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AN INTEGRATIVE MODEL FOR THE STUDY OF BEHAVIORAL MOMENTUM

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Behavioral momentum is the product of response rate and resistance to change. The data on relative resistance to change are summarized for pigeons responding on single-key two-component multiple schedules, in the initial links of two-key multiple chained schedules, and in equivalent components of two-key serial schedules. For single-key procedures, the ratio of resistance to change in two schedule components is shown to depend on the ratio of reinforcer rates obtained in the presence of the component stimuli. For two-key procedures, the ratio of resistance to change in equivalent components is shown to depend on the ratio of reinforcer rates correlated with key locations. A model based on stimulus-reinforcer contingencies that combines the reinforcer rates in schedule components summed over key locations and reinforcer rates correlated with key locations summed over components, each expressed relative to the session average reinforcer rate, gives a good account of the data. An extension of the relative law of effect for multiple schedules fails to provide a complete account of resistance to change, but both approaches are needed for a comprehensive understanding of behavioral momentum.

Key words: resistance to change, reinforcer rate, reinforcer duration, multiple schedules, chained schedules, serial schedules, concurrent schedules, key peck, pigeon

Two important dimensions of operant behavior are its rate of occurrence under constant conditions and its resistance to change when those conditions are altered. Response rate under constant conditions is the subject of steady-state research on schedules of reinforcement; resistance to change falls within the domain of behavioral dynamics. Taken together, response rate and resistance to change define *behavioral momentum.*

The relation between these components of behavioral momentum may be understood by adopting a metaphor from the dynamics of physical motion. Imagine a body moving at a constant velocity under constant conditions. Newton's second law states that when an external force is imposed, the change in velocity (acceleration) is directly proportional to the imposed force and inversely proportional to the mass of the body:

$$\Delta V = f/m. \qquad (1)$$

To evaluate the relative masses of two moving bodies, designated by subscripts 1 and 2, it suffices to impose the same force on both and to measure the resulting changes in velocity:

$$\Delta V_1 = f/m_1$$

and

$$\Delta V_2 = f/m_2;$$

therefore,

$$m_1/m_2 = \Delta V_2/\Delta V_1. \qquad (2)$$

As these simple equations show, there is no need to understand how the imposed force works in order to evaluate relative mass, nor even to know its value so long as it is the same for both bodies.

To apply this metaphor to behavior, let steady-state response rate, designated B, be coordinated with velocity; a variable that disrupts steady-state performance, designated x, with the imposed force; and the resulting change in response rate, ΔB, with ΔV. Behavioral mass emerges as the metaphorical equivalent of resistance to disruption, and is given by

$$m = x/\Delta B;$$

that is, the reciprocal of the slope relating B to x. However, it is not possible to estimate the absolute value of "behavioral mass" for a

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given performance in a way that permits comparison with the mass of a different performance disrupted by a different variable, because the mass-like term in the equation above is expressed in units of the disruptive variable relative to behavior, and different disruptive procedures (e.g., satiation and extinction) are measured in different units. Nevertheless, as with physical forces (see Equation 2), relative measurement is possible via the dimensionless ratio

$$\frac{m_1}{m_2} = \frac{x/\Delta B_1}{x/\Delta B_2}, \qquad (3)$$

which is the ratio of the reciprocals of the slopes of functions relating response rate to the disrupting variable x. This quantity will be termed the *resistance ratio* throughout this paper.

In classical physics, momentum is defined as the product of velocity and mass. Translating metaphorically, behavioral momentum is the product of response rate and resistance to change. The determiners of response rate are fairly well understood (see review chapters by Morse, 1966; Nevin, 1973; and Zeiler, 1977); Herrnstein (1970) has provided a quantitative model of the relation between response rate and reinforcer rate. The determiners of resistance to change are less well understood, and no quantitative model has been advanced to integrate the existing data. This paper will review some data on resistance to change in relation to reinforcer rate, and will argue that response rate and resistance to change are empirically as well as conceptually independent. It will then suggest that response rate depends on response–reinforcer contingencies, whereas resistance to change depends on stimulus–reinforcer contingencies. Finally, it will present an integrative model of the data relating resistance ratios to stimulus–reinforcer contingency ratios and compare it with an alternative approach derived from the matching law for steady-state behavior.

TWO-COMPONENT MULTIPLE SCHEDULES

Paradigm and Data

The multiple-schedule paradigm arranges two independent schedules of reinforcement in succession, each signaled by a distinctive stimulus. It thereby establishes two discriminated operants, defined by the antecedent stimulus signaling the component, the response, and its consequences, with experimental control over their successive availability. The paradigm is convenient for comparing the resistance to change of two discriminated operants as well as their steady-state response rates, because a disrupting operation can be applied to both component performances within an experimental test session so that their relative resistance can be evaluated directly in an individual subject.

The independence of response rate and resistance to change of each discriminated operant is suggested by comparing experiments by Fath, Fields, Malott, and Grossett (1983) and Nevin, Mandell, and Atak (1983). Both studies arranged two-component multiple schedules with timeout periods between components. Fath et al. (1983) used pacing requirements to produce differing response rates in the two components, with equal rates of reinforcement arranged by identical variable-interval (VI) schedules. Nevin et al. (1983) employed different VI schedules that happened to maintain similar response rates, perhaps because of the timeout period between components. When Fath et al. (1983) presented response-independent food during periods between components in single test sessions and varied the duration of food presentations across test sessions, response rates decreased as a function of food duration in a way similar to that observed by Nevin et al. (1983) when they varied the rate of food presentations between components in similarly arranged test sessions. The average data of both studies are shown in Figure 1.

When the data are expressed as proportions of baseline and plotted on a logarithmic y axis (lower panels), the functions relating response rates to food presentation during resistance tests are roughly linear. The slopes of these functions provide quantitative information on the relative behavioral masses of the two discriminated operants in each experiment, as suggested by Equation 3. For the data of Fath et al. (1983), the ratio of the reciprocals of the slopes is about 1.0, indicating similar resistance to change in both components, despite the difference in baseline response rates. By contrast, for the data of Nevin et al. (1983), the ratio of the reciprocals of the slopes is about

