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Strength of Conditioned Reinforcement in Chain Schedules: The Effect of Altering Minimum Time to Reinforcement

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STRENGTH OF CONDITIONED REINFORCEMENT IN CHAIN SCHEDULES:  
THE EFFECT OF ALTERING MINIMUM TIME TO REINFORCEMENT

by

Robert P. Ludlow

A Thesis
Submitted to the
Faculty of The Graduate College
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of the
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Robert P. Ludlow
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Relative rate of responding to left key during concurrent initial links as a function of relative harmonic rate of reinforcement obtained in terminal link of left key. Initial links were both VI 1 min. schedules. Left-key terminal link was always VI 15 sec; right-key terminal link was one of three FI schedules: FI 4 sec., FI 8 sec., and FI 15 sec.

Hypothetical gradient of delay. Units on abscissa are timed from onset of conditioned reinforcing stimulus. See text for explanation.

Response rate in the first link of a two-link chain as a function of the mean VI schedule in the second link. Chain was heterogeneous: i.e. a different response topography was required in each component. First-link response was a chain pull; second link was a bar press.

The median increase in response rate for brief-stimulus schedules (key-color change or hopper light) over equivalent tandem schedules. The points are from the responding in only the initial components. Three points designated HL were obtained from the hopper-light presentations at the end of each component. Remaining points are from schedules involving key-color changes at end of components. See text for further explanation.

Mean and median PRPs for each of seven experimental conditions. Bars are mean (upper figure) and median (lower figure) PRPs for the last five sessions of each experimental condition. Filled circles are mean and median PRPs for previous five sessions in each condition. See text for further explanation.
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In a chain schedule of reinforcement the subject is confronted by a succession of discriminably different exteroceptive stimuli. Progress from one stimulus condition, or link, to the next in sequence depends upon meeting the response requirement for the link which is in effect. Fulfilling the response requirement, or schedule, in the terminal link produces primary reinforcement and reinstates the initial link. The subject may obtain one or more primary reinforcements in the terminal link (see Fig. 1).

A complex variant of a chain is the concurrent chain schedule, in which the initial links of two (or more) chains are concurrently available, usually with the restriction that responses cannot occur simultaneously in both schedules. Frequent changeovers from one schedule to the other are permitted and commonly occur when the initial links are interval schedules. Meeting the response requirement for either of the independently programmed initial links produces its associated terminal-link stimulus, and, while that terminal link is in effect, the other schedule is not available. Thus, the initial links operate concurrently and independently; terminal links are mutually exclusive. Ordinarily, a different exteroceptive stimulus is associated with each terminal link. Completion of a terminal link produces primary reinforcement and reinstates the initial links (see Fig. 2).

Chain schedules and concurrent chains are widely accepted as productive methods for studying conditioned reinforcement, primarily because the putative conditioned reinforcing stimuli are not being
Figure 1. Schematic drawing of a hypothetical four-link chain schedule typical of chains employed in animal experiments. The stimulus associated with each link remains present until the subject completes the response requirement, whereupon the stimulus associated with the succeeding link is immediately presented. The chain may consist of two or more links. The terminal-link schedule may be in effect for more than one food reinforcement, with food being presented each time the subject meets the response requirement. The stimuli and the response requirements are merely illustrative: in practice, a wide variety of stimuli and response requirements are employed.
FIRST LINK

ORANGE KEY LIGHT

RESPONSE REQUIREMENT:
FIRST KEY PECK AFTER
1 MIN. IN FIRST LINK
(FI 1 MIN.) PRODUCES

SECOND LINK

GREEN KEY LIGHT

RESPONSE REQUIREMENT:
FIRST KEY PECK AFTER
VARIABLE 1 MIN. INTERVAL
(VI 1 MIN.) PRODUCES

THIRD LINK

BLUE KEY LIGHT

RESPONSE REQUIREMENT:
50 KEY PECKS
(FR 50) PRODUCE

TERMINAL LINK

WHITE KEY LIGHT

RESPONSE REQUIREMENT:
10 SEC. WITHOUT A
KEY PECK (DRO 10 SEC.)
PRODUCES FOOD
Figure 2. Schematic drawing of a hypothetical two-link concurrent chain schedule typical of concurrent chains employed in animal experiments. Note that there are two keys, each of which is associated with a different chain schedule. The vertical broken line in the first link indicates that the subject is free to switch between the two independently programmed initial-link schedules.

When the first-link response requirement for one of the keys is met, its associated second link goes into effect. Second-link schedules are mutually exclusive: when the second-link schedule for one key is in effect, the other key is inoperative. Typically, the concurrent initial links are both variable-interval 1 min. schedules. A wide variety of terminal-link conditions may be compared.
FIRST LINK
LEFT KEY  (WHITE)
RESPONSE REQUIREMENT:
VARIABLE-INTERVAL
1 MIN. SCHEDULE
(VI 1 MIN.)
PRODUCES

FIRST LINK
RIGHT KEY  (WHITE)
RESPONSE REQUIREMENT:
VARIABLE-INTERVAL
1 MIN. SCHEDULE
(VI 1 MIN.)
PRODUCES

SECOND LINK
LEFT KEY  (BLUE)
50 KEY PECKS
PRODUCE

SECOND LINK
RIGHT KEY  (DARK)
KEY IS INOPERATIVE

SECOND LINK
LEFT KEY  (DARK)
KEY IS INOPERATIVE
100 KEY PECKS
PRODUCE

SECOND LINK
RIGHT KEY  (RED)

FOOD
weakened in the course of the experiment. Earlier studies, in which the effects of conditioned reinforcement were assessed during extinction, produced many conflicting results and "emphasized the weakness and transitory nature of conditioned reinforcement" (Autor, 1960).

The following experiment by Ferster and Skinner (1957, p. 667) clearly illustrates the use of a chain schedule to demonstrate the effects of a conditioned reinforcer. A pigeon was first exposed to a multiple (mult) schedule in which variable periods of extinction (ext) averaging 1 min. in duration alternated with a fixed-ratio 50 (FR 50) schedule of reinforcement. The extinction component was signaled by the presence of an orange light; at the end of the extinction period the light changed to blue without regard to the bird's behavior. After ten sessions on this mult ext FR 50 schedule, response rates were low in extinction (orange) and high in FR 50 (blue). In the 11th session the schedule was changed: the transition from the orange component to FR 50 was no longer non-contingent; instead, when the variable 1 min. interval elapsed, a response was required to produce the FR 50 component. The new schedule was a two-link chain in which the first link was a variable-interval 1 min. (VI 1 min.) schedule. This chain VI 1 min. FR 50 schedule was in all respects identical to the preceding multiple schedule, except that the onset of the terminal FR 50 link was made contingent upon responding in the presence of the orange light. The response rate in the VI 1 min. initial link, formerly extinction, increased to an intermediate value characteristic of VI responding maintained by primary
reinforcement.

This experiment purportedly showed that the blue stimulus light was a conditioned reinforcer which strengthened responding in the preceding link. The possibility that the results could be attributed solely to a delayed effect of primary reinforcement was controlled for because the temporal proximity between responses in orange and delivery of the primary reinforcer was similar in both the multiple and chain schedules.

Because they maintain the effectiveness of conditioned reinforcers indefinitely, chain schedules have facilitated detailed investigations of variables that determine the strength of conditioned reinforcers. For example, a two-component chain, with a VI schedule programmed in the initial link, can be used to study the effects of a variety of terminal-link manipulations. Changes in the rate and pattern of responding in the initial link are assumed to reflect changes in the conditioned reinforcing strength of the terminal-link stimulus (Kelleher and Gollub, 1962; Hendry, 1969).

