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HOW TO SCHEDULE REINFORCERS: NAT SCHOENFELD AND THE T-τ SYSTEM

CÓMO PROGRAMAR REFORZADORES: NAT SCHOENFELD Y EL SISTEMA T-τ

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ABSTRACT

The temporal system of reinforcement schedules devised by Professor W. N. (Nat) Schoenfeld permitted the study of continuous relations among a wide variety of schedule effects. In addition, the system clearly separated the schedule rules from the behavior being studied. Parametric exploration of purely temporal variables generated performances characteristic of ratio schedules as well as traditional interval schedules. The system was expanded to incorporate the intrusion of neutral or aversive as well as reinforcing stimuli into the behavioral stream, and thus encompassed a wide variety of traditionally disparate research topics, including Pavlovian relations between stimuli and reinforcers.

Key words: contingencies of reinforcement, t-τ system, interval schedules, ratio schedules, intruded stimuli, behavioral stream.

RESUMEN

El sistema temporal de programas de reforzamiento diseñado por el profesor W. N. (Nat) Schoenfeld, permitió el estudio de relaciones continuas entre una gran variedad de efectos producidos por los programas de reforzamiento. Además, el sistema claramente separó las reglas de programación de los reforzadores, de la conducta bajo estudio. La exploración paramétrica de variables puramente temporales, generó las ejecuciones características de los programas de razón, así como las de los programas tradicionales de intervalo. El sistema se expandió para incorporar en el flujo conductual la intrusión de estímulos neutrales o aversivos, así como de estímulos reforzantes y, en

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consecuencia, abarcó una gran variedad de tópicos de investigación tradicionalmente diferentes, incluyéndo las relaciones Pavlovianas entre estímulos y reforzadores.

Palabras clave: contingencias de reforzamiento, sistemas t-τ, programas de intervalo, programas de razón, intrusión de estímulos, flujo conductual.

It is hard to imagine a more barren experimental situation than a 30-cm cube with a small back-lighted key on one wall, a dim light overhead, a square opening with a tray of food behind it, and a moderately hungry white pigeon -a retired breeder from a restaurant supply house- imprisoned within. Not much happens: From time to time, a counter registers pecks at the lighted key, and from time to time, control apparatus moves the food tray up so the pigeon can eat from it. A cumulative recorder keeps track of these events in real time, and at the end of the typical one-hour session, the total number of pecks and food presentations are recorded.

Despite the remoteness of this barren environment from the natural life of a pigeon (or, some would say, because of it), the temporal patterns of pecking depicted by cumulative records vary widely and reliably in relation to the experimenter's rules for presenting food, known collectively as schedules of reinforcement. Moreover, when a parameter of a given schedule is varied systematically across several experimental conditions, orderly functions relating average response rates to the value of that parameter are often obtained. To Professor W. N. (Nat) Schoenfeld, the rich and varied data that emerged from the pigeon's chamber were fundamental to the science of behavior, and he worked to systematize them during much of his professional career.

Ferster and Skinner (1957) described a host of rules and combinations of rules for presenting food to generate schedules called adjusting, alternative, chained, concurrent, conjunctive, differential reinforcement of high or low response rates, fixed interval, fixed ratio, interlocking, interpolated, mixed, multiple, tandem, variable interval, and variable ratio. They tried to explain the dizzying array of rates and patterns of responding generated by these schedules by invoking temporal and response-based cues -what the pigeon was feeling and doing- at the moment of reinforcement, when food was presented. However, some of these schedules included the pigeon's behavior in their specification (for example, number of pecks emitted since a previous reinforcer, or length of time elapsed since a previous peck), thus confounding the independent and dependent variables.