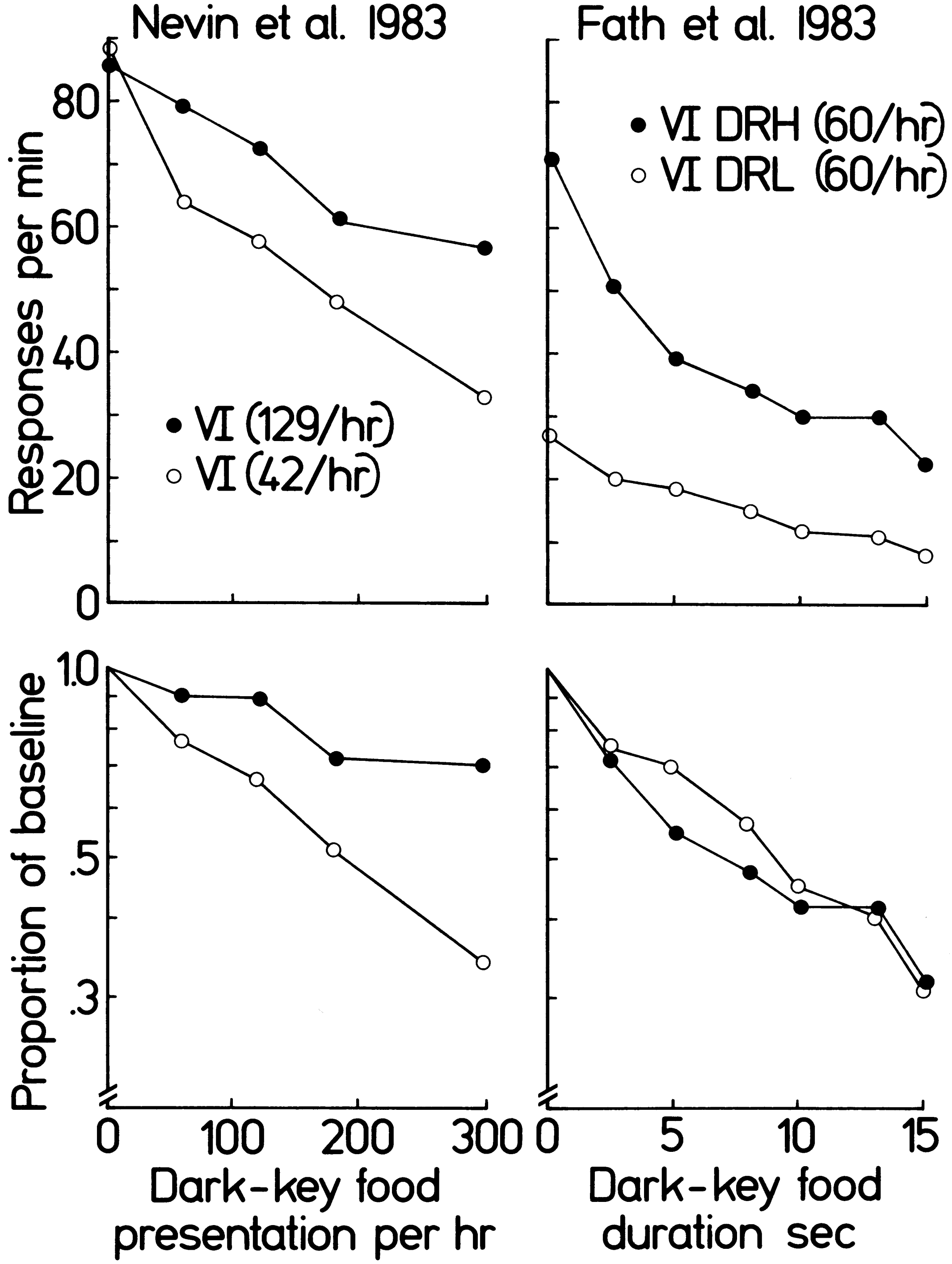

Fig. 1. A comparison of two studies of resistance to change in two-component multiple schedules. For Nevin et al. (1983), the components differed in reinforcer rate, whereas for Fath et al. (1983), the components differed in the pacing requirement superimposed on a single VI schedule. In both studies, resistance to change was evaluated by presenting response-independent food during dark-key periods between components. The upper panels present average response rates as a function of dark-key reinforcer rate or duration, and the lower panels present the average proportions of baseline on a logarithmic y axis. The comparison suggests that resistance to change depends on the rate of reinforcement but not on the response rate arranged in a schedule component.

2:1, indicating that performance in the richer component is about twice as resistant to change as that in the leaner component, despite the similarity of baseline response rates. In these two studies, response rate depended on the schedule contingencies, but resistance to change, expressed as a slope in semilogarithmic coordinates, depended on the rate of reinforcement in a component. In general, response rate also depends on the rate of reinforcement in a schedule component; the separate determination of response rate and resistance to change will be discussed in conjunction with studies reviewed below.

Nevin (1974) reported several studies of multiple-schedule performance in pigeons demonstrating that resistance to extinction and to the introduction of free food during timeout periods between components was greater in the component that had the higher rate, the longer duration, or the shorter delay of reinforcement. The findings were discussed in relation to the traditional notion of "response strength," on the ground that the connotations of strength were more akin to the persistence of responding than to its rate. In a subsequent chapter that also used the metaphor of "strength," a number of multiple-schedule experiments were reviewed, demonstrating that response rate in the component with the higher rate of reinforcement was more resistant to the rate-decreasing effects of alternative reinforcement (whether arranged successively or concurrently), intermittent punishment, conditioned suppression, satiation, increased response effort, and extinction (Nevin, 1979). Qualitatively similar findings were obtained in experiments that differed widely in procedural detail and that employed rats as well as pigeons, suggesting considerable generality.

The separate determination of response rate and resistance to change, suggested by comparing the Fath et al. (1983) and Nevin et al. (1983) experiments reviewed above, was explored directly by Nevin, Tota, Torquato, and Shull (1990). In their Experiment 1, pigeons were trained on multiple schedules with identical VI schedules in both components, and with alternative reinforcers arranged by a variable-time (VT) schedule added to one component in some conditions. The addition of response-independent reinforcers weakened the response–reinforcer contingency in the concurrent VI VT component relative to the VI-only component, and the steady-state response rate was lower in the concurrent VI VT component. However, the addition of VT reinforcers also increased the rate of food presentation in the concurrent VI VT component, and resistance to satiation and to extinction was greater in that component than in the VI-only component. Experiment 2 repeated these results with alternative reinforcers added to one component via a concurrent VI schedule arranged on a separate key. Specifically, the rate of a target response that produced a given rate of reinforcement was reduced in a component that included concurrently available reinforcers on a second key, relative to a component that did not provide concurrent reinforcers, but the resistance of the target response rate to satiation and to extinction was enhanced. Nevin et al. (1990) concluded that the steady-state baseline rate of a target response depended on the operant contingency between the response and the reinforcer, which was weakened in the component with added reinforcers, whereas its resistance to satiation and extinction depended on the contingency between the component stimulus and the reinforcer, which was strengthened in the component with added reinforcers.