The concurrent chain procedure is generally regarded as a refinement on the use of chain schedules because relative initial-link response rate to either of two keys is a more sensitive and more orderly dependent measure than initial-link response rate in simple chain schedules (Catania, 1963; 1966). Relative rate of responding in the concurrent operant paradigm is a widely accepted operational definition of preference.

Autor (1960) first employed concurrent chains to investigate the relative strength of conditioned reinforcers. The concurrent
initial links in his series of experiments were always VI 1 min. schedules. Terminal links consisted of either a pair of VI schedules or a pair of DRO schedules. The terminal-link schedule on one key (key F) was held constant; the schedule on the other key (key X) was varied systematically. Thus, in one experiment, the terminal schedule on key F was VI 15 sec.; the VI schedules on key X were: 3.75 sec., 7.5 sec., 15 sec., 30 sec. and 60 sec. The stated purpose of the experiment was to determine quantitative properties of conditioned reinforcement in chain schedules, specifically the relationship between the strength of a conditioned reinforcing stimulus and the frequency of primary reinforcement in its presence. The results indicated that the relative strength of a conditioned reinforcer is roughly proportional to its associated relative frequency of primary reinforcement. That is, the proportion of initial-link responses to key F tended to match the proportion of reinforcements obtained on key F in the second link. Figure 3 shows how the results of this kind of experiment are usually presented. The diagonal line is the matching line: if the relative number (or relative rate) of initial-link responses on a key is proportional to the relative rate of primary reinforcement in its terminal link, data points should fall very close to the diagonal. Such a proportionality is commonly called a matching relationship. It was closely approximated in Autor's experiments and in a related study by Herrnstein (1964a). Autor obtained similar results when the terminal links were DRO schedules which eliminated key pecking. The implications of the latter finding will be discussed in a later
Figure 3. Relative initial-link rate of response to one of two keys in a concurrent chain schedule as a function of the relative rate of primary reinforcement obtained on that key in the terminal link.
MATCHING LINE

RELATIVE RATE OF PRIMARY REINFORCEMENT
IN TERMINAL LINK

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section of this paper.

The recent prominence of the concurrent schedule in behavioral research can be readily traced to the encouraging prospects it offers for the development of a straightforward, quantitative analysis of the effects of a wide range of reinforcement and schedule parameters (Herrnstein, 1970). For example, matching in concurrent chains may be expressed by the following simple formula:

$$\frac{R_l}{R_l + R_r} = \frac{1/t_l}{1/t_l + 1/t_r},$$

where $R_l$ and $R_r$ are the rates of responding on the left and right keys, and $t_l$ and $t_r$ are the mean times to reinforcement on the left and right keys calculated from the onset of the terminal links. Use of this formula entails two assumptions: (1) that the relative response rate is independent of the time required to reach the terminal links, and (2) that the organism's preference conforms to the relative rate of reinforcement determined from the arithmetic means of the terminal links. The first assumption is incorrect; the second has very limited generality.

With reference to assumption (1), Fantino (1969) employed several values of equal, concurrent initial-link VI schedules in addition to the commonly employed concurrent VI 1 min. schedules. Values of the equal initial links which exceeded 1 min. produced a smaller proportion of responses to the preferred key than was predicted by the matching equation. Fantino suggested that preference may be determined by the relative amount of reduction in expected (mean) time to reinforcement signified by entry into a
terminal link—that is, a constant difference in terminal-link rate of reinforcement should have a greater effect upon preference when the initial links are short. Fantino tendered a formula which incorporated this intuitive notion in the form of T, the expected time to primary reinforcement calculated from the onset of the initial links. The computation of T can best be illustrated with an example. Consider a concurrent chain schedule in which the schedule on the left key is chain VI 60 sec. VI 60 sec., and the schedule on the right key is chain VI 90 sec. VI 30 sec. Assuming that the subject responds at a sufficient rate—including changeover rate—to obtain all entries into the terminal links as they become due, he will enter the left-key terminal link three times for every two entries into the right-key terminal link. Consequently, the probability of entering the terminal link in the left key is .60 (it is .40 for the right key). The expected time to terminal link entry, measured from the onset of the concurrent initial links, is 36 sec.—5 entries for every 180 sec. in the initial links. Thus, for every 36 sec. in the initial links, on the average, the subject secures entry to one of the terminal links. And 60% of the time he enters the VI 60 sec., left-key terminal link. Of course he enters the VI 30 sec., right-key terminal link 40% of the time. Combining, one obtains T, the expected time to primary reinforcement from the onset of the initial links:

\[ T = 36 \text{ sec.} + (.60) (60 \text{ sec.}) + (.40) (30 \text{ sec.}) = 84 \text{ sec.} \]

The preference equation expresses mathematically the idea that the relative rate of responding in the concurrent initial links is a
function of the reduction in expected time to primary reinforcement signified by entry into one terminal link relative to the reduction signified by entry into the other terminal link. The equation is:

\[
\frac{R_l}{R_l+R_r} = \frac{T-t_l}{(T-t_l)+(T-t_r)}
\]

Fantino demonstrated that this equation predicted preference in a variety of concurrent chains more accurately than the arithmetic matching equation. It was also successful in predicting preference when both the initial and terminal links were unequal. Unfortunately, the computation of \( T \) makes no provision for the differential rate of entry into the terminal links—i.e. the relative rate of conditioned reinforcement. This leads to the curious prediction that relative response rate in the initial links will always be .50 when the terminal links are equal, regardless of the values of the initial links. This is clearly at variance with a considerable body of data which indicate that relative rate of responding to a key is directly related to the relative rate of reinforcement obtained on that key (Herrnstein, 1970). Fantino was aware of this problem and stated in a personal communication (1970) that the formula had been revised to handle the effects of relative rate of conditioned reinforcement.

Herrnstein (1964b) used concurrent chains to compare the effects of periodic \textit{versus} aperiodic reinforcement delivery in the terminal links. He pointed out that although aperiodic schedules of reinforcement are usually identified by their arithmetic means (as, for example, VI schedules), subjects confronted by these schedules seem to average the component intervals in a manner which gives
more weight to shorter intervals. He did not suggest a transforma-
tion on the VI schedule which could be used to predict the results
satisfactorily. Figure 4 shows the locus of Herrnstein's data
points in relation to the arithmetic matching line.