Nat Schoenfeld took an utterly different approach. Working with Bill Cumming and Eliot Hearst at Columbia in the mid-1950s, he attempted simultaneously to make the schedule a pure independent variable, uncontaminated by the behavior generated by the schedule, and to provide a rational system within which schedule effects could be seen as continuously related. In particular, Nat disliked the notion that ratio schedules, which delivered food after some number of pecks, and interval schedules, which delivered food for the first peck after some time had elapsed, were dichotomous categories in much the same way as operant and respondent conditioning appeared to be. He wanted schedule research to be as close as possible to the precise temporal control of events in Pavlovian conditioning paradigms, and he particularly resented the fact that on ratio schedules, the subject, and not the experimenter, controlled the time at which reinforcers were presented. The *t* system was his first step, intended initially to demonstrate that ratio-like behavior could be generated by purely temporal scheduling rules coupled with the operant contingency between behavior and its consequences. In Nat's words, the system "reduced the involvement of the experimental subject as a partner in the experiment to the bare minimum."

The *t* system defined two temporal intervals, t^D and t^Δ, that were fixed in duration and alternated regularly. Pecks during t^Δ were never reinforced, and only the first peck in t^D was reinforced. The ratio of t^D to total cycle length, $t^D + t^\Delta$, was termed T.The system's operation is illustrated in Figure 1. If no pecks occurred during t^D, as in the second cycle of the illustration, the cycle continued and the reinforcer that had been available during t^D was missed. Thus, if t^D was short, the pigeon would miss reinforcers unless it responded at a high rate; and if t^Δ was relatively long, the pigeon would usually pause after each reinforcer because no further reinforcers were available until t^Δ elapsed. The resulting pattern of responding -a pause followed by rapid pecking until a reinforcer was obtained- was strikingly like the pattern generated by a conventional fixed-ratio schedule, except that the number of pecks per reinforcer was not constrained to be constant.

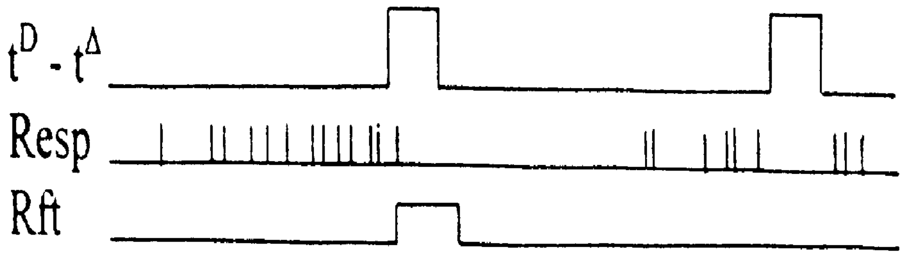
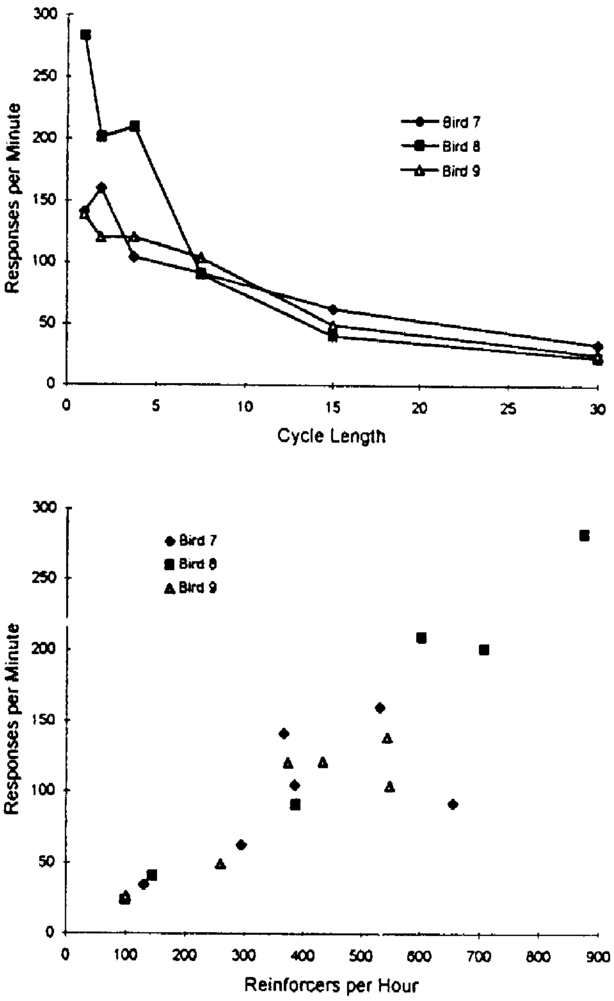