A Quantitative Summary of the Data

A simple but powerful characterization of the stimulus–reinforcer contingency is suggested by Gibbon's (1981) work on autoshaped key pecking in relation to the duration of the keylight conditioned stimulus (CS) that precedes food. Gibbon proposed that the effectiveness of a stimulus–reinforcer contingency depended on the ratio of the average reinforcer rate in the presence of the CS to the average reinforcer rate in the presence and absence of the CS (i.e., the session average). This ratio is expressed as r_C/r_S, where r_C is the average number of reinforcers per unit time in the presence of a particular discriminative stimulus, and r_S is the average number of reinforcers per unit time for the experimental session as a whole. Nevin (in press) showed that this contingency ratio permitted at least ordinal prediction of resistance to change across two sets of conditions that differed in session average reinforcer rates (this study will be reviewed in more detail below). The present paper attempts a more complete and quantitative account.

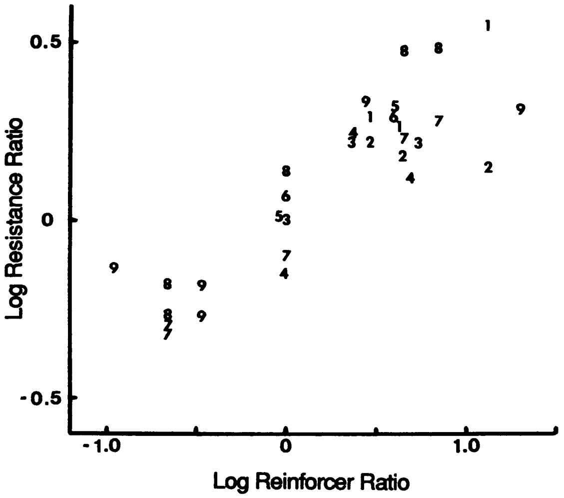

Fig. 2. For single-key two-component multiple schedules, the ratio of resistance to change is related to the ratio of reinforcer rates or durations arranged in the components. Both variables are expressed as logarithms. The data points are averages across subjects for separate experimental conditions and methods for evaluating resistance to change, coded as follows: Nevin et al. (1983) 1: dark-key food; 2: extinction. Nevin et al. (1990) 3: Experiment 1, prefeeding; 4: Experiment 1, extinction; 5: Experiment 2, prefeeding; 6: Experiment 2, extinction. Nevin (in press) 7: prefeeding; 8: extinction. Points numbered 9 represent single conditions from Shettleworth and Nevin (1965), extinction; Nevin (1974) Experiment 1, dark-key food; Nevin (1974) Experiment 2, extinction; Nevin (1974) Experiment 3, dark-key food; and Nevin (1988), extinction.

Within an experimental condition, resistance to change in one component of a two-component multiple schedule should be related to the reinforcer rate in that component relative to the session average, and likewise in the other component. Because the session average reinforcer rate is the same for both components, the ratio of resistance to change in one component to that in the other should depend on the ratio of reinforcer rates in the two components, r_{C1}/r_{C2}.

Figure 2 presents a reanalysis of all the relevant published data that I have obtained with pigeons as subjects in single-key two-component multiple schedules. Most of the experiments involved different reinforcer rates in the two components, but two (Nevin, 1974, Experiment 3; Shettleworth & Nevin, 1965) involved different reinforcer durations. These two studies were treated as if reinforcer duration was equivalent to reinforcer rate with respect to overall rate of access to food per unit time in a component. The y axis gives the logarithm of the average resistance ratios of the two discriminated operant performances. As suggested by Equation 3 and Figure 1, this is the ratio of the reciprocals of the average slopes of the functions relating the logarithm of response rates during resistance tests to the value of the disrupting variable. The x axis gives the corresponding ratios of reinforcer rates or durations obtained in the two components during baseline. These studies employed different pigeons in procedures involving different reinforcement schedules, component lengths, timeout durations between components, and disrupting variables; nevertheless, there is fair agreement in the data. To a respectable first approximation, the resistance ratio is a power function of the reinforcer ratio with an exponent of about 0.35, with no evidence of systematic deviations that depend on any of the factors that differed between experiments.

MULTIPLE CHAINED AND SERIAL SCHEDULES

Paradigms and Data

The results for two-component multiple schedules reviewed above demonstrate that resistance ratios depend on reinforcer-rate ratios in a way that is at least ordinally similar to steady-state preferences in concurrent chained schedules. Specifically, if the initial-link schedules of two concurrent chains are equal, the initial-link relative response rate is directly related to the terminal-link relative reinforcer rate (for review, see Davison & McCarthy, 1988). Would resistance to change of initial-link performances be similarly ordered?

To explore this question, Nevin, Mandell, and Yarensky (1981) examined resistance to change of pigeons' key-pecking rates in both the initial and terminal components of multiple chained VI VI schedules with identical initial links. They arranged one chained VI VI schedule on the left-hand key and an independent chained VI VI schedule on the right-hand key of a three-key pigeon chamber. In Experiment 1, the terminal links were identical in their average length but differed in the duration of food reinforcement. In Experiment 2, the terminal links differed in both rate and duration of reinforcement. For both initial and terminal links, resistance to prefeeding and concurrent signaled center-key reinforcement depended directly on the reinforcer duration or rate in the terminal links. In addition, the data suggested that when reinforcer rate and duration were arranged so that overall rate of access to food was the same in two terminal links, resistance to change was similar. In both experiments, initial-link performances were always less resistant to change than were terminal-link performances, but the ratio of left-key to right-key resistance was about the same for initial-link and terminal-link performances. Thus, relative initial-link resistance to change in multiple chained schedules was ordered in the same way as initial-link preferences in concurrent chained schedules.

These results suggest that resistance to change in an initial link on a side key depends directly on the reinforcer rate in the component that follows it. Nevin (1984) tested this notion by arranging pairwise sequences of multiple-schedule components on separate keys (hereafter termed *serial schedules*) in which only one key was operative at a time and the pairs of components were separated by timeout periods. Food reinforcement was arranged by identical VI schedules in the first member of each of three pairs. If the first member appeared on the left key, it was followed by a richer second member; if it appeared on the center key, it was followed by the same reinforcer rate; and if it appeared on the right key, it was followed by nonreinforcement. The procedure differed from multiple chained schedules in that food reinforcement was arranged in the first member of each pair, and the transition between successive members of a pair was independent of responding.

The results showed that steady-state response rates in the first member of a pair were not systematically related to reinforcer rate in the second member for individual subjects, but the average data confirmed Williams' (1981) finding of "following-schedule contrast" in that response rate in the first member depended inversely on the following reinforcer rate. However, resistance to prefeeding and to extinction in the first member was directly related to reinforcer rate in the second member of a pair, as for initial-link performance in chained schedules.