Herrnstein's results have been supported in a number of
systematic replications. Fantino (1967) found preference for a
two-component mixed-ratio schedule versus a fixed-ratio schedule
and showed that the results could be predicted by the relative rates
of reinforcement determined from the geometric means of the terminal-
link interreinforcement intervals. Preference for the mixed-ratio
schedule increased as the disparity between its two component fixed-
ratios increased. That is, as the smaller of the mixed fixed-ratio
schedules approached FR 1, the relative conditioned reinforcing
strength of the mixed terminal link increased. Killeen (1968)
compared variable-interval schedules with fixed-interval (FI)
schedules in the terminal links of concurrent chains. He found that
preference for the variable-interval schedules could be predicted
from the harmonic means of the terminal-link component intervals.
He also obtained matching from Herrnstein's (1964b) data by
employing relative harmonic rate of reinforcement as the independent
variable. This method for determining preference is depicted in
Fig. 5, which should be compared with Fig. 4 where the same data are
presented as a function of the relative arithmetic rate of rein-
forcement. Both the geometric and harmonic means assign progres-
sively more weight to progressively shorter interreinforcement
intervals.
Figure 4. Relative rate of responding to left key during concurrent initial links as a function of relative arithmetic rate of reinforcement obtained in terminal link of left key. Initial links were both VI 1 min. schedules. Left-key terminal link was always VI 15 sec; right-key terminal link was one of three FI schedules: FI 4 sec., FI 8 sec., and FI 15 sec.
Figure 5. Relative rate of responding to left key during concurrent initial links as a function of relative harmonic rate of reinforcement obtained in terminal link of left key. Initial links were both VI 1 min. schedules. Left-key terminal link was always VI 15 sec; right-key terminal link was one of three FI schedules: FI 4 sec., FI 8 sec., and FI 15 sec.
RELATIVE FIRST-LINK RATE OF RESPONDING TO LEFT KEY

RELATIVE HARMONIC SECOND-LINK RATE OF REINFORCEMENT FOR LEFT KEY (APERIODIC SCHEDULE)
Davison (1969) reviewed these three studies and also conducted a study of preference for fixed- versus mixed-intervals in the terminal links of concurrent chains. While his results were in agreement with earlier findings--i.e. animals prefer variable schedules of reinforcement to fixed schedules of similar value--he emphasized that "the problem of specifying an appropriate measure of reinforcement rate in the terminal links of concurrent chain schedules has not yet been solved." Davison found that the shorter intervals were weighted more heavily in his study than in Killeen's.

Perhaps the specification of an "appropriate measure" of terminal-link reinforcement rate will have to await more rigorous standardization of experimental procedures and, as will be seen, clarification of the nature of conditioned reinforcement itself. In the meantime, the evidence at least seems to warrant postulating a principle which might aptly be termed the gradient of delay. Figure 6 is a hypothetical gradient relating the strength of a conditioned reinforcer to the temporal interval (or delay) imposed between its onset and the delivery of a primary reinforcer. An increase of 6 unit intervals added to an already substantial delay produces a smaller decrement in conditioned reinforcer strength than an increase of only one unit added to a short delay. This function is reminiscent of classical psychophysical difference thresholds (Kretch and Crutchfield, 1959, pp. 53-54), in which the subject's ability to discriminate between values of a stimulus continuum is dependent upon the relative rather than the absolute difference between values of the stimulus. In this case, the
Figure 6. Hypothetical gradient of delay. Units on abscissa are timed from onset of conditioned reinforcing stimulus. See text for explanation.
CONDITIONED REINFORCER STRENGTH

TIME TO REINFORCEMENT (ARBITRARY UNITS)
continuum is duration of the terminal-link stimulus, and the index of discrimination is the change in the response measure employed in the first link. The negatively accelerated decline in conditioned reinforcer strength also conforms to mathematical transformations which assign greater weight to shorter intervals.

A study by Findley (1962), in which a heterogeneous chain schedule was employed, produced results consistent with the preceding analysis. Figure 7 (from Findley, 1962) depicts the rate of responding in the first link of a two-link chain as a function of the mean time to reinforcement in the second link. The first link was a VI 4 min. schedule; the second link was varied systematically from VI 8 min. to VI 0.5 min. The response rate in the first link declined in a negatively accelerated fashion, suggesting a progressively decreasing effect of a constant reduction in second-link reinforcement rate. Millenson (1967, p. 271) obtained a similar relationship by employing different fixed-interval values in the second link.

Of the several methods for studying conditioned reinforcement, none produces more powerful effects than the brief-stimulus procedure (de Lorge, 1967; Findley and Brady, 1966; Kelleher, 1966a, 1966b; Thomas and Stubbs, 1967; Stubbs, 1969). This method consists of brief, response-contingent presentations of a stimulus which is paired with primary reinforcement. Brief (0.5 sec.) presentations of the grain-hopper light are frequently employed in experiments with pigeons, although an arbitrary stimulus, such as a change in key-light color, is also very effective if its onset is contiguous.
Figure 7. Response rate in the first link of a two-link chain as a function of the mean VI schedule in the second link. Chain was heterogeneous: i.e. a different response topography was required in each component. First-link response was a chain pull; second link was a bar press.
with primary reinforcement (Thomas, 1969).

One major effect of occasional, response-contingent presentations of a brief stimulus is to strengthen otherwise weak behavior. For example, Kelleher (1966b) required pigeons to complete a sequence of fixed-interval components in order to obtain food. Brief stimulus presentations at the end of each FI component produced the positively accelerated pattern of responding within each component which characterizes FI behavior maintained by primary reinforcement. When the contiguity between the brief stimulus and food was eliminated (by omitting the brief stimulus which accompanied primary reinforcement in the terminal component), rates of responding declined to low and relatively constant values in each component. Kelleher interpreted the results as an indication "that it may be necessary to present a stimulus in temporal contiguity with a reinforcing stimulus if the former stimulus is to become an effective conditioned reinforcer" (1966b, p. 84).

Stubbs (1969) expressed doubt that the effect of pairing a brief stimulus with food was "an all-or-none phenomenon," and he tested that supposition by imposing various delays between the brief stimulus and food. His schedules were similar to those used by Kelleher: i.e. second-order schedules, each consisting of a sequence of FI components. The major difference was in the systematic manipulation of the interval between the brief stimulus and primary reinforcement. This was accomplished by omitting the brief stimulus (0.5 sec. change in key-light color) at the end of the terminal link and varying the duration of the terminal link. Thus, the minimum
interval between the brief stimulus and food was determined by the length of the terminal link. The effects of minimum intervals of 1 sec., 5 sec., and 30 sec. were studied under this procedure. The respective second-order schedules were: (1) FI 45" (BS), FI 45" (BS), FI 45" (BS), FI 1" (SR+); (2) FI 30" (BS), FI 30" (BS), FI 30" (BS), FI 5" (SR+); (3) FI 30" (BS), FI 30" (BS), FI 30" (BS), FI 30" (SR+). The parenthetical abbreviations refer of course to the presentation of either a response-contingent brief stimulus (BS) or food (SR+) at the end of each component. In this condition there was no delay between the brief stimulus and food.

The response rate in the initial link of each second-order schedule was compared with the response rate in the initial link of an equivalent tandem schedule. Consider, for example, the second-order FI 30" (BS), FI 30" (BS), FI 30" (BS), FI 5" (SR+) schedule. The rate of responding in the initial FI 30 sec. link was compared with the rate in the initial link of a tandem FI 30" FI 30" FI 30" FI 5" (SR+) schedule. The only difference between the two schedules was the omission of brief-stimulus presentations in the tandem schedule. The dependent measure in this study, therefore, was the difference in first-link response rate between the second-order and tandem schedules. If brief, response-contingent stimulus presentations were effective conditioned reinforcers, initial-link response rates should have been higher under the brief-stimulus (second-order) conditions. Also, if the imposition of a delay between the brief stimulus and food weakened the conditioned reinforcing strength of the brief stimulus, then the amount of increase in
initial-link response rate should have been inversely related to the length of the delay. The results of this experiment, which are depicted in Fig. 8 (from Stubbs, 1969), supported both assumptions: response rates under brief-stimulus conditions were higher than they were under the equivalent tandem schedules, and the amount by which response rates increased was a positively accelerated function of the temporal proximity between the brief stimulus and food. There was no enhancement of response rate when the delay between the brief stimulus and food was 30 sec. The shape of the curves is congruent with the gradient of delay and other formulations which assign greater weight to short intervals.

