COMPARISONS BETWEEN ONE-KEY AND TWO-KEY VERSIONS OF THE SINEWAVE SCHEDULE FOR PIGEONS

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When the rate of reinforcement for pigeons' key pecking varied over time following a sine waveform, performances were more consistent and reliable if a constant-rate reinforcement schedule was concurrently available on a second key than if only the sinewave-varying reinforcement schedule was available. In the two-key version, response rates clearly followed varying reinforcement rates with the same frequency, with no phase lag, and without breaks. In both versions, pecking rate was a power function of reinforcement rate. Sinewave-schedule performance waveforms qualified for engineering methods of frequency analysis and met criteria for a standard measurement system.

Key words: sinewave schedule, concurrent-reinforcement schedule, general systems analysis, research technology, pigeons

Staddon (1964) first designed a procedure that he hoped would permit reduction by "engineering methods of frequency analysis (p. 410)." His strategy was to inject a waveform signal into a system and to examine the resulting output waveform for characteristic effects. He devised a cyclic-interval reinforcement schedule in which reinforcement rate for a pigeon pecking a single key varied over time in a sinewave-like fashion. Intervals between reinforcers changed from one interval to the next, interval by interval. At times the intervals were short and reinforcers occurred at a high rate; about 30 minutes later, intervals were long and reinforcers occurred at a low rate. By changing the duration of every schedule interval, Staddon varied reinforcement rate from 12 to 60 reinforcers-per-hour (rph) with a period of thirty minutes in a sinewave-like fashion. Later, Keller (1973) defended a dissertation based on several actual sinewave frequencies with pigeons on cyclic-interval reinforcement schedules. Both Keller and Staddon observed individuals' pecking rates to following reinforcement rates at the same frequency and in smooth periodic waveforms with a modulation-amplitude of about 2 to 3 deci-

bels (dB); but both also found phase lags from the reinforcement-rate input signal to the response-rate output signal. Staddon's waves were 135 degrees or 12.5 minutes out of synchrony. With such phase lags, response rates were often highest when reinforcement rates were lowest and vice versa, and hopes for frequency analysis of the resulting waveforms were dampened.

Meanwhile, Krossner (1967) devised a different sinewave-schedule procedure. He reinforced pigeons' key pecking on a fixed-interval schedule for twenty minutes daily, and he changed the interval value every day following a sinewave. Reinforcement rate varied sinusoidally from 32.7 to 360 rph every eight days. This way, Krossner obtained only very low frequencies, but he sampled each reinforcement-rate value for several reinforcers at a time and thereby removed the phase lag. As a result, Krossner observed individuals' pecking rates to follow sinusoidally-varying reinforcement rates at the same frequency and with synchronized peaks and troughs.

Our sinewave-schedule procedure combined various features of the work of Staddon, Keller, and Krossner and others (Farmer, 1963; Ferster & Skinner, 1957; Herrnstein, 1961; Millenson, 1963). In addition, we explored the effects of a concurrently available schedule having a constant average rate of reinforcement on a second key. Because independent, concurrent performances are noted for their sensitivity to reinforcement schedule parameters (Catania,

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1966; de Villiers, 1977), we speculated that performance would be especially sensitive to sinusoidal variation in reinforcement rate when a concurrent schedule was arranged.

First, following Krossner, we sampled reinforcement rates in a wide range from 15 to 465 rph for five reinforcers at each value. Random-interval reinforcement schedules (Farmer, 1963; Millenson, 1963) were used to obtain consistent rates of responding. Whereas Staddon, Keller, and Krossner used only a single pecking key and reinforcement schedule, we employed a two-key chamber and systematically compared effects when (a) only the sine-wave schedule was arranged on the right key to when (b) a constant-rate reinforcement schedule was also arranged on the left key (Ferster & Skinner, 1957; Herrnstein, 1961).

METHOD

Subjects

Four White King cock pigeons were run in daily sessions five days a week for eight weeks; no experimental session was ever missed. All were six years old and veterans of several experimental procedures. Feeding regimens of Purina Top-Flite grain mixture kept them about 80% of their free-feeding weights.