In a closely related study, Nevin, Smith, and Roberts (1987) made an explicit comparison between response-independent and response-contingent transitions from the first to the second member in serial schedules. They also compared transitions to a richer schedule with those to a period of nonreinforcement. Steady-state response rates were consistently lower when the first member was followed by a richer second-member schedule than when it was followed by nonreinforcement, confirming Williams' (1981) following-schedule contrast results. However, as found earlier by Nevin (1984), resistance to extinction was greater when the first member had been followed by a richer schedule. Response-contingent transitions from the first member to a richer following schedule enhanced first-member response rate relative to noncontingent transitions, but there was no effect of the response contingency on resistance to extinction. All in all, the results of Nevin (1984) and Nevin et al. (1987) suggested that resistance to change in the first member of a serial pair was independent of steady-state response rate, and depended instead on the relation between the stimulus signaling the first member and the reinforcer rate in the following member of each serial schedule pair. Tota[1] replicated these results, and showed that they held equally when the order of components was reversed. That is, when the second members of two serial pairs signaled identical schedules and the first members were either richer or leaner, resistance to change was greater in the second member signaled by the same key location as the richer first member.

A Quantitative Summary of the Data

A stimulus–reinforcer contingency analysis can account for the resistance-to-change results of chained and serial schedules if key location, rather than component stimulus value, is considered as the relevant stimulus dimension. As in single-key two-component multiple schedules, the contingency between key location and reinforcement may be represented by the ratio of the total reinforcer rate correlated with the location of a lighted response key, r_K, to the session average, designated r_S as above. When multiple chained and serial schedules

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[1] Tota, M. E. (1990, May). *Resistance to change in multiple schedules: Pavlovian influences.* Paper presented at the meetings of the Association for Behavior Analysis, Nashville, TN.

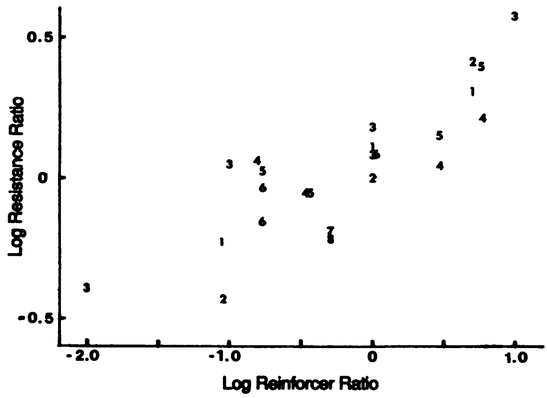

Fig. 3. For two-key multiple chained and serial schedules, the ratio of resistance to change in equivalent components is related to the ratio of reinforcer rates or durations correlated with key location. Both variables are expressed as logarithms. The data points are averages across subjects for separate experimental conditions and methods for evaluating resistance to change, coded as follows: Nevin et al. (1981) 1: Experiment 1, concurrent reinforcement; 2: Experiment 1, prefeeding; 3: Experiment 2, concurrent reinforcement. Nevin (1984) 4: prefeeding; 5: extinction. Nevin et al. (1987) 6: extinction. Nevin et al. (1990) 7: Experiment 2, Component A, prefeeding; 8: extinction.

are compared within a condition, the session average is the same for all components. Therefore, the ratio of resistance to change on the left key relative to that on the right key for schedule components having the same rate of reinforcement should depend on the ratio of reinforcer rates summed across all components for each key, r_{K1}/r_{K2}.

Figure 3 presents a reanalysis of all the relevant published data that I have obtained with pigeons as subjects in two- or three-key multiple chained or serial schedules. The *y* axis gives the logarithm of the average resistance ratios in equivalent components arranged on different keys, and the *x* axis gives the ratio of reinforcer rates summed for all components correlated with those keys. As in Figure 2, the resistance ratio was given by the ratio of the reciprocals of the estimated slopes of the functions relating the logarithm of response rate during a resistance test to the value of the disrupting variable. Also as in Figure 2, studies involving differences in reinforcer duration were treated as if reinforcer duration and reinforcer rate were equivalent with respect to overall rate of access to food per unit time. Although the data come from studies that differed with respect to the reinforcer rate in the equivalent components of each schedule pair, response-contingent versus response-independent component transitions, timeout duration between pairs, and disrupting variables, there is fair agreement among them. Moreover, to a first approximation, the results presented in Figure 3 conform to the same power function as that for single-key two-component multiple schedules illustrated in Figure 2.

AN INTEGRATIVE MODEL

The results presented in Figures 2 and 3 are consistent with a model that relates resistance ratios for two schedule components to the ratio of reinforcer rates in their presence (r_{C1} and r_{C2}) multiplied by the ratio of reinforcer rates correlated with key location (r_{K1} and r_{K2}), expressed relative to overall session reinforcer rate (r_{S1} and r_{S2}) and raised to powers that characterize the sensitivity of resistance ratios to reinforcer ratios. The model is

$$\frac{m_1}{m_2} = \left(\frac{r_{C1}/r_{S1}}{r_{C2}/r_{S2}}\right)^a \times \left(\frac{r_{K1}/r_{S1}}{r_{K2}/r_{S2}}\right)^b, \qquad (4)$$

where the values of the exponents *a* and *b* indicate the relative control by the component stimuli and the keys on which they are arranged.

Applying the model to different components within a single experimental condition implies that $r_{S1} = r_{S2}$, simplifying Equation 4 to

$$m_1/m_2 = (r_{C1}/r_{C2})^a \times (r_{K1}/r_{K2})^b. \qquad (5)$$

When the model is applied to two-component multiple schedules arranged on a single key, all reinforcers are correlated with the same key location, so that $r_{K1} = r_{K2}$. The second term on the right side of Equation 5 therefore becomes 1.0, and (because $r_{S1} = r_{S2}$) the equation simplifies to $m_1/m_2 = (r_{C1}/r_{C2})^a$, or

$$\log(m_1/m_2) = a \log(r_{C1}/r_{C2}). \qquad (6)$$

This is the form in which the data of Figure 2 are portrayed, and the model provides an adequate account of the main trend exhibited in the figure.

When the model is applied to the equivalent first members of serial schedules arranged on two keys, so that $r_{C1} = r_{C2}$, the first term on the right side of Equation 5 becomes 1.0, and (with $r_{S1} = r_{S2}$ again) the equation simplifies to $m_1/m_2 = (r_{K1}/r_{K2})^b$, or

$$\log(m_1/m_2) = b \log(r_{K1}/r_{K2}). \qquad (7)$$

This is the form in which the data of Figure 3 are portrayed, and again the model provides an adequate account of the main trend exhibited in the figure.

When the model is applied to the identical initial links of chained schedules, the reinforcer rate in the initial links is zero, so that the first term on the right side of Equation 5 is indeterminate. Therefore, in order to use Equation 7, it is necessary to assume that there is a small and equal reinforcement term in both initial links, arising perhaps from response-contingent transition to the terminal links. With this assumption, the first term on the right of Equation 5 reduces to 1.0, as for equivalent members of serial schedules. Alternatively, one could assume that initial-link reinforcement terms differ, perhaps because of differential conditioned reinforcement, but the value of a approaches zero in the absence of unconditioned reinforcement. The rough agreement between the data of serial and chained schedules shown in Figure 3 suggests that either assumption is plausible.