Stubbs' procedure could be used to conduct a strongly indicated manipulation which would help to clarify further the question of the importance of contiguity between conditioned and primary reinforcement. This could be accomplished by including a condition in which the key light presented at the end of the penultimate link remains on throughout the final link, terminating with primary reinforcement. In other words, while Stubbs' experiment showed that strict contiguity was not required to establish an effective conditioned reinforcer, the suggested procedure would determine if contiguity promotes any additional enhancement of the strength of the conditioned reinforcer. For the present, the gradient of delay may be assumed only to express a relationship between the onset of a stimulus and primary reinforcement without reference to the interval between termination of the stimulus and primary reinforcement.

There is, by analogy to classical conditioning, no distinction made
Figure 8. The median increase in response rate for brief-stimulus schedules (key-color change or hopper light) over equivalent tandem schedules. The points are from the responding in only the initial components. Three points designated HL were obtained from the hopper-light presentations at the end of each component. Remaining points are from schedules involving key-color changes at end of components. See text for further explanation.
between "trace" and "delayed" conditioned reinforcers.

It should also be noted that the gradient of delay is restricted to the case where the final link terminates after a single primary reinforcement. Previous attempts to derive a functional relationship between frequency of primary reinforcement and conditioned reinforcer strength have failed to appreciate this nuance. The various formulations have tacitly covered instances in which the terminal-link stimulus and its associated schedule remain in effect for two or more reinforcements. The data upon which the formulations were based do not seem to justify extending the generality to terminal links of more than one component. For instance, it does not seem intuitively implausible that there may be an effect due to ordinal position of reinforcements in multiple-component terminal links. If this were the case, it would be inappropriate to average interreinforcement intervals without regard to their position in the sequence.

Thus, the gradient of delay emphasizes the temporal distribution of terminal-link primary reinforcements, assigning greater weight to shorter delay intervals. Also, because it is explicitly restricted to single-component terminal links, it indirectly emphasizes the possible importance of ordinal position in a series of terminal-link reinforcements. Finally, by not distinguishing between "trace" and "delayed" conditioned reinforcers, the gradient of delay calls attention to the need for investigation of the duration of conditioned reinforcers.

In the light of the previous considerations it seems likely
that a changed conception of conditioned reinforcement will emerge from further experimentation: does a conditioned reinforcer, for instance, accrue an independent reinforcing strength of its own as a result of the rate of primary reinforcement in its presence? Or does its strength depend upon the fact that it mediates, or enhances, a direct effect of primary reinforcement upon first-link responding? The latter (mediational) hypothesis suggests that the conditioned reinforcing stimulus is best conceptualized as a temporal bridge between first-link responding and primary reinforcement. This conception resembles information theory hypotheses (Hendry, 1969), which stress the predictive, or signalizing, properties of conditioned reinforcement. It is uncertain just how this hypothesis, which is admittedly—and deliberately—nebulous, can be expressed quantitatively.

Killeen (1968) suggested that the question could be settled by employing more than one reinforcement in each terminal link of a concurrent chain. Terminal-link intervals would be averaged in two different ways in order to correspond to each of the two conceptions of conditioned reinforcement. One method, which is consistent with interpretations that stress rate of primary reinforcement, would utilize an average based on interreinforcement intervals. On the other hand, "(if) reinforcement acts directly on responses in the first link with an effectiveness inversely proportional to its delay," then it would be appropriate, from Killeen's viewpoint, to compute an average based on the time to each reinforcement measured from the onset of the terminal link. Unfortunately, the
second method strains credibility because it predicts that the conditioned reinforcing strength of the terminal link will always be weakened by the addition of a second schedule of reinforcement. (Technically, adding a second schedule converts the terminal link from a simple to a mixed reinforcement schedule.) Consider, for example, conversion of the terminal link from a simple VI 1 min. schedule to a mixed VI 1 min. FI 10 sec. schedule. The average of the component intervals computed by the second method will be increased by 5 sec. because the VI 1 min. schedule will, in effect, be averaged with a VI 70 sec. schedule. That is, the average will be computed from the intervals composing the VI schedule and each of those same intervals plus 10 sec. The notion that an increase in reinforcement density of this magnitude will weaken the conditioned reinforcing strength of the terminal link is patently untenable.

The mediational hypothesis may, however, be construed as conferring greater significance on the first in a series of terminal-link reinforcements without unduly minimizing the importance of subsequent reinforcements. A straightforward experimental test could be conducted by using a concurrent chain in which the terminal links differed only with respect to the order of the component intervals. For example, each terminal link could be a two-component mixed-interval schedule. On one key the shorter interval would always be presented first; the order would be reversed on the other key. If preference is exclusively a function of the rate of reinforcement associated with the terminal link, approximately fifty per-cent of the first-link responses should be
allocated to each key. But if the first reinforcement has special significance, a greater proportion of initial-link responses should occur to the key on which the shorter interval is presented first. An alternative method would also employ two-component mixed schedules in the terminal links of a concurrent chain. The first component of each terminal link would always be, say, an FI 15 sec. schedule; the second component would consist of VI schedules of different values. If the time between the onset of a terminal link and the first reinforcement is of greater significance than subsequent inter-reinforcement intervals, then the usual effects (e.g. matching) of differences in terminal-link reinforcement rate will be attenuated. It should be evident, given that these results prove incompatible with the mathematical formulations discussed earlier, that a reconsideration of some widely held assumptions about the nature of conditioned reinforcement would be in order. Thus, the proposed gradient of delay is not offered merely as an imprecise substitute for the harmonic transformation: it is intended to emphasize the prospect that attempts at precise quantification may have to await further experimental clarification of the effects of a number of possibly influential variables that have so far received inadequate attention.

There is no doubt that under some circumstances a stimulus can act as an effective conditioned reinforcer although it has no mediational, or cue, properties. Studies employing brief-stimulus presentations (cited on pages 22-28) have provided cogent demonstrations of this phenomenon. A noteworthy example was furnished by
Thomas (1969), who showed that brief-stimulus presentations (0.5 sec. hopper light) could maintain FR 30 behavior indefinitely in the signalled absence of primary reinforcement. Thomas employed a multiple schedule in which one component was either an FR or DRO schedule of primary reinforcement; the other component was an FR 30 schedule of conditioned reinforcement. The conditioned reinforcement component (hopper light only) maintained high rates of responding indefinitely as long as the hopper light was paired with food in the other component (see also Zimmerman, 1967). The brief-stimulus paradigm represents the upper limit of the frequency-of-reinforcement interpretation of conditioned reinforcer strength: the onset of the stimulus is precisely contiguous with primary reinforcement, and in some cases the stimulus remains present throughout the feeding period.

There are, however, other paradigms for investigating conditioned reinforcement which produce results that cannot be interpreted from a frequency-of-primary-reinforcement standpoint. One such paradigm--based on information theory--attributes the strength of conditioned reinforcement to its predictive, or informational properties (Hendry, 1969). Kendall (1968) designed an experiment which provided a direct test between the information and frequency-of-primary-reinforcement hypotheses. His experimental chamber contained two pigeon keys: one (the FR key) produced primary reinforcement on either an FR 10 or an FR 50 schedule. Each peck on the other (information) key produced an 0.5 sec. flash of either green or blue illumination. For a 30 sec. period following each FR
reinforcement, both keys were dark and the FR key was inoperative. Pecks on the information key produced brief flashes of blue light if the ensuing schedule were FR 10 and flashes of green light if it were FR 50. At the end of the 30 sec. information component, the FR key was illuminated with yellow light and the information key became inoperative. Responding on the FR key produced food on either an FR 10 or an FR 50 schedule, depending upon the color just associated with the information key.

