REWARDING AND PUNISHING EFFECTS FROM STIMULATING THE SAME PLACE IN THE RAT'S BRAIN[1]

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Delgado, Roberts, and Miller (1) found that electrical stimulation in hypothalamic structures of the cat brain would motivate the learning and performance of escape and avoidance habits. In another line of research, Olds and Milner (7) and Olds (6) reported a positive reinforcing effect from electrically stimulating septal and hypothalamic areas in the rat's brain. Finally, Roberts (8) discovered areas in the posterior hypothalamus of cats in which electrical stimulation would motivate the cats to learn the correct turn in a T maze to escape (i.e., terminate) the stimulation, but would *not* motivate them to learn to leave a distinctive starting box in time to avoid the stimulation. One hypothesis that Roberts suggested to explain this odd effect was that the onset of stimulation in these structures may actually be rewarding, although it becomes punishing quickly thereafter. To support this hypothesis, Roberts (9) tested his cats in a Skinner box and found indeed that they would press the bar to receive brief electrical stimulation of the brain (ESB). On the basis of this and other allied results, he inferred that brief stimulation in these structures produced a positive reinforcing effect. His hypothesis, then, was that the onset of stimulation in these structures was rewarding and that it became punishing only after it had been on for a few seconds. With this in mind, we can understand why his *S*s might never learn to avoid the stimulation, although they would learn to do something to turn it off (escape) after it had been on for several seconds.

The present study further investigates this hypothesis using albino rats as *S*s. The over-all plan of the experiment is to start with a heterogeneous group of reward rats and to give several behavioral tests which will differentiate *S*s having reward *and* aversion effects of ESB from those *S*s having a reward effect only. For example, the Roberts hypothesis implies that those *S*s showing the reward-aversion effect should prefer short intervals of ESB since longer intervals are likely to hurt them. One way to find out an *S*'s preferred interval of ESB is to let *S*'s operant responses control the interval *S* receives. To accomplish this, in one of our tests (ad lib. bar-pressing) the *S* received ESB for as long as it held down on the bar. Therefore, holding time was perfectly correlated with the duration of ESB the rat received. Under such conditions, the *S*'s preferred interval may be estimated by its mean holding time. The hypothesis leads us to expect that reward-aversion *S*s will have shorter mean holding times than will *S*s having reward effects only from ESB.

Another implication of the hypothesis arises if tests are given in which each bar-press produces a predetermined constant duration of ESB. The response rate of reward-aversion *S*s should decrease as the duration of ESB is increased in such tests. This will happen because longer intervals are more likely to hurt them and, consequently, reduce their rate of pressing for such stimulation conditions. On the other hand, the rate of responding of *S*s with only reward effects should be less controlled by small variations in the duration of ESB. To evaluate this prediction, two bar-pressing tests were run in which a bar-press produced either 0.4 sec. or 3.0 sec. of ESB, respectively.

METHOD

Subjects and Electrode Implantation

The *S*s were male albino rats of the Sprague-Dawley strain, between the ages of 90 and 150 days at the beginning of the experiment. Thirteen *S*s were used in the main part of the experiment, and 21 additional *S*s were used in tests of specific subhypotheses. The *S*s were housed in individual cages and maintained on ad lib. water and lab chow throughout the experiment.

Single-pole electrodes were chronically implanted with a stereotaxic instrument, aimed at various hypothalamic areas. The electrodes were stainless-steel needles

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1 mm. thick, completely insulated except for the cross section of the tip. The electrodes were secured in place by dental cement anchored to screws on the skull. The leads from the stimulator made contact with the electrodes through clasping "pin-protectors." A wire secured to the top of the skull by dental cement served as the indifferent electrode. The exact procedure has been described elsewhere (3, 4).

Stimulation Parameters

Brain stimulation was provided by ordinary 60-cps current. A potentiometer varied the voltage across a 100,000-ohm resistor in series with the rat's brain. Good reward effects were usually obtained in the range 0.5 to 10 v. (rms.). Thus, the approximate range of current through the brain was around 3.5 to 70 μa.