Figure 1. An illustration of the operation of a t^D - t^Δ schedule. The top line shows the regular alternation of t^D and t^Δ, the second line shows responses, and the third line shows the presentation of the reinforcer. Note that if a response fails to occur during t^D, there is no reinforcer, as in the second cycle.

Schoenfeld, Cumming, and Hearst (1956) described the system in detail and presented a set of cumulative records from an experiment in which T was held constant at 0.05 while cycle length was varied from 30 s down to 0.94 s. A complete set of quantitative data from this experiment was reported by Schoenfeld and Cumming (1957), and is replotted in the upper panel of Figure 2. There is a striking increase in response rate for each pigeon as cycle length decreases -clear evidence of the power of their schedule variable. The lower panel of Figure 2 also shows that as the obtained rates of reinforcement increased, response rate increased in a roughly linear fashion.

Current molar approaches to reinforcement schedules might interpret the powerful effect of decreasing cycle length in relation to increases in obtained rate of reinforcement (e.g., Herrnstein, 1970), acting in concert with molar feedback functions of the sort sketched in Figure 3. These feedback functions reverse the roles of the axes in the lower panel of Figure 2 in order to show how obtained reinforcer rate depends on average response rate under a given schedule (Baum, 1973). For a conventional interval schedule, the feedback function rises rapidly to an asymptote at the maximum reinforcer rate the schedule can provide; further increases in response rate have no effect on reinforcer rate. As suggested in Figure 3, the feedback function for a 30-s cycle length is interval-like. However, as cycle length becomes short and approaches the minimum time between responses, the feedback function becomes more like that for a variable-ratio schedule: Reinforcer rate increases linearly with response rate. For the average data of Figure 2, one reinforcer is obtained for every 20 responses when cycle length is 0.94 s. Accordingly, the function for 0.94 s sketched in Figure 3 is the same as for a variable-ratio 20 schedule, which provides differential reinforcement for rapid responding, unlike the interval function for a 30-s cycle length.

A more molecular approach to schedule performance would emphasize differential reinforcement of interresponse times. If the pigeon responds uniformly throughout the interval between reinforcers, responses are reinforced with increasing probability, as interresponse time increases, up to 0.05 (the value of T). Therefore, the probability of reinforcement for short interresponse times increases as cycle length decreases. The relation between interresponse time and reinforcer probability is sketched for cycle lengths of 0.94 s and 30 s in Figure 4. There is some debate as to whether differential reinforcement of average response rate as portrayed in Figure 3, or differential reinforcement of interresponse times as portrayed in Figure 4, are crucial for the determination of schedule performance (e.g., Baum, 1973; Vaughan & Miller, 1984). But I think Nat would say that these are *theories* concerning the effective variable -and why do we need such theories when we have identified an effective variable and manipulated it directly?



from Schoenfeld & Cumming (1957)

Figure 2. The upper panel shows the effect of varying cycle length of a $t^D - t^\Delta$ schedule with $\bar{T} = 0.05$ on response rates of three pigeons. The lower panel shows the same response rates as a function of obtained reinforcers per hour.

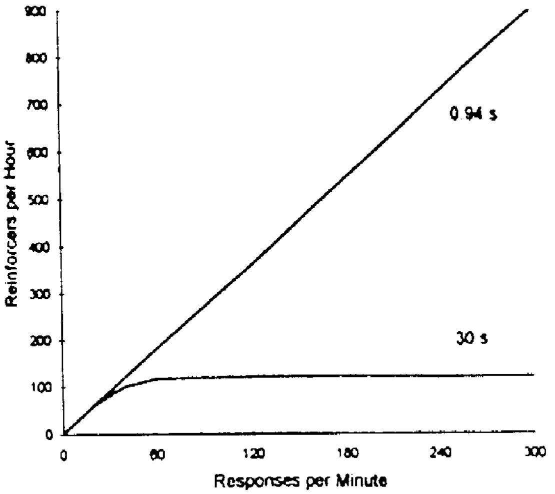


Figure 3. Molar feedback functions for t^D - t^Δ schedules with cycle lengths of 0.94 s and 30 s. See text for explanation.