Up to this point the results were consistent with traditional frequency interpretations of conditioned reinforcement: responding to the information key was maintained at a higher rate in the pre-FR 10, or blue, component. However, when conditions were altered so that the color appearing on the information key was no longer systematically related to the ensuing ratio schedule, response rates on the information key declined substantially in both green and blue components. Response rates on the information key also declined when the schedule on the FR key was always FR 10. The results of both of these manipulations are clearly at variance with traditional interpretations of conditioned reinforcement, which in both cases predict increased rates to the green component.

The results of a study by Fantino and Herrnstein (1968) further complicate the conditioned reinforcement picture. They employed concurrent chains which differed only with respect to the duration of the terminal links. That is, the schedules associated with each terminal link were identical, but the time in the terminal link of one key (and hence the number of reinforcements) was substantially
greater. If the strength of a conditioned reinforcer is a function of its associated rate of primary reinforcement, whether that rate is expressed arithmetically, harmonically, or according to some other transformation, then the additional reinforcements in the longer terminal link should not affect preference. The results conflicted with this interpretation: both birds consistently allotted a greater proportion of initial-link responses to the key that provided more primary reinforcements. Preference was small, however, relative to the effects produced by manipulations of reinforcement density. Although there was a monotonic relationship between preference for a key and the relative amount of time (and reinforcement) in its terminal link, the relationship fell substantially short of arithmetic matching.

It is clear, then, that there are many variables which may be operating at any time to influence the strength of conditioned reinforcement. One factor not yet mentioned is magnitude of primary reinforcement associated with the terminal link. Schwartz (1969) showed that relative rate of response in the initial (FI) links of a concurrent chain was a matching function of the relative duration (magnitude) of the reinforcement associated with identical terminal FR links. He also compared various combinations of reinforcement duration and ratio requirement in the terminal links. He found under these conditions that relative response rate in the initial links could not be predicted solely from either the relative reinforcement duration or relative ratio requirement associated with the terminal FR links. When both variables were expressed as
relative amount of reinforcement per response, there was a matching relationship between this measure and response rate in the initial FI members of the concurrent chain schedule. In this study, number of FR responses and time to reinforcement were confounded; and since FR rates were relatively invariant, the matching relationship could equally well have been expressed as a function of amount of reinforcement per unit time.

Another factor which probably influences the strength of conditioned reinforcement is the relative reinforcing strength of schedules operating at different times. In other words, is the strength of a conditioned reinforcer in a given stimulus situation sensitive to changes in the amount, rate or quality of the reinforcement associated with different situations? Technically, this question asks if the relationships demonstrated with concurrent chain schedules also hold for multiple chain schedules. Interactions between multiple schedule components are generally discussed in terms of "behavioral contrast" (Reynolds, 1961).

Up to this point temporal factors have been emphasized, possibly at the expense of response variables. There is no convincing reason, however, to dwell on the effects that terminal-link response requirements may have on the strength of conditioned reinforcement. Available evidence indicates that the conditioned reinforcing effectiveness of a stimulus is directly related to temporal aspects of the primary reinforcement occurring in its presence, "but is independent of the response rate or response pattern occurring in its presence" (Kelleher and Gollub, 1962,
p. 543). Subsequent research (e.g. Neuringer, 1969) has not greatly modified this conclusion, although Fantino (1968) has demonstrated that requiring a high rate of response (DRH) in the terminal link of a chain weakened its relative reinforcing effectiveness. It seems to be the case that, within quite broad limits, measures of conditioned reinforcement strength are relatively insensitive to terminal-link response requirements but highly sensitive to terminal-link rate of reinforcement. Also, the rates and patterns of responding that occur in the terminal link of a chain schedule are not necessarily controlled by the same variables that determine preference for that schedule in competition with other schedules (condurrent operants) nor of the disposition to enter the schedule when the opportunity is presented (latency, first-link response rate).

The present study may be viewed as a systematic replication of earlier experiments which compared various rates and distributions of primary reinforcement in the terminal links of chain and concurrent chain schedules. This study sought to extend the generality of previous findings to another dependent variable--the post-reinforcement pause (PRP). The design was the simplest arrangement for studying the PRP: a single response (FR 1) produced a compound stimulus (delay stimulus) which terminated with primary reinforcement. The schedule will be designated chain FR 1 delay x, where x is either a fixed value or the average of two or more delay intervals. The duration of the PRP was studied as a function of variations in time to reinforcement, defined by the duration of the
delay stimulus. The several experimental conditions and measurements employed were intended to clarify the following questions: (1) is the PRP a useful dependent measure when reinforcements are scheduled according to a variable time basis? (2) Will the PRP reflect differences in terminal-link frequencies and distributions of reinforcement in a manner similar to initial-link rate and preference measures? (3) Will a modest increase in minimum time to reinforcement affect the PRP in a manner consistent with the proposed gradient of delay? (4) Will the effects of changing the minimum time to reinforcement depend upon other characteristics of the schedule, especially mean time to reinforcement? (5) Will a two-component mixed schedule, providing a high proportion (50%) of short delays, be more effective than an equivalent variable schedule with the same mean time to reinforcement? (6) How will the various conditions influence the distribution of PRPs?
METHOD

Subjects

Two adult, male, experimentally naive albino rats were main­
tained at 80% of their free-feeding body weight throughout the
experiment.

Apparatus

An experimental chamber of 12 in. length, 8 in. width and 10 in.
height was housed in a plywood box which served to attenuate
extraneous noise and eliminate visual distractions. The front and
back of the chamber were constructed of 1/16 in. aluminum stock.
The sides and top were 1/8 in. clear plexiglass. The front wall was
the intelligence panel, on which were mounted a Foringer cylindrical
response lever, .75 in. in diameter, and five 7.5 watt white cue
lights. A Foringer liquid dispenser (dipper) provided reinforce­
ments (.10 g of 20% sucrose solution) through a circular, 1.5 in.
diameter opening located .5 in. above the grid floor in the center
of the intelligence panel. Access to the reinforcer (dipper time)
was limited to 3.8 sec. A relay, mounted behind the intelligence
panel, provided an audible click which accompanied each operation of
the dipper. The response lever (operandum) was located 1 in. above
the floor, approximately 3 in. to the left of the dipper opening.
One cue light was located 3 in. above the floor in the center of the
intelligence panel. The remaining cue lights were mounted in two
vertical pairs 3 in. from the floor, one pair directly above the operandum and the other pair similarly placed on the opposite side of the intelligence panel. A vibrating relay (buzzer) was mounted on the outside of the intelligence panel. Ambient illumination came from a 7.5 watt bulb mounted in the wall of the plywood box to the rear of the experimental chamber. Continuous white noise was provided by a Grason-Stadler White Noise Generator. A centrifugal exhaust fan provided ventilation and additional masking of extraneous sounds. Automatic programming and recording apparatus was located in an adjoining room.