TWO-KEY MULTIPLE CONCURRENT SCHEDULES

An interesting test of Equation 5 arises when r_C and r_K vary independently. Although the study was not designed for this purpose, Nevin et al. (1990, Experiment 2) varied reinforcer rate independently with respect to both component stimuli and key locations. The experiment arranged three successive two-key concurrent schedules, signaled by red, green, or white lights on both keys and presented for a fixed period, as in multiple schedules. Specified as reinforcers per hour, with the left key listed first, the schedules were: concurrent 45, 15 (Component A), concurrent 0, 15 (Component B), and concurrent 0, 60 (Component C). Summing across keys within components, there are 60, 15, and 60 reinforcers per hour in Components A, B, and C, respectively, and summing across components within keys, there are 45 reinforcers per hour correlated with the left key and 90 reinforcers per hour correlated with the right key. The results showed that resistance to prefeeding and extinction on the right key was similar in Components A and C, and was consistently greater than in Component B. These results are plotted as points numbered 5 and 6 in Figure 2, and confirm the notion that resistance to change depends on the total reinforcer rate correlated with a component stimulus. However, comparing the two responses in Component A, the results also showed that resistance to change was greater for responding on the right key than on the left key. This outcome contradicts the notion that resistance to change depends on the reinforcer rate in the presence of a component stimulus, which predicts that all responses made in the presence of that stimulus should be equally resistant to change regardless of the schedule correlated with each key within a component. However, when key location is included as a stimulus factor correlated with reinforcement summed across components, the prediction is that right-key responding should be more resistant to change than left-key responding, as found for Component A. (The level of left-key responding in the other components was too low to permit assessment of its resistance to change.) The resistance ratios for left-key and right-key responding in Component A are included in Figure 3 as points numbered 7 and 8. These points fall within the general pattern of the data for other experiments that varied the reinforcer rate across keys in chained and serial schedules, confirming the predictions of Equation 5. Further studies designed explicitly to explore the independent effects of reinforcers correlated with component stimuli and key locations are needed.

COMPARISONS ACROSS EXPERIMENTAL CONDITIONS

The terms representing session average reinforcer rates (r_{S1}, r_{S2}) enter into the predictions of Equation 4 when they differ across two experimental conditions. Nevin (in press) conducted a two-component multiple-schedule study that permitted comparison across conditions. There were two experiments, each including two successive conditions designated A and B, with the schedule in one component remaining constant across conditions. Component duration was always 2 min. In Condition A, the constant component signaled a VI schedule yielding 60 reinforcers per hour, whereas the alternated component signaled a VI schedule yielding 300 reinforcers per hour. In Condition B, the constant schedule remained at 60 reinforcers per hour, and the alternated schedule yielded 10 reinforcers per hour. In Experiment 1, there was a 2-s timeout between components, and there was clear evidence of behavioral contrast (i.e., baseline response rate in the constant component was lower in Condition A than in Condition B). In Experiment 2, there was a 2-min timeout between components, and there was no evidence of behavioral contrast in the constant component. These baseline results are entirely in accord with expectations based on the multiple-schedule literature.

In both conditions of both experiments, resistance to prefeeding and to extinction was assessed after baseline performance was well established. The resistance ratios for responding in the constant and alternated components within conditions (represented as points numbered 7 and 8 in Figure 2) were in general agreement with the data of the other experiments in that figure. Average resistance ratios were also calculated between conditions for both the constant and alternated components for both experiments, and are presented in Figure 4 as a function of the product of the ratios of component to session average reinforcement rates, as given by the first term on the right of Equation 4 (termed the *contingency ratio*). For example, the session average reinforcer rate was 177 per hour in Condition A, and 34 per hour in Condition B, whereas the reinforcer rate in the constant component was 60 per hour in both conditions. Thus, the contingency ratio between conditions for the constant component is (60/177)/(60/34). For the alternated component, which was correlated with 300 and 10 reinforcers per hour in Conditions A and B, the contingency ratio is (300/177)/(10/34). The logarithms of the resistance ratios for performance in both the constant and alternated components were plotted against the logarithms of the contingency ratios. The results for both components compared between Conditions A and B within Experiments 1 and 2 are connected by lines. The slopes of these lines average about 0.35, which is similar to the slope of the function for the within-condition data portrayed in Figure 2. This suggests that Equation 4 accommodates between-condition differences in session average reinforcer rates about as well as within-condition differences in component reinforcer rates.

The data points based on comparisons between Experiments 1 and 2 are all plotted over −0.29, which is the logarithm of the ratio of session average reinforcer rates between experiments. Their location is generally consistent with the comparisons between conditions within experiments.

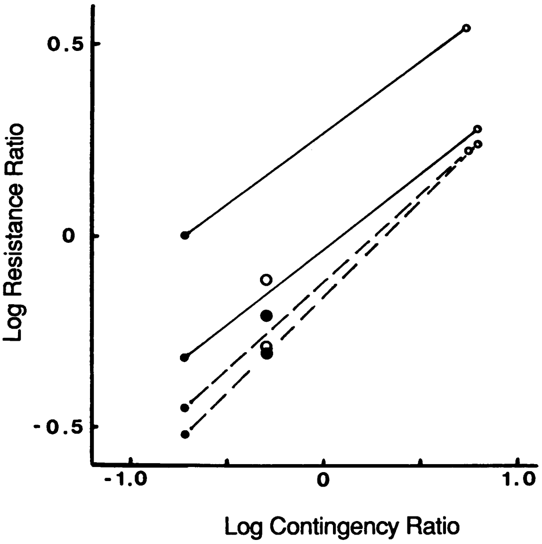

Fig. 4. Resistance-to-change ratios for a given component of two-component multiple schedules across successive conditions within or between experiments as a function of the contingency ratio expressing component reinforcer rates relative to session average reinforcer rates. All data are taken from a study of behavioral contrast by Nevin (in press). The small circles represent comparisons between Conditions 2 and 3 of Experiment 1 and between Conditions A and B of Experiment 2; data points for prefeeding and extinction are connected by solid and dashed lines, respectively. The large circles represent comparisons between Condition 2 of Experiment 1 and Condition A of Experiment 2; the remaining pair of comparisons is omitted because it is redundant. Filled and open circles represent the constant and varied components, respectively. Both variables are expressed as logarithms.

The overall adequacy of Equation 4 as a description of the relation between resistance ratios and reinforcer ratios is suggested by Figure 5, which combines the data plotted in Figures 2, 3, and 4. Although there is a good deal of variation in the data, there are no clear systematic differences between within-condition ratios for single-key experiments with different reinforcer rates in two components, within-condition ratios for equivalent two-key chain or serial schedule components with different reinforcer rates on two keys summed across components, between-condition between-experiment ratios for single-key multiple schedules, and within-condition ratios for the sole experiment that varied reinforcer rates correlated with both component stimuli and key location. Equation 4, with $a = b$, may therefore be accepted as a good first approximation to a descriptive model of the relation between resistance to change and reinforcer rates, at least with pigeons as subjects, key pecking as the response, and food as the reinforcer.