Testing Apparatus

There were two pieces of apparatus, a Skinner box used for reward tests and a T maze used in tests for escape and avoidance learning. The Skinner box was 6 in. by 24 in. by 30 in. high, painted flat gray with an open top for electrode leads and a glass panel front for *E* to observe the rat's behavior. Flexible wire leads extended from the stimulator to the rat's electrodes, suspended well above the rat by a free-swinging boom. A 2.5- by 4-in. paddlelike bar protruded in one end of the box, 1 in. above the floor. Depressing the bar $\frac{1}{4}$ in. made a contact which started a clock and delivered brain stimulation. The clock stopped when *S* released the bar, thus recording cumulative time on the bar. A counter cumulated the number of bar-presses. The duration of ESB produced by each bar-press was a variable of the experiment. In one condition (ad lib.), *S* received ESB for as long as it held down on the bar. In the other conditions, *E* switched a Hunter timer into series with the stimulator so that a fixed duration of ESB was delivered for each bar-press. In one test, this fixed duration was 0.4 sec.; in a second test, it was 3.0 sec.

The T maze is described in detail elsewhere (5). Essentially, it had guillotine doors separating a start box and two end boxes. The two arms of the maze were white and white-black striped, respectively, and the start box was painted black. A swinging overhead boom suspended the electrode leads above the rat in the T maze. When *S* entered the correct end box, it completed the circuit of an electronic relay, stopping a clock which measured running time to the nearest .01 sec.

Procedure

Preliminary test. Following the implantation of electrodes, the rats were allowed three days to recuperate from the operation. Then all *S*s were tested in the Skinner box to determine whether or not they had a reward effect. If they did not, they were discarded. If a rat showed a reward effect, *E* determined for this animal the minimal voltage at which a good reward effect was obtained. In all subsequent tests, the *S* was stimulated with this voltage.

Starting with a group of 13 reward rats, further tests were given to determine which ones also had an aversive effect from prolonged brain stimulation.

Bar-pressing. Each *S* was given three different bar-pressing tests. In the first (ad lib.), *S* received ESB for as long as it held down the bar. In the second and third tests, a bar-press delivered a fixed 0.4 sec. or 3.0 sec. of stimulation, respectively. Each test was 20 min. in duration, with the bar delivering ESB during the middle 10 min. only. The number of bar-presses and the total time on the bar were recorded in each minute. Following this, the *S*s were given the T-maze tests.

Escape-avoidance training. To test whether prolonged stimulation was aversive or not, each *S* was given escape training in the T maze. The rat was placed in the start box, the door was opened, and ESB was turned on. When *S* went to the side opposite its initial preference, ESB was turned off. A correction procedure was used throughout. If an animal failed to leave the start box on more than 5 of its first 10 stimulation trials (30 sec. of ESB), then we eliminated it from the procedure and inferred that prolonged brain stimulation was not aversive for *S*. Such *S*s were always tested with the avoidance procedure, but there again the results were negative. Animals that did show emotional activation to prolonged stimulation were continued at 20 trials per day, with a 30-sec. intertrial interval, until they met the criterion of 9 errorless runs in 10 successive trials.

After an animal had learned the initial escape response, we reversed the correct side where stimulation was turned off. The *S* was then trained to a nine-of-ten criterion on this escape reversal problem.

Finally *S*s were given 100 avoidance trials. The animal was placed in the start box, the door was dropped, and ESB was turned on 5 or 15 sec. later. If *S* went to the correct side during the delay, it avoided ESB. If *S* failed to make the avoidance response during the delay period, ESB was turned on and not terminated until *S* ran into the correct arm of the maze. The delay period was 5 sec. or 15 sec. in alternate blocks of 20 trials. It was believed that such a procedure would maximize the chances of getting avoidance learning from these animals. The learning criterion was 9 avoidance responses in 10 successive trials.

One animal had a circling motor reaction to stimulation and, therefore, could not be run with escape or ordinary avoidance procedures. The avoidance procedure was modified for this animal so that failure to avoid brought on a fixed 10 sec. of ESB.

Following the T-maze tests, all three bar-pressing tests were readministered to determine whether the long periods of ESB in the T maze had altered the *S*s' reward effects. Thereafter, the animals were perfused and the brains sectioned for histology.

RESULTS AND DISCUSSION

Escape Learning

Six of the 13 animals met the criterion for escape learning in the T maze. All those learning to escape also showed rapid reversal during the escape reversal training. Because these animals showed reliable bar-pressing, we can conclude that the onset of central stimulation was reinforcing. Because they showed escape learning, we can conclude that prolonged stimulation is aversive and that its termination is reinforcing.

These tests have demonstrated separately the reward and aversive components of this dual effect. In subsequent experiments the combined action of both components have been studied in the same apparatus. For example, Kirschner (reported in Miller, 3), in studying drug effects, trained his reward-aversion rats to press Bar A to turn on ESB and then press Bar B to turn it off. Reward-aversion rats will repeat this cycle continuously throughout the test period. Pictures of this type of performance have been published elsewhere (2, 3).