Procedure

Each subject initially received a two hour session of adaptation to the stimuli which were employed in the study. These stimuli--cue lights, buzzer, dipper operation, and feedback relay--were presented at irregular intervals, for variable durations, singly and in different combinations. In the second session, subjects were trained to consume the sucrose and to promptly approach the dipper cup when the dipper was operated. Following this "magazine training" the compound delay stimulus was introduced: each free sucrose reinforcement was preceded by a 5 sec. period during which the buzzer and all cue lights were operated simultaneously. The operation of the dipper was precisely contiguous with the termination of the delay stimulus. Non-contingent presentations of this sequence of stimulus events continued at irregular intervals until visual observation confirmed that the subject was under stimulus control of

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of the delay stimulus. Onset of the delay stimulus was then made contingent upon successive approximations to lever pressing. Once lever pressing was acquired, the length of the delay was gradually adjusted to a variable duration of approximately 10 sec. A protective DRO contingency was instituted to insure that a response during the delay period (an "error") could never occur within 10 sec. of primary reinforcement. That is, each response that occurred during the last 10 sec. of the delay interval postponed termination of the interval, and primary reinforcement, by 10 sec. This schedule of reinforcement (chain FR 1 variable delay 10 sec.) remained in effect for two sessions. A probe to test the extent of stimulus control was conducted at the end of the second session. The probe consisted simply of leaving the delay stimulus in effect on the final trial until an error occurred. The error was followed immediately by a shutdown of the apparatus.

At this point several exploratory sessions were conducted to find a range of delay intervals which would produce PRPs of sufficient length to be potentially variable in either direction. The various conditions employed in the study, the order in which they were presented, and the number of sessions per condition are listed for each subject in Table 1. Table 2 lists the individual delay intervals, in seconds, which comprised the variable (VAR) delay schedules. The first set of figures under each schedule are the component intervals listed in ascending order; the second set of figures are the same intervals listed in the order in which they were punched in the VI tape—and hence, the order in which
Table 1. The experimental conditions for each subject in the actual order in which they were introduced. All schedules were two-link chains in which the first links were FR 1 schedules and the second links were various delays of reinforcement. In designating the schedules, the initial-link FR 1 has been deleted. A minimum of 10 sessions were conducted in each experimental condition.
### Rat D2

<table>
<thead>
<tr>
<th>Second-Link Delay</th>
<th>Minimum Delay</th>
<th>No. Sessions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable 18 sec.</td>
<td>1.5 sec.</td>
<td>10</td>
</tr>
<tr>
<td>Fixed 18 sec.</td>
<td>18.0 sec.</td>
<td>17</td>
</tr>
<tr>
<td>Variable 18 sec.</td>
<td>1.5 sec.</td>
<td>13</td>
</tr>
<tr>
<td>Variable 18 sec.</td>
<td>6.0 sec.</td>
<td>19</td>
</tr>
<tr>
<td>Fixed 12.5 sec.</td>
<td>12.5 sec.</td>
<td>10</td>
</tr>
<tr>
<td>Variable 36 sec.</td>
<td>1.5 sec.</td>
<td>17</td>
</tr>
<tr>
<td>Variable 18 sec.</td>
<td>6.0 sec.</td>
<td>36</td>
</tr>
<tr>
<td>Variable 18 sec.</td>
<td>1.5 sec.</td>
<td>20</td>
</tr>
<tr>
<td>Fixed 12.5 sec.</td>
<td>12.5 sec.</td>
<td>15</td>
</tr>
<tr>
<td>Variable 36 sec.</td>
<td>6.0 sec.</td>
<td>23</td>
</tr>
</tbody>
</table>

### Rat D4

<table>
<thead>
<tr>
<th>Second-Link Delay</th>
<th>Minimum Delay</th>
<th>No. Sessions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed 18 sec.</td>
<td>18.0 sec.</td>
<td>14</td>
</tr>
<tr>
<td>Variable 18 sec.</td>
<td>1.5 sec.</td>
<td>12</td>
</tr>
<tr>
<td>Variable 18 sec.</td>
<td>6.0 sec.</td>
<td>18</td>
</tr>
<tr>
<td>Variable 18 sec.</td>
<td>1.5 sec.</td>
<td>10</td>
</tr>
<tr>
<td>Variable 36 sec.</td>
<td>6.0 sec.</td>
<td>26</td>
</tr>
<tr>
<td>Variable 36 sec.</td>
<td>1.5 sec.</td>
<td>32</td>
</tr>
<tr>
<td>Variable 36 sec.</td>
<td>6.0 sec.</td>
<td>22</td>
</tr>
<tr>
<td>Variable 36 sec.</td>
<td>1.5 sec.</td>
<td>18</td>
</tr>
<tr>
<td>Fixed 18 sec.</td>
<td>18.0 sec.</td>
<td>15</td>
</tr>
<tr>
<td>Mixed 36 sec.</td>
<td>1.5 sec.</td>
<td>10</td>
</tr>
<tr>
<td>Mixed 36 sec.</td>
<td>6.0 sec.</td>
<td>15</td>
</tr>
<tr>
<td>Mixed 36 sec.</td>
<td>1.5 sec.</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 2. The individual delay intervals, in seconds, which comprised each of the variable delay schedules.
VAR 18, MIN. 6

5.8, 6.1, 6.4, 6.6, 7.0, 7.2, 7.3, 7.8, 8.2, 8.8, 8.8, 9.1, 9.2,
11.0, 11.3, 11.3, 11.7, 11.8, 12.9, 14.7, 15.4, 16.8, 19.0, 21.0,
23.0, 25.4, 32.2, 38.0, 38.6, 44.5, 53.6, 59.9

VAR 18, MIN. 1.5

1.5, 1.5, 2.0, 2.5, 3.3, 4.0, 4.4, 5.1, 6.1, 8.0, 8.5, 9.4, 9.5,
11.7, 12.1, 13.3, 14.1, 14.8, 16.6, 17.5, 18.0, 19.3, 20.0, 24.4,
27.9, 30.0, 31.6, 35.0, 38.6, 45.8, 53.7, 60.0

VAR 36, MIN. 6

5.9, 6.0, 6.2, 6.5, 7.4, 7.7, 8.3, 8.9, 9.6, 11.0, 12.3, 15.4, 18.3,
25.9, 26.8, 30.0, 33.0, 36.0, 40.7, 44.2, 44.3, 48.1, 54.0, 60.7,
65.0, 70.9, 75.6, 84.0, 88.0, 91.2, 99.8, 15.3

VAR 36, MIN. 1.5

1.5, 1.5, 2.0, 2.5, 3.3, 4.0, 4.4, 5.1, 6.1, 8.0, 12.5, 16.0, 19.5,
25.2, 27.4, 32.6, 37.6, 43.0, 45.8, 47.1, 49.0, 50.2, 54.6, 62.3,
64.9, 72.0, 75.6, 84.0, 88.0, 91.2, 99.8, 15.3

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they were presented to the subjects. The protective 10 sec. DRO contingency was in effect for all conditions. The only stability criteria were: at least 10 sessions per condition and no evidence of a systematic trend in the data. All sessions lasted for 100 reinforcements.

In designating the schedules, the initial-link FR 1 has been dropped. Thus, VAR 36 (1.5) stands for the experimental condition in which each response initiated one of 31 terminal-link delay intervals whose average length was 36 sec. The number in parentheses indicates that the minimum delay was 1.5 sec. In the MIX schedules, each response produced either of two terminal-link delay intervals whose average was 36 sec. In the MIX 36 (1.5) schedule, the two intervals were 1.5 sec. and 70.5 sec; in MIX 36 (6) the intervals were 6 sec. and 66 sec. The sequence of short (S) and long (L) intervals in the MIX schedules was SLSSLLSSLLL. Only subject D4 was exposed to the MIX schedules.
RESULTS

Characteristics of the Schedules

Because the method of scheduling reinforcements in the terminal link was unorthodox, a few comments on the training procedure and the adequacy of stimulus control in the second link seem to be in order. It should be recalled that magazine training was followed by a non-contingent phase in which 5 sec. presentations of the delay stimulus, each presentation terminating with 3.8 sec. access to the dipper cup, occurred at irregular intervals. Both subjects quickly acquired the response of promptly approaching the dipper at the onset of the delay stimulus. The subjects' behavior in front of the dipper opening during the delay period was animated, consisting chiefly of rapid head movements and "anticipatory" licking in and around the dipper opening. When the length of the delay was increased, all of these activities persisted, but the subjects also began to exhibit more extensive stereotyped movements. During longer delays subjects would occasionally turn towards the operandum. Errors, however, seldom ever occurred. In rare instances subjects would wander from the intelligence panel during a delay interval. The predominant impression was that both subjects were engaging in highly stereotyped, superstitious behavior during delay intervals.