THE QUESTION OF GENERALITY

The potential generality of Equation 4 to other species, responses, reinforcers, and disruptors is suggested by the recent replication of some pigeon results with human subjects in a group-home setting whose performances were disrupted by a distracting stimulus (Mace et al., 1990). A number of earlier studies providing at least qualitative support for the present account were reviewed by Nevin (1979). There are, however, some conflicting findings.

The most serious challenge to the general model described here comes from the voluminous literature on the partial-reinforcement extinction effect, demonstrating greater resistance to extinction following training with partial (PRF) than with continuous (CRF) reinforcement. This line of research has typically employed between-group discrete-trial runway designs with rats as subjects, and has tested resistance to extinction after relatively brief training (see Nevin, 1988, for summary). In an effort to evaluate the importance of these factors, Nevin[2] trained pigeons in a within-subject design in which either the left or right key was illuminated in discrete trials, with keylight offset following a single peck. Left-key pecks produced food on every left-key trial (CRF), and right-key pecks produced food on 25% of the right-key trials (PRF). Training continued until 2,000 reinforcers had been obtained, and then extinction began. Responding extinguished more slowly on the right (PRF) key than on the left (CRF) key, thus confirming the standard partial-reinforcement extinction effect with pigeons after extensive training in a within-subject multiple-schedule design. However, when resistance to change was evaluated by prefeeding or by presenting food during the intertrial interval, responding was more persistent on the CRF (left) key than on the PRF (right) key, consistent with the free-operant multiple-schedule results reviewed above. Moreover, when previous free-operant extinction data obtained after extensive training in between-group designs were reanalyzed, the slopes of the extinction curves proved to be consistent with the within-subject multiple-schedule results (Nevin, 1988). Thus, it appears that extinction after intermittent reinforcement in discrete trials has special properties that remain to be analyzed.[3]

Another challenge to the generality of the results reviewed above arises when pharmacological agents serve as disruptors. Both Cohen (1986) and Lucki and DeLong (1983) studied the effects of various drugs on rats in multiple schedules in which the components differed in reinforcer rate, and found no difference between components in the resistance of response rate to drug effects. However, Hughes and Branch (1991) have reported acute effects of cocaine injections on monkeys' performances in three-component multiple fixed-ratio (FR) schedules that are consistent with the results reviewed above. Related research in my own laboratory, conducted with John Robinson, has yielded inconsistent results for pigeons on multiple VI VI schedules. Evidently, the effects of drugs as disruptors remain to be understood.

Studies that have employed pharmacological agents as reinforcers are also relevant. A series of studies by LeMaire, Meisch, and Kliner arranged equal concurrent FR schedules for two different drug doses in monkeys, and examined the effects of progressive doublings of the FR value and of food satiation as disruptors (see Kliner & Meisch, 1989; LeMaire & Meisch, 1984, 1985; Meisch & LeMaire, 1990). These studies obtained consistently greater resistance to disruption in performance

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[2] Nevin, J. A. (1989, March). *Extinction, satiation, and partial reinforcement.* Paper presented at the meetings of the Eastern Psychological Association, Boston.

[3] Mellgren and Elsmore (1991) have recently reported an analysis of free-operant extinction responding into bursts and pauses. They found that burst length was positively related to baseline reinforcer rate, consistent with the analyses of Nevin (1988). However, number of bursts was inversely related to baseline reinforcer rate, consistent with the usual partial-reinforcement extinction effect. Thus, their analysis may help to reconcile the effects of intermittent reinforcement on extinction in free-operant and discrete-trial procedures.

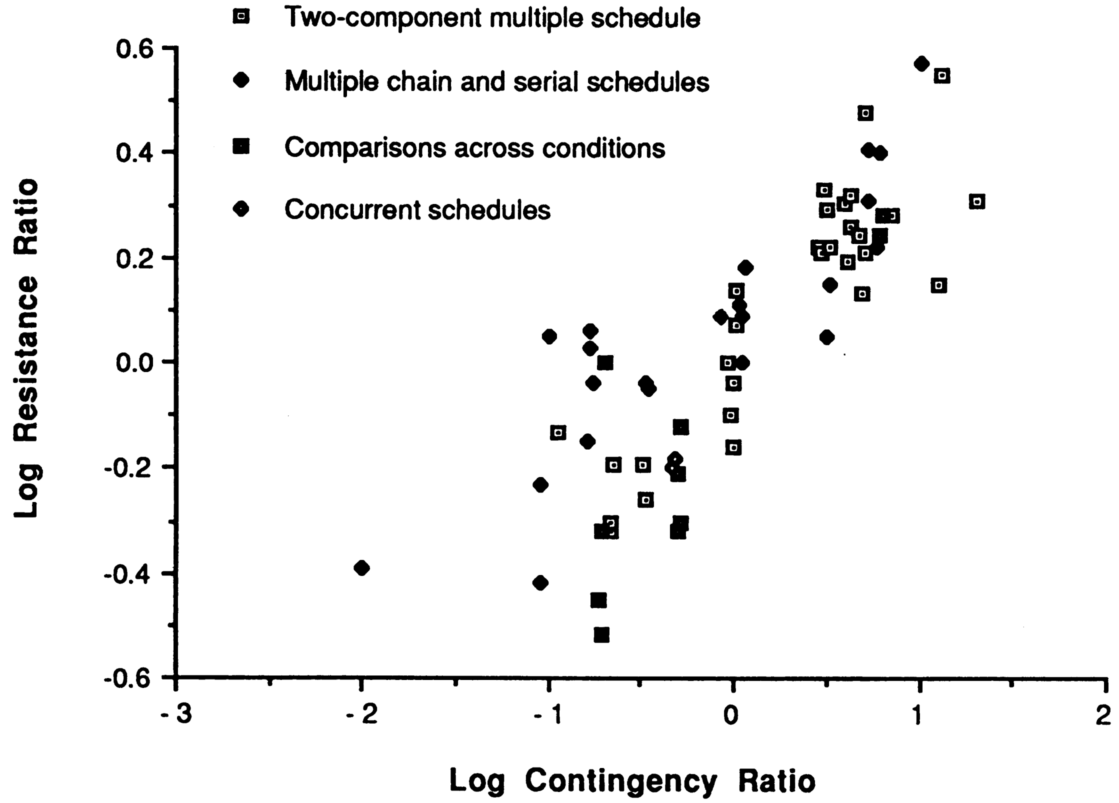

Fig. 5. All data points from Figures 2, 3, and 4 are combined into a single figure relating log resistance ratios to log contingency ratios, as given by Equation 4.

maintained by the larger drug dose, much as with different numbers of food pellet reinforcers (Kliner, LeMaire, & Meisch, 1988). Thus, their data are consistent with expectations derived from multiple-schedule research on resistance to change. However, a reanalysis of these data from a behavior-economic perspective by Hursh (1991) suggested that drug consumption changed similarly with price increases (FR values) when price was reexpressed in units of drug dose per response. As will appear below, the use of concurrent schedules raises questions of interpretation in relation to the model of Equation 5, and ratio schedules necessarily confound response rate and rate of reinforcer consumption, so comparable research with interval schedules may be needed to clarify the relation between the persistence of drug-reinforced behavior and dose size.

