A METHOD FOR INCREASING THE REINFORCEMENT MAGNITUDE OF INTRACRANIAL STIMULATION¹

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Schedules of intermittent brain-stimulation reinforcement have been shown to maintain performances when a reinforcement is defined as several response-produced, brief trains of stimulation. The present experiments show that the number of response-produced trains permitted per reinforcement is a variable analogous to amount or magnitude of reinforcement in the conventional food-reinforcement experiment. Systematic effects were obtained when that variable was manipulated within a multiple schedule and also on variable-interval schedules programmed concurrently.

Recent experiments by Pliskoff, Wright, and Hawkins (1965) and by Hawkins and Pliskoff (1964) showed clearly that brain-stimulation reinforcement (at least with the electrode tips in the region of the posterior hypothalamus) can maintain performances by rats in the range of schedule-parameter values often used with food and water reinforcement. These experiments differed from the typical experiment employing brain-stimulation reinforcement in several respects, important among them being the definition of a reinforcing event. Ordinarily, a reinforcing event is a single, relatively brief train of stimulation delivered to the rat while at the response lever. The present work defined a brain-stimulation reinforcement as a succession of several brief trains of stimulation. Each train was delivered by a press on a retractable lever separate from the lever on which responding was intermittently reinforced by access to the retractable lever. The overall procedure, then, had the formal character of a behavioral chain (Keller and Schoenfeld, 1950) analogous to the case involving food reinforcement. The terminal chain member, a sequence of stimulation-reinforced presses, was likened to consummatory activity involving a sequence of chewing re-

sponses. The thesis was advanced by Pliskoff *et al.* (1965) that the number of stimulation-reinforced presses per reinforcement (designated CRF-N throughout the present report) was a variable in their experiment analogous to "amount of reinforcement" in the more typical experiment employing food.

The experiments reported below employed two procedures of demonstrated value in studying "amount of reinforcement" or "reinforcement magnitude" as an experimental variable. The first experiment is derived from a procedure employed by Brady and Thatch (1960), while the second experiment is closely allied to procedures employed by Autor (1960) and by Catania (1963).

METHOD

Experiment I

Subjects and apparatus. Three experimentally naive male albino rats were placed under Nembutal anesthesia and surgically implanted with bipolar stainless steel electrodes. The electrodes were 10 mils in diameter and insulated throughout except at the tips. The stereotaxic coordinates (Massopust, 1961) were chosen so as to place the electrode tips in the region of the mammillary bodies of the posterior hypothalamus. Experimentation began after a postoperative recovery period. Food and water were freely available to the rats in the home cages.

The apparatus consisted of an experimental chamber made of Plexiglas, a stimulator and associated equipment, and the usual automatic

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programming and recording devices. The animal chamber was fitted with two response levers. One of them was permanently mounted on the left side of the front wall, and the other, a retractable lever (Lehigh Valley Electronics), was mounted on the right side of the front wall. In addition, the box was provided with a commutator and cable arrangement through which stimulation could be delivered to the rat. The stimulator provided biphasic, square-wave stimulation; each excursion of a pulse pair was 0.2 msec in duration with 0.2 msec "off time" between positive and negative excursions. Pulse pairs were delivered at a rate of 100 per sec; amplitude and train duration (125 msec) were constantly monitored on a cathode ray oscilloscope.

Procedure. The retractable lever was fixed in the work position, and each rat was trained to lever press on a continuous reinforcement schedule. During the 1 to 2 hr devoted to continuous reinforcement, the current intensity was adjusted (and thereafter maintained for the duration of the experiment) for each rat to a value that maintained uniform, sustained performance. The current intensity 500 μ A (zero to peak) was chosen for each of the rats.

Following unlimited continuous reinforcement, the second step in the procedure was initiated. The retractable lever was available for 20 stimulation-reinforced presses; it was then retracted from the box, and a single response on the permanent lever was required to return the retracted lever. After two or three daily sessions, the requirement on the permanent lever was changed to a variable-interval schedule of 30 sec (VI 0.5-min), and that schedule was maintained throughout the experiment.