Shaping of the bar press by means of contingent presentations of the 5 sec. delay stimulus proceeded quickly, possibly with greater ease than conventional shaping with immediate reinforcement.
It may be that the tendency to make abortive approaches to the dipper during shaping was attenuated by this procedure, facilitating acquisition of the bar press. No data were obtained which had any bearing on this conjecture.

**Effects of Terminal-Link Schedules**

The dependent variable was the length (in seconds) of the post-reinforcement pause (PRP), which was assumed to be functionally related to the conditioned reinforcing effectiveness of the terminal-link stimulus. All PRPs were recorded on an event tape and measured to the nearest .5 sec. Data from each daily session were summarized in three ways: (1) mean PRP, (2) median PRP, (3) frequency distribution of PRPs in 2 sec. class intervals. Mean and median PRPs generally covaried, and, unless otherwise noted, will be discussed conjointly. The two subjects were not exposed to identical conditions, and analysis of D2's performance was complicated by a generalized reduction in the sensitivity of the dependent measure midway through the study. Consequently, each subject's performance will be analyzed separately. Subject D4 is considered first.

Figure 9 summarizes the results obtained from subject D4. Experimental conditions are listed on the abscissa in the order in which they were introduced. The abbreviations FIX, VAR and MIX apply, respectively, to experimental conditions in which delays were scheduled for fixed, variable and mixed durations. Variable schedules comprised approximately 30 delay intervals (see Table 1); mixed schedules consisted of only two intervals. Numbers immediately
Figure 9. Mean and median PRPs for each of seven experimental conditions. Bars are mean (upper figure) and median (lower figure) PRPs for the last five sessions of each experimental condition. Filled circles are mean and median PRPs for previous 5 sessions in each condition. See text for further explanation.
D4 MEANS

MEDIANS

EXPERIMENTAL CONDITIONS

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below schedule abbreviations are the mean delay intervals (in seconds) of the respective schedules. Numbers in parentheses identify the minimum delays associated with each condition. For further clarification, schedules with 1.5 sec. minimum delays are represented by shaded bars. The bars in the upper figure show the mean PRPs over the last five sessions of each experimental condition; bars in the lower figure are median PRPs over the last five sessions of the same conditions. Filled circles are mean (upper figure) and median (lower figure) PRPs for the previous five sessions of each condition.

The results for this subject are consistent with the principle, first enunciated by Herrnstein (1964b), that subjects tend to average component intervals in a manner which gives greater weight to shorter intervals. Variable and mixed schedules with minimum intervals of 1.5 sec. maintained shorter pauses than the FIX 18 schedule. This was true when the mean delay in the variable schedule was 36 sec.—twice that of the FIX 18 schedule. Variable and mixed schedules with 1.5 sec. minimum delays were superior to variable and mixed schedules which provided the same rate of reinforcement, but with minimum delays of 6 sec. Also, of the schedules providing reinforcement at 36 sec. mean intervals, the mixed schedule with the 1.5 sec. minimum interval was the most effective. This schedule, of course, contained the highest proportion of 1.5 sec. intervals.

Figure 10 presents frequency distributions of PRPs, in selected class interval sizes, for each of the seven conditions to which D4
Figure 10. Relative frequencies of PRPs falling in selected class intervals over the last five sessions of each experimental condition. See text for further explanation.
was exposed. Relative frequencies were computed for the last 5 sessions of each experimental condition. Distributions for VAR 36 (1.5) and VAR 36 (6) are means of two determinations for each of these conditions. The two determinations for FIX 18 are plotted separately.

Comparisons of the three pairs of schedules which differed only with respect to the length of the minimum interval (1.5 sec. versus 6 sec.) reveal a common effect: the major change engendered by the elimination of short (1.5 sec.) delays was a sizeable reduction in the proportion of PRPs falling in the lowest class intervals. In the case of the VAR 18 schedules, approximately 66% of the PRPs in the lowest class interval shifted to the next highest interval when the schedule was changed from a 1.5 sec. to a 6 sec. minimum interval. Otherwise the effects of the two schedules were quite similar. In the VAR 36 schedules, the major shift was to PRPs between 7.75 and 19.75 sec; hence, the greater absolute difference between this pair of schedules than between the two VAR 18 schedules. The most pronounced difference between any pair of equivalent schedules was produced by the MIX schedules. Both VAR 18 schedules were superior to any other conditions. The FIX 18 terminal link produced the weakest conditioned reinforcing effect, both in terms of the proportion of PRPs in the lowest two class intervals and the proportion of long pauses.

Subject D2's performance is summarized in Fig. 11. Experimental conditions are listed in the order in which they were introduced. The results of the first six conditions were consistent with those
Figure 11. Mean and median PRPs for each of five experimental conditions. Bars are mean (upper figure) and median (lower figure) PRPs for the last five sessions of each condition. Filled circles are mean and median PRPs for previous five sessions. See text for further explanation.
obtained from subject D4. There was a pronounced effect due to increasing the minimum interval from 1.5 to 6 sec. A fixed 12 sec. delay also produced longer pauses than VAR 18 (1.5). The FIX 18 schedule was abandoned because prolonged pauses of several minutes' duration frequently occurred in the latter portions of the sessions. Following the introduction of VAR 36 (1.5) there was a generalized reduction in pause length, as evidenced by the failure to recover original data points. The cause of this change was not determined, but it appears to have occurred during the VAR 36 (1.5) condition. This schedule was originally ineffective, resulting in early termination of seven of the first ten sessions because the subject stopped responding. The condition would have been abandoned at about this point, but the subject abruptly accommodated to the schedule with greatly reduced PRPs. Subsequently, differences among conditions were very small, but always in the expected direction. The discrepancy between mean and median PRPs in the VAR 36 (6) schedule resulted from a tendency for long pauses to develop late in each session. Figure 12 depicts relative frequencies of PRPs in selected class intervals for each of the experimental conditions.
Figure 12. Relative frequencies of PRPs falling in selected class intervals over the last five sessions of each experimental condition. Roman numerals I and II refer to the first and second determinations for each of the designated conditions. See text for further explanation.
DISCUSSION

The present study showed that the strength of a conditioned reinforcing stimulus may be enhanced by a relatively small decrease in the minimum time between its onset and delivery of a primary reinforcer. The amount by which such an operation strengthens the conditioned reinforcer is related to the frequency of short intervals in the schedule. Thus, in the variable schedules, the minimum intervals constituted a comparatively small proportion of the delay intervals comprising the schedule, and reducing the minimum time to reinforcement resulted in a relatively small increase in the conditioned reinforcing strength of the terminal-link stimulus. In the two-component mixed schedules, the minimum intervals constituted fifty per-cent of the total, and the effect of reducing the minimum time to reinforcement was considerably greater. Frequency of reinforcement, per se, was not an important factor, as evidenced by the comparative ineffectiveness of fixed terminal-link schedules.