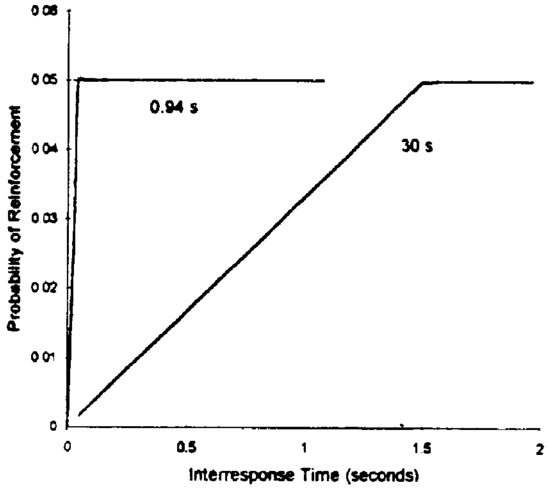


Figure 4. Probability of reinforcement for responses ending interresponse times of various lengths for t^D - t^Δ schedules with cycle lengths of 0.94 s and 30 s. See text for explanation.

Schoenfeld and Cumming (1960) published a summary of research using the *t* system to date, including dissertation research by Eliot Hearst, Carl Brandauer, and Bob Clark. The main figure from that article is reproduced here as Figure 5. It is an elegant example of systematic, parametric exploration of an empirically defined domain, and is noteworthy for the ranges of the variables explored. For example, cycle length varied between studies from .001 s to 30 min -a range of more than six log units. Correspondingly, average response rates maintained by different combinations of t^D and t^Δ ranged from about 5 pecks per min to about 200 pecks per min- essentially the entire dynamic range for sustained key-pecking.

Nat and Bill were especially concerned about the stability of responding under extended exposure to each schedule, so each data point was based on average performance for each individual bird in a set of sessions that met a stability criterion. Later, lab procedure changed to conducting a constant number of sessions per condition: Nat never liked the idea of allowing the subject to tell the experimenter when to end a condition, so changing conditions after a fixed number of sessions was another way to "reduce the involvement of the subject to a bare minimum."

The inset in Figure 5 suggests some domains of the t^D, t^Δ continuum that correspond to conventional schedules. For example, region A corresponds to fixed interval, region B to continuous reinforcement, and region C to extinction. Region E corresponds to random (or variable) ratio, because t^D and t^Δ are alternating so rapidly that the probability of reinforcement is essentially constant for each response; and region D, with short t^D and long t^Δ, produced ratio-like behavior: a post-reinforcement pause followed by sustained high-rate responding until the next reinforcer occurred. Thus, a wide array of traditional schedules and their effects could be seen as continuously related.

The question of whether the *t* system "really" generated ratio-like performance was a hot topic on the second floor of Schermerhorn Extension, where the Columbia animal labs were located. For example, Bob Berryman argued that "real" ratio schedules were like chopping down a tree, where each whack with the axe moved the woodsman progressively closer to the reinforcer of a felled tree, whereas the "ratio-like" *t*-system performance was more like banging on the tree until a blow happened to coincide with a time window and set off a bomb that blew the tree over. Clearly, the woodsman would chop differently under these two conditions, so we would argue about response topography and how it might change within a conventional fixed ratio and whether it might change differently within a cycle of a *t* schedule. The question remains unresolved, but it is also beside the point because it assumes a dichotomy of interval vs. ratio schedules, and Nat always urged us to ignore seemingly dichotomous categories and identify the continua that encompassed them.