Apparatus

Birds worked in a standard operant chamber with three pecking keys. Keys were 2.54 cm in diameter, aligned horizontally on the keyboard wall, 25.4 cm above the floor and 6 cm apart. A 5-cm square access port to the grain magazine was just below the center key, about 12 cm above the floor.

Experimental contingencies applied to the left and right keys. The center key was never lit and pecks at it had no effect; center-key pecks were counted and recorded, but they never added to the analysis. In-line stimulus projectors lighted both side keys with white light when they were in effect. A 3-W house-light, centered near the ceiling, gave general illumination. A ventilating fan ran continuously, and white noise (at 86 dB above SPL), presented through a speaker in the lower right corner of the keyboard wall, masked extraneous sounds. Automatic switching circuitry administered the experimental contingencies, and several counters and a cumulative recorder monitored performance.

Procedure

With exceptions noted, birds worked five-day experimental weeks at daily sinewave-schedule sessions that lasted until 75 reinforcers were collected. Each session had fifteen sections separated by timeouts (when the houselight remained but keys were turned off); each section lasted until five reinforcers were collected and ordinarily required from less than thirty seconds to more than twenty minutes depending upon the programmed rates of reinforcement. Between-section timeouts, when schedule values and recording equipment were reset, ranged from 90 to 120 seconds in duration. (Experimenters were instructed to reset equipment for the upcoming section and then to wait 60 seconds before starting it.) Sessions of the two-key version of the sinewave schedule took 60 to 75 minutes. At first, two hours were allotted for each one-key version of the sinewave schedule, but no bird finished. After that, four hours were allotted for each one-key session every other day; sessions were terminated after birds completed their fifteen sections or after four hours, whichever came first.

In the two-key version of the sinewave schedule, left-key pecks were always reinforced on a random-interval schedule yielding an average of 120 reinforcers per hour (120 rph or 2 rpm; $t = 7.5$ sec, $p = \frac{1}{4}$, $t/p = 30$ sec). Right-key pecks were also reinforced on a random-interval schedule, but the reinforcement rate that was fixed within a section was changed during between-section timeouts to yield from 15 rph to 465 rph ($t = 7.5$ sec, p varied) according to a sinewave pattern. The probability, p , that reinforcement would be available every 7.5 seconds changed from $\frac{3}{32}$, $\frac{1}{15}$, $\frac{3}{4}$, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{15}$, $\frac{1}{32}$, $\frac{1}{15}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and $\frac{1}{15}$, back to $\frac{3}{32}$ in twelve sections. As in Millenson (1963), reinforcers were held until collected unless the fifth reinforcer in a section was collected on the other key. In these two-key, concurrent-schedule sections, every switch between keys started a 2-sec changeover-delay (COD) timer, and reinforcement deliveries were prevented during the delay. White light transilluminated both keys when experimental sections were on, except during 3-sec reinforcement deliveries.

Fifteen sections made one session and twelve sections made one sinewave cycle so that 1.25 cycles were completed every day. Four daily sequences of sections, listed on four datasheets

labeled A, B, C, and D that changed every day without exception in the order ABCDABCD... etc., fit together to make five continuous sinewave cycles. Thus, 6.25 cycles were completed every five-day, 75-section experimental week.

In the one-key version of the sinewave schedule, only the sinusoidally varying schedule was available on the lighted right key; pecks to the dark left key and center key had no effect and did not add to the analysis.

Design

One-key and two-key versions were compared in a simple reversal design. The one-key version (A) and the two-key version (B) were alternated in an ABA design for Birds 80 and 81, and in a BAB design for Birds 83 and 84. Conditions were shifted only between weeks. ABA birds took 3, 3, and 2 weeks on conditions and BAB birds took, 3, 2, and 3 weeks. ABA birds started the first week on the one-key version with two-hour daily sessions. But afterwards, birds were given four-hour sessions every other day on the one-key version.

RESULTS

One-key and two-key versions of the sinewave schedule led to effects with differing practical worth, as may be seen in Figure 1. Performance waveforms from the two-key version, constructed by connecting response-rate and reinforcement-rate values from successive experimental sections across a 75-section, five-day week, were continuous and relatively smooth (middle panel b). Performance waveforms representing results from the one-key version (top panel a) were broken and segmented. In general, the two-key sinewave schedule exercised far better management over behavior than the one-key version.