Another set of discrepant results has been reported by Cohen, Furman, Crouse, and Kroner (1990).[4] They trained rats on various FR schedules in both open and closed economies and evaluated resistance to the disruptive effects of response-independent food and of extinction across successive conditions with different FR values. Overall, they found no consistent difference in resistance to disruption between the open and closed economies. Resistance to response-independent food was essentially constant across a broad range of FR schedules, despite the fact that reinforcer rate decreased as the FR value increased; the results reviewed above suggest that resistance should have decreased with increasing FR values. Furthermore, resistance to extinction increased with the FR value, contrary to expec-

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[4] See also Cohen, S. L., Weigle, P. A., & Shaulis, K. S. (1991, May). *Resistance to change in fixed-ratio, variable-ratio, fixed-interval, and variable-interval schedules of reinforcement: Some contradictory data.* Paper presented at the meetings of the Association for Behavior Analysis, Atlanta.

tations based on results reported above and by Nevin (1988). It is clear that a good deal of research will be needed to identify the factors that are critical for the orderly and internally consistent findings with pigeons on multiple, chained, and serial schedules summarized above.

A different sort of problem arises from the work of Harper and McLean (1992). Using pigeons as subjects in multiple schedules with different reinforcer durations, they demonstrated that the differential changes in response rates observed when free food was introduced between components may persist in the steady state. They go on to raise the general question of whether differential resistance to change carries implications for sensitivity to reinforcement schedules in steady-state performance, and suggest that the answer is no. Although their research clearly raises the question of where short-term effects on response rate in resistance-to-change analyses leave off and steady-state analyses become relevant, it may be construed as confirming the independence of steady-state response rate and its resistance to change that is implicit in the momentum metaphor, and is empirically demonstrated by a number of studies. This topic will be revisited below.

SOME IMPLICATIONS AND UNCERTAINTIES

When two successive components of a multiple schedule are arranged on separate keys, the component stimuli and key locations are redundant, and it is not clear whether reinforcers should be tallied by stimuli, by key locations, or both. The problem is similar to that of identifying the controlling features of stimuli with redundant elements, as in Reynolds' (1961) study of attention. The extent to which resistance to change depends on correlations between reinforcers and component stimuli or key locations can be addressed by varying reinforcer rates independently and evaluating the parameters *a* and *b* of Equation 4.

A more complex problem arises with two-key concurrent schedules. Here, the component stimulus is the experimental chamber itself, and Equation 4 predicts equal resistance to change for both concurrent performances because chamber cues are equally correlated with the two reinforcer rates. Such results have been reported by Myerson and Hale (1988) and Skinner (1950) for extinction after training with concurrent VI VI schedules.

A common finding with two-key concurrent VI VI schedules is matching, which implies that reinforcer rates for the two alternatives are equal per unit time spent on each. If reinforcers are effectively correlated with keys on the basis of time spent attending to them, the same prediction of equal resistance to change follows.

However, if reinforcers are effectively correlated with keys on the basis of overall session time, Equation 4 predicts greater resistance to change on the key with the greater reinforcer rate. Such a result has been reported for pigeons when responding was disrupted by intermittent punishment (de Villiers, 1977; Farley, 1980). Similar results for rats have been reported by de Villiers and Millenson (1972) for concurrent schedules differing in reinforcer duration when responding was disrupted by stimuli correlated with shock, and by Leslie and Millenson (1973) for schedules differing in reinforcer quality when responding was disrupted by stimuli correlated with food.

Finally, if different reinforcer rates are arranged for responding to two different, concurrently available key colors but those colors and their correlated schedules are arranged equally often on the left and right keys, and if key locations are the controlling factor for resistance to change, pecking should be equally persistent at each of the keys regardless of color. Therefore, responding should shift toward indifference with respect to the colors during a resistance test, as found by Nevin (1969) for extinction after discrete-trial concurrent VI VI training.

Thus, it appears that every reported outcome for the relative resistance to change of concurrent performances can be construed as consistent with the predictions of Equation 4. In view of the interpretive freedom required to achieve this consistency, however, this is not a satisfying state of affairs.

THE RELATIVE LAW OF EFFECT AND RESISTANCE TO CHANGE

The relation between steady-state response rate and reinforcer rate was derived from the matching law by Herrnstein (1970), on the assumption that every experimental situation allows behavior other than the target response and includes reinforcers other than those arranged by the experimenter. His formulation, known as the "relative law of effect," is

$$B = kr/(r + r_e), \qquad (8)$$

where B is the rate of the target response, r is the rate of arranged reinforcers, r_e is the rate of uncontrolled, extraneous reinforcers, and k is the asymptote of response rate as reinforcer rate increases indefinitely.

Herrnstein (1970) extended Equation 8 to account for multiple-schedule performance by including reinforcers in the alternated component, weighted by a parameter m ($0 < m < 1$) reflecting the degree of interaction between components, in the denominator:

$$B_1 = \frac{kr_1}{r_1 + mr_2 + r_e}, \qquad (9)$$

where B_1 is response rate and r_1 is reinforcer rate in the target component, and r_2 is the reinforcer rate in the alternated component. Several predictions of this equation have been disconfirmed, but Williams (1988) has shown that these difficulties can be resolved by rewriting the denominator as follows:

$$B_1 = \frac{kr_1}{\frac{r_1 + mr_2}{1 + m} + r_e}. \qquad (10)$$

This relative-reinforcement approach to multiple-schedule performance can be extended to the study of resistance to change by construing all of the disruptive operations used to decrease responding in order to evaluate resistance to change as increases in the value of extraneous reinforcers, r_e, relative to those of the experimentally arranged reinforcers, r_1 and r_2. Equations 9 and 10 both predict that if r_e is increased equally for two-component performances maintained by different reinforcer rates, the resulting decrease in response rate is relatively greater for the component with the lower reinforcer rate. The reason is that, because m is typically less than 1.0, the denominator is greater for whichever component has the larger value of r_1, so that the relative increase in the denominator that results from adding a given value to r_e is smaller. The results for all of the standard two-component multiple-schedule experiments summarized in Figure 2 are at least ordinally consistent with this prediction.