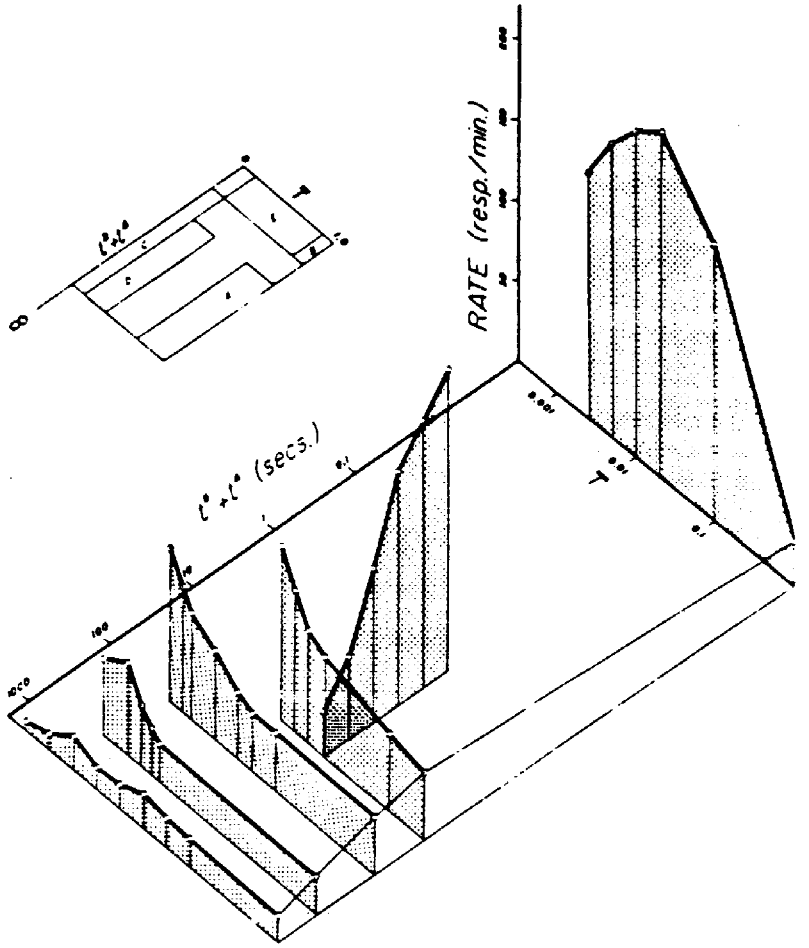


Figure 5. Summary of the effects of various t^D - t^Δ schedules on response rate. The inset shows various regions of the t^D - t^Δ schedule continuum that correspond to traditionally defined schedules, as described in the text. From Schoenfeld and Cumming (1960); reprinted from Schoenfeld and Cole (1972).

Quite apart from the ratio vs. interval problem, Nat was not satisfied with the *t* system on logical grounds. In particular, he was uncomfortable with the restriction that only the first response in t^D was eligible for reinforcement, because "first," like "tenth" or "twentieth," implies a count-based contamination of the otherwise pure temporal system. Schoenfeld and Cumming (1960) proposed a solution: Let t^D and t^Δ alternate more rapidly than the pigeon could possibly peck -say, every .001 s- and then reinforce every peck that coincided with t^D. Under this arrangement, each peck has a constant probability of reinforcement, independent of time since the previous peck, and no aspect of behavior figures into the specification of the schedule. A period of high-rate alternation of t^D and t^Δ, termed τ^D, could then alternate with a period termed τ^Δ in which t^D was zero (or some smaller value than in τ^D), to establish a fixed superordinate cycle of reinforcement availability. The operation of the system is illustrated in Figure 6. Nat recognized that the τ system was the first step of a potentially infinite regress of cycles within cycles within cycles, but the first step was sufficient to achieve a purely temporal system of reinforcement schedules.