The study demonstrated that the PRP is functionally similar to the two more common measures of conditioned reinforcer strength, viz. initial-link VI response rate and relative rate of response in concurrent initial-link VI schedules. The results were not accurately predicted by the harmonic transformation on the terminal link intervals for subject D4: the VAR 18 (6) schedule maintained shorter pauses than the VAR 36 (1.5) and the MIX 36 (1.5) schedules, although the harmonic means of the latter two schedules (8.2 sec. and 2.9 sec.) were lower than that of the VAR 18 (6) schedule, which
was 11.1 sec. The harmonic mean of the MIX 36 (6) schedule was also
11.1, but its terminal-link conditioned reinforcing strength was
considerably less than that of the VAR 18 (6) schedule. Comparisons
of this sort are not meaningful for D2 because of the locked rate
which developed midway through the study.

No attempt was made to discover a transformation which predicted
D4's results. There are a number of reasons militating against such
an effort, primarily that the schedule employed in this study doesn't
seem to offer any advantages over the more usual procedures employed
in studies of conditioned reinforcement. Consequently, there is
little justification for embarking upon the lengthy series of
studies which would be required to establish the appropriate
transformation. Such efforts should continue to be expended in the
much more advanced area of concurrent chain schedules. As pointed
out earlier in this paper, attempts to quantify preference have
produced results which are promising but also very limited in
generality.

The present study should not be taken as a confirmation of the
hypothesized gradient of delay, which predicts a negatively
accelerated reduction in the strength of a conditioned reinforcer
as a function of successive equal increases in the time between its
onset and primary reinforcement (see Fig. 6). For one thing, the
study was designed primarily to assess the effects of changing the
minimum time to reinforcement—not to establish a gradient of delay.
The correct procedure for determining the shape of the gradient
would be to begin with immediate reinforcement (FR 1), followed by a
series of small, equal increases in the delay interval. Intuitively, it does not seem that this strategy would yield a function like that of Fig. 6. Rather, it seems probable that, near the lower limit of the delay interval (FR 1), small increases in time to reinforcement would have a negligible effect upon the PRP. That is, the PRP may have a threshold—a delay of reinforcement below which it is a relatively insensitive dependent measure. If this were true, it might still be possible to generate a negatively accelerated increase in the PRP by employing a sufficiently large increase in the delay interval; but the value of such a demonstration would be questionable.

In the present experiment, problems of this sort were precluded by assessing the effects of the minimum interval in the context of variable and mixed schedules which generated substantial PRPs.

The above considerations are actually part of a much broader methodological problem faced by those who are searching for quantitative laws of conditioned reinforcement. This problem is revealed in a lack of correspondence among experiments which differ in one or more respects. For example, the study cited on page 11 of this paper (Fantino, 1969) demonstrated that the length of the equal, concurrent initial-link VI schedules was an important factor in the degree of preference shown for the shorter of two terminal-link schedules. Recently, Duncan and Fantino (1970) employed concurrent chains to study preference for periodic terminal-link schedules. Several pairs of terminal-link fixed-ratio schedules were compared in one of their studies. Each pair of ratio schedules differed by the same amount: FR 10 vs. FR 20, FR 20 vs. FR 30, and
FR 50 vs. FR 60. The results were incompatible with previous formulations of choice behavior which assigned increasing weight to progressively shorter intervals. Instead, preference for the shorter member increased dramatically with increases in the size of the terminal-link ratio schedules. Preference for FR 50 over FR 60 averaged 95% for 5 subjects, preference for FR 30 over FR 20 was 73%, and preference for FR 10 vs. FR 20 was 68%. These results suggest that the decrement in conditioned reinforcer strength represented by a gradient of delay would be positively accelerated over part of its range. Applied to the present study, Duncan and Fantino's findings would predict that increasing the minimum delay interval from 6 to 10.5 sec. would generate a larger increase in the PRP than that produced by increasing the minimum delay from 1.5 to 6 sec.

In spite of the new difficulties and complexities revealed by their findings, Duncan and Fantino (1970, p. 84) were optimistic that "the development of a quantitative description of choice behavior having adequate generality may be close at hand." Should subsequent events confirm their optimism, it is highly questionable that the formulation would be generally applicable to the larger problem of conditioned reinforcer effectiveness. The study by Stubbs, for example, which is cited on page 25, supports the gradient of delay in the form proposed in this paper. A study by Chung and Herrnstein (1967) was also consistent with the gradient of delay. They found that preference for the shorter of two fixed delays of reinforcement matched the relative harmonic mean of the delay intervals. It seems

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likely that there are many gradients of delay, that the conditioned
reinforcing strength of a stimulus interacts with the characteris-
tics of the procedure used to assess its effectiveness.

None of the foregoing criticisms and reservations were intended
to disparage the value of attempts at precise quantification of
preference in concurrent chain schedules. On the contrary, beginning
with Autor's (1960) original study, the numerous attempts to
discover the correct transformation on terminal-link intervals have
produced an abundance of new and important data, have clarified many
procedural problems, and have doubtless brought us much closer to
a general, comprehensive understanding of choice behavior and
conditioned reinforcement.
1. Differential reinforcement of other behavior (DRO) is a procedure for reducing the frequency of a selected response by scheduling reinforcement every \( t \) sec. in the absence of a response. Each time the response occurs, reinforcement is delayed by \( t \) sec. Therefore, reinforcement may never follow the response by less than \( t \) sec. The schedule is designated by appending the value of \( t \). For instance, when \( t \) is 10 sec., the schedule is written DRO 10 sec.

2. "Unhappily, the task of discovering the correct principle of transformation, while certainly worthwhile, seems forbidding" (Herrnstein, 1964b, p. 247).

3. Killeen (1968) pointed out that there was no necessary inconsistency between his results and the results of experiments which reported matching to some other scale of reinforcement frequency (e.g. arithmetic rate of reinforcement). As long as there is a proportionality between the intervals composing the terminal links, several methods of computing relative reinforcement rate will yield equivalent results.

4. In addition to the empirical importance of the suggested study, it would be of theoretical interest to see if the results could be related to Kamin's (1965) experiments on traced conditioning of the conditioned emotional response (CER). Kamin found no difference between the effects of a trace versus a delayed conditioned warning stimulus (CS) when the onset of both stimuli was favorably close to the US (shock). At relatively long intervals, the delayed CS tended to be more effective. In another experiment, Kamin employed a "long" CS-US interval of constant duration and manipulated the length of the trace between CS termination and US onset. Maximum suppression occurred when CS termination was contiguous with the US (delayed conditioning). A traced interval of only 0.5 sec. produced a considerable reduction in the suppression ratio. The additional reduction produced by a 15 sec. trace interval was comparatively small, and further increases in the trace interval had a negligible effect. The negatively accelerated reduction of the suppression ratio suggests that the gradient of delay may be applicable to the CER.

5. Killeen was actually considering the possibility that the results of his study (described on p. 31) could be interpreted in terms of delayed reinforcement, without the necessity of appealing to any strengthening properties of the terminal-link stimuli. The present discussion assumes, on manifestly sufficient evidence.
(Kelleher and Gollub, 1962), that the presentation of a terminal-link stimulus is a positive conditioned reinforcer under many conditions. But questions are raised which seriously impugn the validity of interpretations based on rate of primary reinforcement in the terminal link.
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