The prediction of greater resistance to change in the component with the greater reinforcer rate holds for any schedule arrangement that increases the value of the denominator of Equation 9, or 10, or any similar expression. Thus, when alternative reinforcers are arranged concurrently within a schedule component, as in the experiments by Nevin et al. (1990), the denominator for that component is increased by the alternative reinforcer rate, and resistance to change should be greater than in a component without concurrent alternative reinforcers. Nevin et al. (1990) obtained such results in both experiments (see Figure 2), but the data deviated from predictions derived from the relative law of effect in several important particulars (see their discussion).

Equation 10, proposed by Williams (1988), can be extended to predict that resistance to change in the equivalent components of serial schedules should depend directly on the reinforcer rate in the following link. Williams (1988) proposed that response rate in a schedule component depends separately on the reinforcer rates in the preceding and following components, as well as its own reinforcer rate. Writing his equation in full,

$$B_1 = \frac{kr_1}{\frac{1 + pr_p + fr_f}{1 + p + f} + r_e}, \qquad (11)$$

where p and f are constants reflecting the relative weights of the reinforcer rates in the preceding and following components, with $f > p$. Thus, when a component with a given reinforcer rate is followed by a richer schedule, the denominator is greater than when a component with the same reinforcer rate is followed by a leaner schedule. Accordingly, response rate should be lower and resistance to change should be greater in a component followed by a richer schedule, as found by Nevin (1984) and Nevin et al. (1987). Resistance to change in the initial links of multiple chained schedules can be explained similarly if it is assumed that there is some conditioned reinforcement for initial-link responding, so that r_1 is greater than zero.

All in all, it appears that relative-reinforcement accounts of response rate in multiple schedules based on the relative law of effect can plausibly be extended to account for the majority of the resistance-to-change findings presented in this paper, despite the fact that Herrnstein's (1970) formulation and its successors were proposed to account for steady-state response rate, not resistance to change.

It may be asked why the study of resistance to change deserves separate status in view of its general conformity to expectations derived from the relative law of effect for steady-state behavior. To answer this question, we need an experimental situation in which a stimulus–reinforcer contingency account of resistance to change predicts results that differ in direction as well as detail from expectations derived from the relative law of effect. One such situation involves behavioral contrast in successive experimental conditions. It is well known that, at least for pigeons pecking keys for food reinforcers, response rate in a constant component of a multiple schedule depends inversely on the reinforcer rate in the alternated component. Resistance to change appears to follow the same principle, as shown by Nevin (in press). However, for this situation, an approach based on the relative law of effect predicts the opposite. To see this, consider the predictions of Equations 9 or 10 for two successive conditions in which one component schedule is a constant 60 reinforcers per hour and the other is either 300 or 10 reinforcers per hour. Both equations correctly predict steady-state behavioral contrast in the constant component because the denominator is larger when the alternated component arranges 300 reinforcers per hour than when it arranges 10 reinforcers per hour. For the same reason, both equations also predict greater resistance to change in the constant component in the former condition. However, Nevin (in press) found that resistance to change in the constant component was greater in the latter condition. This result is consistent with an account based on stimulus–reinforcer contingency ratios as shown in Figure 4, and contradicts expectations based on the relative law of effect. Therefore, although the relative law of effect provides an excellent account of steady-state response rate, a separate account based on stimulus–reinforcer contingencies appears to be necessary to accommodate the data on resistance to change.

RESISTANCE TO CHANGE AND MATCHING

The preceding section asked whether the relative law of effect, derived from the matching law for concurrent-schedule performance, could account for the data on resistance to change. Here, the question is reversed: Can the principles of resistance to change account for matching in concurrent VI VI schedules?

A two-response concurrent schedule arranges two operants, each of which is in competition with the other. According to the principles summarized above, the resistance to change of an operant depends directly on the rate of reinforcement correlated with its controlling stimulus. Therefore, whichever operant obtains the greater rate of reinforcement should be more persistent in the face of competition from the other. For the purposes of this argument, assume that the controlling variable is the local rate of reinforcement per unit time spent on each key. Now suppose that a subject initially allocates time equally to the left key, where responding is reinforced on a VI 1-min schedule, and to the right key, where responding is reinforced on a VI 3-min schedule. The local reinforcer rate on the left key will be about three times that on the right key. Therefore, responding will be less disrupted by competition on the left than on the right key, with the result that time spent on the left key will increase and the obtained local rate of reinforcement will decrease while the reverse occurs on the right key. This process will continue until the subject allocates more than three fourths of its time to the left key, at which point the local reinforcer rate on the left key will fall below that on the right key. Now, responding on the right key will be less disrupted by competition than on the left key, and the subject will allocate more time to the right key until the reinforcer rate on the right key falls below that on the left key. The only stable allocation of behavior in this situation is at equal local reinforcer rates (i.e., matching). Thus, matching may be seen as the outcome of a process that tends to equate the reciprocal resistance to competition of two concurrent operants. The proposed process is strikingly like melioration (Herrnstein & Vaughan, 1980), according to which a subject is said to prefer whichever operant yields the higher local rate of reinforcement.

The same outcome follows from the effects of disrupting variables applied equally to both operants. If the subject allocates time equally to two operants yielding 60 reinforcers per hour on the left key and 20 reinforcers per hour on the right key, as in the example above, responding on the left key will be less disrupted than responding on the right key by any variable, thus increasing left-key responding relative to right-key responding and reducing the difference in their obtained local reinforcer rates. Random events that perturb baseline responding will continue to have this sort of differential effect until relative response allocation stabilizes at matching, where the local rates of reinforcement are equal. In this sense, matching may be seen as derivative from the principles of resistance to change.[5]

SUMMARY AND CONCLUSIONS

The notion of behavioral momentum involves two terms: response rate and resistance to change. Both terms are important in practical applications as well as basic behavioral analyses. For example, one purpose of instruction is to make a class of desired behavior (e.g., doing arithmetic) occur rapidly and reliably in a teaching situation, and to make it persist effectively outside the classroom. It is equally important to understand the effects of procedures (e.g., alternative reinforcement) that are designed to decrease the frequency of undesirable behavior, but that may also increase its persistence (see discussion by Mace et al., 1990). The relative law of effect provides an excellent account of response rate under constant conditions. The stimulus–reinforcer contingency model proposed in this paper is a first step toward an account of resistance to change. Together, these accounts may provide a comprehensive understanding of behavioral momentum.

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[5] This idea was suggested to me some years ago by A. Charles Catania. It is possible to extend it to account for undermatching by noting that deviations in the direction of undermatching produce smaller differences in local reinforcer rates than do deviations in the direction of overmatching (see Herrnstein & Vaughan, 1980, Figure 5.12), and the variation in local reinforcer rates within a session may mask small differences between them. The result is approximately equal resistance to change at behavioral allocations that undermatch overall obtained reinforcer proportions.

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