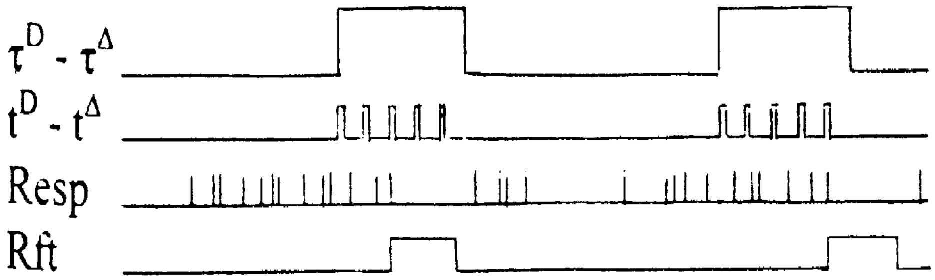


Figure 6. An illustration of the operation of a τ^D - τ^Δ schedule. The top line shows the regular alternation of periods of τ^D, during which a t^D - t^Δ schedule operates as in Figure 1 but with a short cycle length so that the probability of reinforcement is constant with respect to interresponse times, and periods of τ^Δ, during which reinforcement is not available.

The τ system produced some strikingly orderly results. In the second experiment of a comprehensive doctoral dissertation, Snapper (1962) arranged a τ cycle of 600 s with τ^D constant at 120 s while the reinforcement probability in τ^D varied across successive conditions. Average data are shown in Figure 7. Clearly, the τ cycle exerts powerful control: A high response rate during τ^D gives way to a much lower rate early in τ^Δ, followed by a steady increase, reminiscent of a fixed-interval "scallop," as the cycle progresses and the next period of τ^D approaches. Moreover, the rapidity and magnitude of the reduction in responding after τ^D increases with the probability of reinforcement within τ^D, suggesting that the τ system provides a method for studying the discriminability of the transition from intermittent reinforcement to extinction.

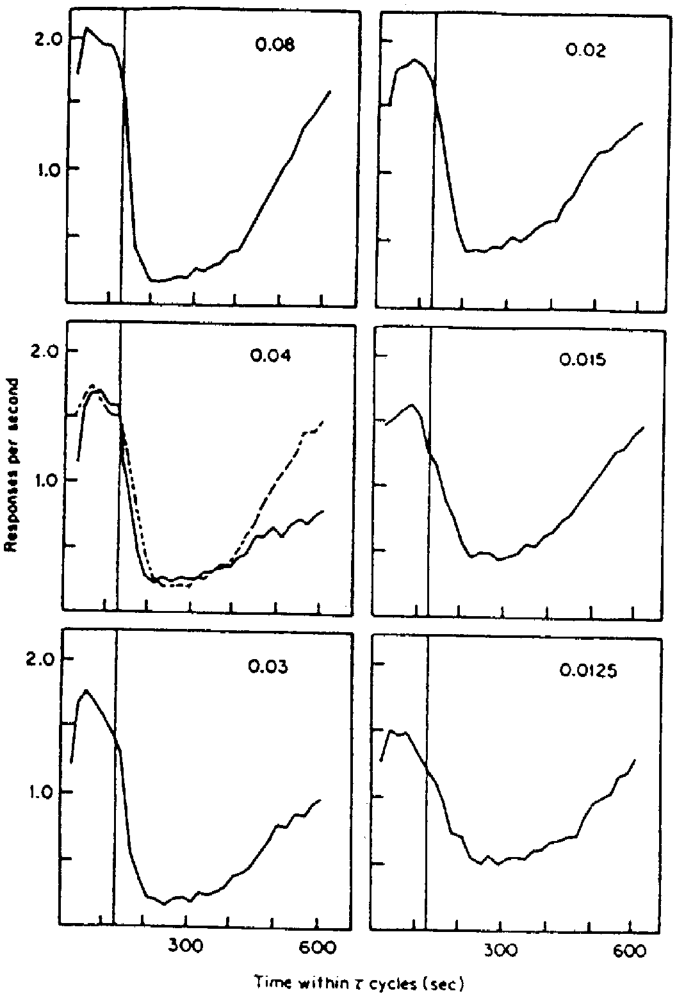


Figure 7. Average response rate throughout cycles of τ^D-τ^Δ schedules with cycle length equal to 600 s and τ^D equal to 120 s. The value of $\bar{T}$ during τ^D, which is equivalent to the probability of reinforcement, is indicated in each panel; the dashed lines in the middle left-hand panel represent replication data. From Snapper (1962); reprinted from Schoenfeld and Cole (1972).