Each of the three panels in Figure 1 contains data from a single subject. Data in top panel a represent results from the one-key version with four-hour sessions; Bird 80 was selected because his records contained the fewest interruptions and most completed sessions. Data in the middle panel b from Bird 84 represent performances from the two-key version; virtually any other bird's performance could have been selected. Data in the bottom panel c from Bird 83 represent the only exceptional type of performance observed when birds were first ex-

Fig. 1. Sinewave-schedule performance waveforms. Each panel represents a single subject across a 75-section five-day experimental week. Panel a, with data from Bird 80, represents results from four-hour sessions on the one-key version. Panel b, with data from Bird 84, represents typical results from the two-key version. Panel c shows Bird 83's exceptional transitional performance during his first week of exposure to the two-key sinewave schedule; three birds showed left-key preference, but Bird 83 was unusual in taking a week and a half before stabilizing on typical, two-key performance. Right-key pecking rates appeared as filled circles; right-key reinforcement rates appeared as unfilled circles; "T" symbols represent zero counts. In the two-key version, total pecking rates and total reinforcement rates appear as the top edge of halftone screens; switching rates appear in filled triangles. All rates were in events per minute.

posed to the concurrent two-key version of the sinewave schedule; Bird 83 was unique by performing in this manner for a full week before stabilizing the next week on the typical pattern portrayed in the middle panel b.

Typically, P_{rt} (right-key pecks) and R_{rt} (right-key reinforcement) waveforms from a week on the two-key version, as in panel b, contained six full peaks and troughs, leaving a portion at the end. Since P_{rt} and R_{rt} peaks and troughs occurred at the same time, we can say they were coupled as output and input at the frequency of 6.25 cycles per 75 sections with no phase lag. Across the four subjects, P_{rt} modulation-amplitude averaged 12 dB. Rates of switching between keys rose when right-key reinforcement rates were lowest and fell when right-key reinforcement rates were highest. [As recent experiments have observed, longer exposure to this procedure leads to a M-shaped switching rate waveform similar to that observed here between sections 55 and 65; switching rates were maximal when reinforcement rates on the two keys were equal, as shown earlier by Herrnstein (1961).]

Sinewave-schedule variations applied only to the right-key reinforcement schedule, and as rough constancy of total pecking rates showed, left-key rates were essentially determined as the complement of right-key rates; consequently, the analysis was restricted to P_{rt} and R_{rt} waveforms. Also, the left-key schedule yielded a higher reinforcement rate than the lowest rates on the sinewave-varying schedule. As a result, birds often collected all of a section's reinforcements through left-key pecking, and zero right-key reinforcement counts were often observed. Zero counts are not zero rates, which imply zero counts if sections were to continue forever, and so they were estimated conservatively as less-than-one-count per minute of section time; a zero count was plotted with a special "T" symbol that was placed at the rate figure equal to a count of one.

Aside from the fact that there were more of them available, Bird 80's performance waveforms from the one-key version in panel a were like those of the other birds and were broken into segments because fifteen sections were not finished within four-hour sessions; all the birds' one-key waveforms were incomplete. Right-key pecking was also less sensitive to sinewave-schedule variation, as shown by the average modulation-amplitude of 8.6 dB across

the four subjects for the available pieces.

Performance waveforms in panel c represented the only departures from typical results. When the four subjects were introduced to the two-key procedure (first for Birds 83 and 84 and after one-key experience for Birds 80 and 81), three of them (all but 81) went to the left key (away from the chamber door) and stayed there for a while. Two birds dropped their left-key preference within five days and showed typical two-key performance by the weekend; but Bird 83 took a week and a half, and panel c shows its one full week. Then, except during eight different sections, Bird 83 pecked exclusively at the left key; left-key pecking rates bounced randomly around a mean that tracked

Fig. 2. Tracings of four cumulative records of right-key pecking, one from each subject and each sequence of sections, from the two-key sinewave schedule. Beneath each record, unfilled portions of time-event lines show experimental sections, and black bars show between-section timeouts.

Fig. 3. Tracings of four cumulative records of right-key pecking, one from each subject and each sequence of sections, from the one-key sinewave schedule. Beneath each record, open portions of time-event lines show experimental sections and black bars show between-section timeouts.

neither an increasing nor decreasing overall trend, in a manner consistent with the constant overall rate, random-interval reinforcement schedule for left-key pecking.