Two chains as just described alternated after each reinforcement (multiple schedule) during the course of each 1.5-hr daily experimental session. The VI 0.5-min schedule pro-

grammed on the permanent lever served as the initial link of both chains; CRF-N, where N refers to the number of stimulation-reinforced presses permitted during each access to the retractable lever, served as the terminal link of each chain. The value of N was varied as the experimental variable, sometimes being the same (control procedure) in the two chains but most often, different. One chain was accompanied by a clearly audible tone, the other by a clearly audible click (about 5 per sec). The sequence of experimental conditions and the number of daily sessions devoted to each is shown in Table 1.

Experiment II

Subjects and apparatus. Two experimentally naive male albino rats were prepared as described in Exp. I.

The apparatus was essentially as described above, except that both response levers were retractable, and 100 Hz sine wave stimulation was employed. Again, train duration (125 msec) and current intensity were monitored on a cathode ray oscilloscope.

Procedure. Current intensity was set for each of the rats during sessions employing a continuous reinforcement procedure. As before, the criterion for choosing a current intensity was the maintenance of a uniform, sustained rate of lever pressing. The values of current intensity chosen (and thereafter maintained throughout the experiment) were 150 μ A for Rat Con 4 and 200 μ A for Rat Con 16. Both values are zero to peak measurements. During each of the several experimental sessions employing continuous reinforcement, only one of the retractable levers was available; left-right position was alternated randomly during a session.

Following continuous reinforcement, the procedure was changed so that chain schedules were programmed for each of the levers. The initial link of each chain was a VI 1-min sched-

Table 1
The Sequence of Experimental Conditions

Chain	A	B	C	D	E
Tone	CRF-20	CRF-20	CRF-1	CRF-100	CRF-5
Click	CRF-20	CRF-100	CRF-100	CRF-1	CRF-5
Sessions	17	8	14	14	10

ule of reinforcement. The initial links were concurrent, *i.e.*, the two levers were simultaneously available, and the rat could respond on either. Since each schedule assigned reinforcements at an average rate of 1 per min, the two schedules together provided reinforcements at a combined average rate of 1 per 30 sec.

As in the first experiment, the reinforcer for responding in an initial chain member was access to a terminal chain member. When one of the initial-link, VI schedules assigned a reinforcement, a post changeover delay response on the appropriate lever produced the terminal link for that lever. The changeover delay was a 0.5-sec interval following the first response on a lever after the rat had switched responding to the alternate lever; a response could not be reinforced during the changeover delay.

The terminal links, *i.e.*, predetermined numbers of stimulation-reinforced presses on the levers (or CRF-N, as defined above), were mutually exclusive. Exclusion was accomplished by retracting the alternate lever from the box. Upon completion of a terminal member on one of the levers, that lever also was retracted, and both levers were unavailable to the rat for 4 sec, after which they were simultaneously reintroduced. The concurrent, initial links were reinstated when both levers became available.

The experimental variable was the value of N in CRF-N, the terminal link for one of the chains. The number of stimulation-reinforced presses in the terminal link of the other chain was constant throughout the experiment. For one of the rats, Con 4, the constant terminal link was CRF-1; for the other rat, Con 16, the constant terminal link was CRF-100. The values of the experimental variable for both of the rats were, in succession: CRF-1, CRF-2, CRF-3, CRF-5, CRF-10, CRF-50, and CRF-100. Each of the values of the experimental variable was studied for four consecutive, 2-hr daily sessions. During the first two of each block of four sessions, the chain with the constant terminal link was assigned to the left response lever; during the third and fourth sessions, the chain with the constant terminal link was assigned to the right response lever.

Following CRF-100 for Con 4, the terminal links CRF-10 and CRF-2, in that order, were

reinstated in order to assess recoverability of the earlier data points.