Nat's preoccupation with temporal scheduling led to a new paradigm: The intrusion of stimuli other than food reinforcers into the pattern or stream of behavior occurring within the temporal cycle of food presentation. For example, Farmer and Schoenfeld (1966) explored the effects of an intruded "neutral" stimulus -a 6-s change in the key light- at various points in a fixed-interval 1-min schedule, which they termed "an irreducibly primitive paradigm" for the experimental analysis of behavior. Rates of responding before, during, and after the intruded stimulus were modulated in ways suggesting that the light functioned as a discriminative cue, a conditioned reinforcer, or an inhibitory stimulus, depending on its temporal placement. The fact that continuous variation in time could generate these seemingly discrete stimulus functions clearly diminished their utility for behavior theory. Moreover, the intruded-stimulus paradigm made direct contact with Pavlovian delay, trace, and inhibitory conditioning -except that the US, food, was response-contingent as in operant conditioning.

With the advent of the intruded-stimulus paradigm, the notion of the behavioral stream and the role of "contingency" became central to Nat's thinking. Schoenfeld and Farmer (1970) noted that the measured response, R, always occurs in the context of other, undefined behavior, $\not{R}$, where the continuous flow of R and $\not{R}$ define the stream of behavior. They pointed out that "The term *contingency* is often used to mean that a reinforcing stimulus follows a response more or less immediately. This is not satisfactory, of course, because in this loose sense noncontingent reinforcement is never possible ... a reinforcer must necessarily, since behavior is continuous, follow *some* response on some schedule with some variable delay ... The term contingency needs a more precise definition, and this may be: that the distribution in time of responses determines the distribution in time of reinforcements; while, by the opposed token, noncontingency means that the temporal distribution of reinforcements is not determined by the temporal distribution of responses" (1970, p. 221). It would be difficult to improve on this comprehensive definition of contingency, which is entirely in keeping with molar analyses of schedule performance (e.g., Baum, 1973).

A temporal schedule system permits the experimenter to present positive reinforcers, aversive events, or neutral stimuli contingent on discrete occurrences of R, contingent on some duration of $\not{R}$ (as in research on "avoidance"), or independently of either class as in the "intruded stimulus" paradigm. By integrating avoidance and response-independent schedules with schedules of positive reinforcement, Nat broadened the domain of temporal event scheduling to incorporate a host of traditionally separate topics. The program of research that he derived from this approach and carried out with his students, summarized by Schoenfeld and Cole (1972), is truly impressive.

Unfortunately, Nat's program and the temporal system on which it is based are little known or appreciated outside the group of students and colleagues who worked with him. For better or worse, schedules research has been dominated for nearly 30 years by matching-law approaches to single and concurrent schedules, often characterized as the study of "choice." I once discussed these developments with Nat while serving on a doctoral committee for one of his students, and will never forget his reaction. "Choice," he said, and paused as if deep in thought. "What's that all about? Does the retina choose? Then why does the pigeon choose?" I laughed, but of course the question was serious -and no one has more effectively examined what the pigeon does in its barren chamber as a direct, unmediated consequence of the experimentally controlled stimulus input than Nat himself.

I'll conclude with Nat's own words: "The τ system may be coextensive with the area of reinforcement schedules as now understood, and perhaps with all schedules for projecting any stimulus into any segment of the behavior stream. It leaves to be considered, at a different conceptual level, the place of Pavlovian and operant conditioning paradigms within comprehensive behavior theory" (Schoenfeld & Cole, 1972, p.16). The final sentence is deliberately enigmatic -a classic Schoenfeld challenge to make us question his position, think for ourselves, and do good science.

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