	833
	7.0	1,574	708	1,409	785
	8.0	1,402	695	1,276	746
	9.0	1,253	676	1,165	708
	10.0	1,089	659	1,058	684
	11.0	949	653	951	657
	12.0	792	640	865	632
	13.0	672	626	756	615
	14.0	581	617	653	594
	15.0	502	603	547	568
	16.0	416	592	453	546
	17.0	360	577	394	526
	18.0	306	564	346	509
	19.0	273	549	306	492
	20.0	251	537	272	474

APPENDIX

(*Continued*)

Rat	Elapsed time (s)	VI 2 min	VI 8 min	Tandem VT 2 min VR4	Tandem VT 8 min VR4
	21.0	222	518	242	459
	22.0	199	503	221	441
	23.0	177	488	195	409
	24.0	157	473	178	400
	25.0	143	453	161	382
	26.0	135	436	148	366
	27.0	117	421	139	346
	28.0	106	407	122	336
	29.0	96	400	113	324
	30.0	88	386	98	311
G2	0.0	4,561	1,866	9,623	3,320
	0.2	4,398	1,801	8,865	3,183
	0.4	3,988	1,652	6,257	2,574
	0.6	3,526	1,491	5,022	2,070
	0.8	3,190	1,410	4,214	1,804
	1.0	2,961	1,352	3,662	1,662
	2.0	2,421	1,227	2,333	1,353
	3.0	2,190	1,151	1,875	1,218
	4.0	2,035	1,101	1,605	1,075
	5.0	1,885	1,048	1,454	968
	6.0	1,750	1,001	1,378	884
	7.0	1,642	962	1,306	832
	8.0	1,517	932	1,244	795
	9.0	1,374	908	1,189	771
	10.0	1,235	881	1,122	751
	11.0	1,114	862	1,041	737
	12.0	1,011	842	957	725
	13.0	920	829	870	708
	14.0	854	809	790	687
	15.0	781	791	710	677
	16.0	723	764	641	652
	17.0	665	740	579	642
	18.0	604	707	525	620
	19.0	553	681	487	595
	20.0	494	647	455	575
	21.0	454	617	413	554
	22.0	420	600	386	523
	23.0	378	580	362	508
	24.0	362	558	328	491
	25.0	340	529	309	468
	26.0	311	506	293	449
	27.0	278	484	278	429
	28.0	248	458	263	413
	29.0	238	432	243	393
	30.0	215	409	230	375
G3	0.0	5,257	1,684	10,579	2,883
	0.2	4,682	1,614	8,556	2,559
	0.4	4,065	1,508	5,775	2,106
	0.6	3,526	1,420	3,963	1,776
	0.8	3,157	1,349	3,079	1,599
	1.0	2,824	1,314	2,614	1,486
	2.0	2,238	1,175	1,794	1,214
	3.0	2,039	1,120	1,573	1,097
	4.0	1,893	1,082	1,427	1,022
	5.0	1,789	1,048	1,323	962
	6.0	1,652	1,014	1,241	906
	7.0	1,527	983	1,173	861

APPENDIX

(*Continued*)

Rat	Elapsed time (s)	VI 2 min	VI 8 min	Tandem VT 2 min VR4	Tandem VT 8 min VR4
	8.0	1,399	959	1,107	833
	9.0	1,282	944	1,049	801
	10.0	1,198	914	988	775
	11.0	1,105	884	939	753
	12.0	996	852	883	726
	13.0	877	821	832	698
	14.0	763	806	789	666
	15.0	670	788	746	648
	16.0	602	772	702	628
	17.0	534	736	645	611
	18.0	483	708	585	596
	19.0	457	691	525	575
	20.0	429	661	468	553
	21.0	403	645	427	531
	22.0	381	620	383	512
	23.0	362	603	360	491
	24.0	348	578	341	472
	25.0	337	555	327	455
	26.0	325	533	313	442
	27.0	315	517	304	430
	28.0	303	494	292	405
	29.0	289	469	280	389
	30.0	274	452	274	381
G4	0.0	11,744	4,347	19,071	5,428
	0.2	10,466	3,951	15,308	4,760
	0.4	8,565	3,400	10,102	3,907
	0.6	7,128	3,003	7,216	3,381
	0.8	6,033	2,727	5,655	3,021
	1.0	5,287	2,526	4,700	2,757

Rat	Elapsed time (s)	VI 2 min	VI 8 min	Tandem VT 2 min VR4	Tandem VT 8 min VR4
	2.0	3,561	2,044	2,931	2,127
	3.0	2,762	1,836	2,252	1,848
	4.0	2,234	1,700	1,885	1,665
	5.0	1,840	1,581	1,566	1,535
	6.0	1,511	1,499	1,351	1,450
	7.0	1,282	1,425	1,186	1,356
	8.0	1,123	1,350	1,057	1,295
	9.0	971	1,279	944	1,234
	10.0	876	1,213	845	1,172
	11.0	778	1,154	781	1,111
	12.0	698	1,082	714	1,055
	13.0	641	1,006	654	1,004
	14.0	582	938	606	943
	15.0	533	871	553	895
	16.0	499	820	503	829
	17.0	477	764	471	774
	18.0	441	702	429	729
	19.0	410	656	393	671
	20.0	376	605	363	621
	21.0	349	574	338	582
	22.0	317	531	316	537
	23.0	288	489	286	496
	24.0	250	464	262	462
	25.0	206	433	242	432
	26.0	174	406	217	397
	27.0	145	370	201	368
	28.0	122	348	174	347
	29.0	106	323	154	321
	30.0	87	303	138	304