RESULTS

Figure 1 consists of a photomicrograph for each of the rats used in the two experiments. Examination of the electrode tracks, which are indicated by the markers, permits location of the electrode tips during the experiments. The electrode tips were at about the same anterior-posterior level for Rat C2, C3, C4, and Con 4, corresponding to Massopust's (1961) plate F = 2 mm. For Rat C2, the electrode tips were just dorsal to the lateral mammillary nucleus at the foot of the substantia nigra. The penetration of the electrodes was deeper for Rat C3, the tips resting in the lateral mammillary nucleus and, perhaps, the mammillary bodies. For Rat C4 and Con 4, the tips were lateral and dorsal to the mammillary peduncle. The placement for Rat Con 16 appears to have been somewhat anterior to the above placements, the electrode tips having been located dorsal and lateral to the anterior aspect of the mammillary bodies.

Experiment 1

The results of the first experiment are shown in Fig. 2. After each session, the VI response rate was computed separately for each leg of the multiple schedule. The solid line represents the data obtained from the chain correlated with the click stimulus; the dotted line represents data obtained from the chain correlated with tone. The five experimental conditions, A through E shown in Table 1, are labeled in the top panel for C2 and pertain also to the panels for C3 and C4.

The first experimental condition (labeled A) shows the development of the VI 0.5-min performances when both terminal links were CRF-20. The VI response rates of both chains followed the same trend. Different response rates did not develop; this was expected inasmuch as the terminal links of both chains were the same. That different response rates did not develop during the second experimental condition (B) was not expected; the chain correlated with the click (solid line) terminated with CRF-100, while the other chain terminated with CRF-20. Either the value of N in a terminal chain link is not functionally re-

Fig. 1. Photomicrographs for the several rats. Each is a frontal section with the electrode track indicated by a marker. (See text.)

lated to "amount of reinforcement," or that function is asymptotic at or about CRF-20. The second possibility is suggested by the results of the third experimental condition (C). A clear difference in the initial link VI response rates developed when the terminal link of the chain correlated with the tone stimulus was adjusted to CRF-1, with CRF-100 maintained as the terminal link of the chain correlated with the click stimulus. Rat C2 displayed the largest difference in initial link response rates; C3 showed the smallest difference.

Fig. 2. Response rate during each variable-interval schedule plotted against sessions. The solid curve is for the variable-interval performance in the presence of the click stimulus, and the dotted curve is for the variable-interval performance in the presence of the tone stimulus. The experimental conditions A, B, C, D, and E are described in the text and listed in Table 1.

The fourth experimental condition (D) was a control for the qualitative difference between the stimuli correlated with the two chains in the multiple schedule. When the stimuli were interchanged, the terminal link CRF-100, now correlated with the tone stimulus (dotted line), continued to maintain the

higher response rate in the initial chain link. The data for Rat C2 and C4 suggest that stimulus control over the VI response rates of the multiple schedule was exercised by the number of stimulations immediately preceding a VI performance. For both of those rats, there was no change in the separation between the two curves at the transition from Condition C to Condition D. Cruse, Vitulli, and Dertke (1966) have shown that qualitative differences between two kinds of food pellets can exert discriminative control over performances in a multiple schedule, an effect analogous to that shown here with respect to the quantitative difference between two numbers of brain stimulations.

The data for Rat C3 suggest that stimulus control over the VI performances was exercised by the tone and click stimuli; the separation between the two curves vanished at the transition from Condition C to Condition D, although several instances of overlap between the two curves during Condition C make the conclusion with respect to stimulus control somewhat speculative.

In the final experimental condition (E), both terminal links were adjusted to CRF-5. The VI response rates were approximately equal. The elimination of the difference between the initial link, VI response rates when both terminal links were adjusted to CRF-5 reinforces the conclusion that the differences in response rates obtained in Condition C and D were a result of the experimental variable.

Experiment II

In the second experiment, the VI schedules were programmed concurrently. The response rate on each schedule and the manner in which the total response output was divided between the two schedules were determined for different values of the experimental variable.

As noted above, one of the VI schedules of the concurrent pair was associated with a constant number of stimulations per reinforcement at all values of the experimental variable. The constant number was one (CRF-1) for Rat Con 4 and 100 (CRF-100) for Con 16. The other VI schedule was associated with the several values of the experimental variable CRF-N. Each value of the experimental variable was programmed for four consecutive sessions. The percentage of the total response

output emitted on the VI schedule associated with the experimental variable was calculated each day. The means of those percentages, based on the four sessions for each value of CRF-N, were also computed. Figure 3 shows those means plotted against the values of CRF-N. The dotted curve is for Rat Con 16, and the solid curve is for Con 4.