Similarities and differences between performance waveforms are explained in cumulative records because they show the temporal location of every peck. Figures 2 and 3 each present four cumulative records, one from each bird, representing sessions of the two-key version (Figure 2) and of the one-key version (Figure 3). Beneath each record, open portions of the time-event line correspond to experimental sections and black bars correspond to between-section timeouts.

Cumulative records of right-key pecking directly reflected the periodicity of the P_{rt} waveforms from the two-key version, perhaps most clearly in the bottom record for Bird 83; high response rates during short duration, high reinforcement-rate sections and low response rates during long duration, low reinforcement-rate sections gave the record an overall sigmoidal shape. Similar patterns were observed in the other two-key records, but only the high response rate patterns could also be found during high reinforcement-rate sections in the one-key records. During high reinforcement-rate sections, pecking occurred at high regular rates with short post-reinforcement pauses; for example, compare the first twenty minutes from

the top records in Figure 2 and Figure 3, which represented the same sequence of sections in the sinewave cycle.

Low-rate right-key pecking, which was often interrupted and eclipsed by left-key pecking, occurred in small negatively accelerated episodes during low reinforcement-rate sections of the sinewave in the two-key version. In contrast, large amounts of right-key pecking occurred during low reinforcement-rate sections in the one-key version, which explained the shallower troughs and the resulting lower modulation-amplitude. During those sections, right-key rates decreased as in classic extinction patterns: frequency decelerated over long episodes that were broken by increasingly long pauses. Bird 84 (second record from top) continued to decelerate even after midsection reinforcements; and pauses longer than 40 minutes dominated Bird 83's record (bottom record). As a practical result, birds too often failed to complete fifteen sections in four hours.

Extremely long interreinforcement intervals, during which deceleration occurred, are likely with a truly random-interval schedule; consider that the variance for the distribution of intervals around a mean of $t/p = 240$ sec with $p = 1/32$ is 128 minutes. Farmer (1963) observed higher average response rates at the same low reinforcement rates with a single pecking key, possibly because his pigeons were maintained

Fig. 4. Transfer function between right-key reinforcement-rate input values and right-key response-rate output values for the one-key version (left panel) and the two-key version (right panel) of the sinewave schedule. Scatterplots were made from performance waveforms in panels a and b of Figure 1. "T" symbols representing zero reinforcement counts were placed at one count per minute of section time. All rates were in events per minute.

only on these schedules (with limited hold) for 120 minutes every day for twenty days; and although his response rates did not drop as far as ours, he also described a rapid decline in response rates with decreases in the same range of reinforcement rates.

Figure 4 presents input to output transfer functions for the two versions of the sinewave schedule; scatterplots expressed the relationship between coordinate R_{rt} and P_{rt} values from the performance waveforms in panels a and b of Figure 1. Features of the scatterplots corresponded to features of the performance waveforms and were likewise explained by patterns found in the cumulative records.

Although P_{rt} values were more variable at low R_{rt} values in the two-key version, P_{rt} values decreased linearly as R_{rt} values decreased in both versions. Both scatterplots were fitted with straight lines, and with logarithmic axes, points fell on a power function taking the form: $\log P_{rt} = k \log R_{rt} + C$, or $P_{rt} = R_{rt}^k$. The linear model, $\log P_{rt} = (.38) \log R_{rt} + 1.58$, accounted for 74% of the variance in Bird 80's data; and the linear model, $\log P_{rt} = (.68) \log R_{rt} + 1.35$, accounted for 69% of the variance in Bird 84's data. Greater slope (or larger exponent) value in the model for the two-key version corresponded to the greater modula-

tion-amplitude in the performance waveforms from the two-key version. Because the left-key reinforcement schedule was an available alternative, P_{rt} was more sensitive to R_{rt} variations in the two-key version of the sinewave schedule.