Fig. 3. The percentage of the total response output emitted on the lever correlated with the chain terminating in the variable link as a function of CRF-N. The alternative chain terminated in the constant link, CRF-1 for Rat Con 4 and CRF-100 for Con 16, at all values of CRF-N. The two chains were programmed concurrently. The designation CRF-N represents the number of stimulation-reinforced responses in a terminal chain link.

It is evident from an examination of the figure that when the terminal links of the two chains were unequal, the larger proportion of the total response output was associated with the lever on which the larger number of stimulation-reinforced responses served as the terminal chain link. Further, with the single exception at CRF-10 for Con 4, the larger the difference between CRF-N and the base value, the larger the preponderance of responses on the lever associated with the larger number

of stimulation-reinforced responses in the terminal chain link. When the value of CRF-N was equal to the base value, at CRF-1 for Con 4 and at CRF-100 for Con 16, the total response output was very nearly evenly distributed on the two levers. Finally, the data points for Con 4 which are marked with a pointer were determined after the sequence CRF-1 through CRF-100 was completed. Had the function for Con 4 been drawn through the redetermined point at CRF-10, the inversion or exception noted above for this rat would have been removed. More importantly, the redetermined points at CRF-10 and CRF-2 demonstrate approximate recoverability of the original data points.

Figure 4 displays the data for Rat Con 4 and Con 16 in another way. After each session, the number of VI responses for each schedule was divided by the time during which the two levers were concurrently available, thereby providing an absolute response rate for each schedule. Means were then calculated for the four sessions over which a single value of CRF-N was programmed. The means of those response rates are plotted in Fig. 4 against the several values of CRF-N. The data for Con 16 are shown in the upper panel of the figure, and the data for Con 4 in the lower panel. In both panels, the dotted curves show the mean response rates for the schedule associated with the constant number of stimulations, and the solid curves show the mean response rates for the schedule associated with the several values of CRF-N.

The lower panel for Con 4 shows that the overall response rate, which is equal to the sum of the two points (one from each curve) at each value of CRF-N, increased with increasing values of the experimental variable. The increase in overall rate is due to the concave downward increase in response rate on the lever correlated with the chain terminating in the several values of the experimental variable. The response rate on the lever associated with the constant terminal link tended to decline with increasing values of CRF-N. Although the inversion in the lower curve at CRF-10 is striking, an observable feature of that curve is the overall decline; the response rate at CRF-100 was clearly lower than at smaller values of CRF-N. The arrows indicate the redetermined data points at CRF-2 and CRF-10.

Fig. 4. Response rates on the two variable-interval schedules programmed concurrently are plotted against values of the experimental variable, CRF-N. The solid curves show response rates on the schedule associated with the experimental variable, CRF-N. The dotted curves show response rates on the schedule associated with the constant terminal link, CRF-1 for Rat Con 4 and CRF-100 for Con 16. The designation CRF-N represents the number of stimulation-reinforced responses in a terminal chain link.

The upper panel of Fig. 4 shows the data obtained with Con 16. The two functions shown for that rat suggest a mirror-image relationship; as response rate increased on the lever correlated with the chain terminating in CRF-N (solid curve), response rate decreased on the lever correlated with the chain terminating in the constant link, CRF-100. Overall response rate for Con 16, in contrast with that of Con 4, remained approximately unchanged across the several values of CRF-N.

Figure 5 consists of several representative

cumulative records from Exp. I and II. Each of the records shows performance on an initial, variable-interval link of a chain. The "pips" on the records indicate reinforcements, *i.e.*, entries into a terminal chain link. The motor providing paper drive was stopped during each terminal link. The upper third of the figure consists of two pairs of records produced by Rat C4 during Exp. I. The number appended to each record shows the value of CRF-N serving as the terminal chain link when that record was obtained. The absence of a sustained difference in response rates between the two records of the right hand pair, marked 100 and 20, exemplifies the effect shown for all three rats in Fig. 2, Condition B. The difference in response rates which de-