DISCUSSION

In the concurrent, two-key version of the sinewave schedule, when a constant-rate reinforcement schedule was available on the left key as an alternative to the sinewave-varying schedule on the right key, response rates followed reinforcement rates without breaks, at the same frequency, and with no phase lag. Within individuals, performances were stable enough that transfer functions showing the relation between the reinforcement-rate input and response-rate output were plotted directly from observed values. Performances across individuals, illustrated here chiefly by cumulative records, were sufficiently consistent to submit waveforms to power spectrum analysis. Power spectra of performance waveforms revealed characteristic "signatures" of effects, thereby fulfilling the promise of engineering methods of analysis. The ease with which the procedure and the analysis were conducted and

the clarity of their results encouraged us to develop applications and to consider theoretical accounts of the entire measurement system.

Staddon (1964) introduced his cyclic-interval schedule because of the prospect of applying frequency analysis, or spectral analysis, to response-rate output waveforms. However, large phase lags that he and others observed between input and output waveforms cut the effort short. We confirm that Krossner (1967) essentially solved the phase-lag problem by sampling reinforcement rate values for several reinforcers at a time. Although we cannot say how many reinforcers at a given rate would be enough, we delivered five reinforcements per value and never observed phase lags.

Other procedural parameters that may have phase-difference effects should be thoroughly tested. For example, any variable that directly reduced the rate or raised the latency of switching from one key to the other in the two-key version would indirectly lead to phase differences between input and output signals. Also since schedule contingencies specified several time intervals, varying any one could interact with a subject's discriminations of durations and thus increase or decrease certain phase differences. More research is needed that would track switching rates as COD durations varied and as t (minimum schedule interval) differed between left- and right-key reinforcement schedules. Based on our limited success, we recommend varying such parameters as sinewaves over time.

Power spectra of response-rate waveforms from the two concurrent schedules showed characteristic differences that clearly identified their controlling variables. Spectral analysis is a type of analysis of variance that distributes signal modulation into time-periodic components, yielding the amount of power or variance in each frequency-bandwidth. Many computing center libraries hold computer programs that execute spectral analysis; we selected program 02T from the *BMD:Biomedical Computer Programs* package (Dixon, 1971). All 75 sections from an experimental week contributed to spectral estimates that identified the power sources that modulated the response rates. Only two statistics were needed to summarize the important spectral features: (a) the amount of power at the experimental frequency, and (b) its proportion of total power across the spectrum (pve, or percent of variance

explained). On the one hand, the typical P_{rt} waveform from the two-key version was clearly modulated at the experimental frequency, despite a few bumps and notches, and spectral analysis bore this out. For Bird 84's data in panel b of Figure 1 the pve was 65.5%, and for all four individuals, more than 60% of the total variance occurred in the experimental frequency-bandwidth and less than 40% was distributed among eight other equal bandwidths. So the power spectrum for a typical P_{rt} waveform can be fairly represented by a single line at the experimental frequency. On the other hand, no periodic component stands out in the performance waveforms in panel c of Figure 1, and spectral analysis of Bird 83's left-key pecking rates during that week found power equally distributed across the spectrum in no apparent pattern. The spectrum represented the characteristic effect of noise: small random variations around a relatively constant average pecking rate. Since the left-key schedule was a constant-average-rate, random-interval reinforcement schedule, the noise spectrum describing left-key performance incidentally provided a calibration check. Thus, the left-key pecking performance mirrored in this instance the temporal characteristics of the left-key schedule in a noise spectrum just as the right-key pecking performance normally reflected the right-key schedule in a single line at the experimental frequency.

It appeared to us that a behavioral measurement system in which features of the output functions can be directly related to input variables and can be quickly and easily summarized by a few standard statistics presented new opportunities for experimentally analyzing environmental effects on behavior. So in one later experimental series, a keylight was changed as a discriminative stimulus every time reinforcement rate was changed; each sinewave-schedule value appeared with a distinctive color or form keylight stimulus. The major effects were observed as dramatic changes in the modulation-amplitude of performance waveforms and in the power at the fundamental frequency of power spectra (Johnson, Note 1). In another experiment, pigeons performed on the sinewave-schedule procedure, with and without discriminative keylight stimuli, under several dose-levels of a drug (chlorpromazine hydrochloride); various drug effects were clearly revealed in details of sinewave-schedule perfor-

mances (Johnson, Note 2). We submit that sinewave-schedules can provide valuable tools for the analysis of behavior.

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