Fig. 5. Sample cumulative records from both experiments. The upper pair of two records is for Rat C4. The records were obtained during the first experiment. Each pair shows the two variable-interval performances in a multiple schedule, and the number appended to each record gives the value of CRF-N serving as the terminal link associated with that variable-interval schedule. The middle and lower pairs of records for Rat Con 4 were obtained during the second experiment. Each pair shows variable-interval performances obtained concurrently. The records marked "left: 1" were obtained on the lever associated with the constant terminal link CRF-1; the records marked "right: 1" and "right: 100" were obtained on the lever associated with the variable terminal link at two values of CRF-N, *i.e.*, CRF-1 and CRF-100. The designation CRF-N represents the number of stimulation-reinforced responses in a terminal chain link.

veloped when the terminal links in the chains were CRF-100 and CRF-1 is shown by the sample records for Rat C4 shown on the left.

The middle pair of cumulative records was obtained from Con 4 during a single session of the second experiment. The concurrent performances were each maintained by CRF-1. A (perhaps) "satiation" effect is apparent in the two records. The bottom pair of records for the same rat was obtained also during a single session. The variable-interval performance on the left lever was maintained by CRF-1, while the variable-interval performance on the right lever was maintained by CRF-100. Note that the response rate on the left lever, maintained by CRF-1, is lower than that shown in the record immediately above, a performance maintained also by CRF-1. That rate difference on the left lever is due to the difference in terminal links maintaining the performances on the right lever. The effect was noted above in connection with the lower panel of Fig. 4; the absolute response rate maintained by CRF-1 decreased with increasing values of CRF-N.

DISCUSSION

The present experiments showed clearly that the value of CRF-N used as the terminal link in a chain determined performance during the initial link. That fact was substantiated when two chains were programmed in a multiple schedule and also when programmed concurrently. Further, with the restrictions imposed by the choice of stimulation parameters employed, it would appear that the function relating initial link, variable-interval response rate to CRF-N is virtually asymptotic at about CRF-50.

In contrast with the present experiments, studies relating reinforcement magnitude and brain stimulation have most often manipulated the duration of a single train of stimulation (*e.g.*, Hodos, 1965). The method we employed, *i.e.*, multiple, short trains of stimulation, may have an advantage over the single-train method, particularly at certain loci of stimulation. Consider the so-called "ambivalent" loci at which the onset of stimulation is clearly rewarding but at which the rat will emit a second operant that terminates stimulation (Bower and Miller, 1958). While the evidence on this point is not definitive (Val-

enstein, 1964), the second operant has been interpreted to be an escape response. The inference has been drawn, therefore, that while the onset of stimulation is positively reinforcing, stimulation at an ambivalent locus develops aversive properties through continued application, so that the termination of stimulation is negatively reinforcing. If one wishes to employ stimulation at an ambivalent locus and side-step the problems engendered by long-duration trains of stimulation, then the present multiple stimulation technique is clearly preferable to that which employs a single, long-duration train.

That there are brain loci at which the two techniques are largely interchangeable is, perhaps, a common-sense corollary of the foregoing. The electrode placements employed in the present experiments were found to be such loci in an experiment separate from those reported above. In that experiment, the terminal link produced by responding on a variable-interval schedule was a single train of stimulation delivered by one response; the terminal link produced by responding on a variable-interval schedule concurrent with the first was a number of 120-msec trains of stimulation, each one of which was produced by a response (CRF-N). Approximately the same numbers of responses were emitted in the two initial link, variable-interval schedules whenever the duration of the single train of stimulation was equal to the total stimulation time delivered by the CRF-N link, *i.e.*, $N \times 120$ msec. The terminal-link pairs studied were: 1 train at 1.2 sec *vs* 10 at 120 msec; 2.4 sec *vs* 20 at 120 msec; 4.8 sec *vs* 40 at 120 msec; and 9.6 sec *vs* 80 at 120 msec. Further, when the terminal links were adjusted so that total stimulation time was not the same for the two links, more responses were emitted on the variable-interval schedule that produced the terminal link delivering the larger total stimulation time. That result was obtained whether the larger total stimulation time was associated with the CRF-N or single-train terminal link.

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