Avoidance Learning

Of the six *S*s that learned an escape response, none learned an ordinary avoidance response within 100 trials. Of the six animals, five made zero and one made two responses in 100 trials which would be classified as avoidance responses. This result confirms that reported by Roberts with his cats.

In order to show that ESB in rats *can* motivate the learning of an avoidance habit if the electrode is put in the right place, we selected six new *S*s that showed aversive effects of ESB but no reward bar-pressing. All six *S*s learned to escape and avoid ESB in the T maze, the mean number of trials to the avoidance learning criterion being 26.6. Their electrode placements were scattered widely about the hypothalamus but were not in the structures where we find reward-aversion effects.

The hypothesis of the research provides an explanation for these reward-aversion animals learning to escape but not to avoid central stimulation. With our simple avoidance procedure, these animals probably will learn to wait in the start box for the rewarding onset of stimulation, and when the continued stimulation starts to get painful, they will run to the correct side, where it is turned off. Incidental observations of the animals' behavior supports this view. In the avoidance procedure, it was observed that nearly every one of the reward-aversion rats learned and performed "superstitious" responses in the start box during the delay period between the dropping of the start door and the onset of ESB. The superstitions were responses like standing and sniffing in the rear corner of the start box as soon as the start door was dropped. It was inferred that these superstitious "waiting" behaviors were being reinforced by the onset of ESB.

One animal learned to avoid. This was the animal trained with the modified avoidance procedure because of motor side-effects from ESB. Since its motor reaction did not impair its bar-pressing performance, it was kept in the experiment. The avoidance procedure used for this animal gave it a fixed 10 sec. of ESB for a failure to avoid. It learned rapidly, reaching the criterion on Trial 15.

A possible explanation of its avoidance learning is that if this *S* waited in the start box to get the rewarding onset of stimulation, it also had to take a considerable punishment, since it could not turn off the ESB by running as soon as ESB became painful. Perhaps the prolonged punishment counteracted the brief reward for waiting in the start box.

Experiment on Rats Restrained in Starting Box

To test the validity of this explanation, we operated four new reward-aversion rats. These animals were first checked through the usual pattern of reward bar-pressing, escape but not ordinary avoidance learning. They were then trained with a modified avoidance procedure. If *S* failed to leave the start box within 15 sec., the start door was closed, and brain stimulation was turned on. Ten seconds later, the start door was dropped for a second time, and *S* was allowed to run to the correct side, where stimulation was turned off. The major result is that none of these animals made a single avoidance response in 50 trials, at which time the experiment was terminated. Again we observed that these animals learned superstitious responses which kept them in the start box during the 15-sec. delay period. These results suggest that this modified procedure will not necessarily produce avoidance learning in reward-aversion animals.

Experiment on Central Reward Followed by Electric Shock

At this point we began to wonder whether it is at all possible for *S*s receiving ESB reward followed by the punishment of an electric shock to learn to avoid. Conceivably, the ESB reward is so potent that it overrides any aversive stimulus that follows it. To test this possibility, we used a situation in which the aversive stimulus was a grid foot shock controlled by *E*. The four reward-aversion rats mentioned above were given further avoidance training in a Miller two-compartment shuttle box. The *S* was dropped in a distinctive side to start the trial. Fifteen seconds later, if *S* had not run out, it was given a 1-sec. rewarding ESB followed immediately by a foot shock which *S* escaped by running to the "safe" compartment. To mimic the hypothetical recruitment of punishment from ESB, on each trial the foot shock was gradually increased from a low voltage, so that the more time *S* took in escaping, the stronger was the shock it terminated by running. The results of this study show that the animals learn to escape but not to avoid within 50 trials if the foot shock begins at a weak intensity (25 v.) and is turned up slowly over 3 sec. to a value of 200 v. However, they did learn to avoid if either the foot shock began at a strong intensity or was turned up quickly to a strong intensity (from 25 v. to 200 v. in 1 sec.). These results confirm our interpretation by showing that an initial reward can prevent the learning of avoidance to a subsequent noxious stimulus. Furthermore, whether or not an animal learns to avoid depends on the strength and delay of the aversive stimulus relative to the initial reward.

TABLE 1

Correlations of Bar-Pressing Measures[a]

Variables	*df*	Correlation
1. With escape learning		
a. Ad lib.	11	
Rate		.33
Total stim. time		−.42
Preferred interval		−.61**
Off-time		−.11
b. 0.4 sec.	11	
Rate		.09
Off-time		.01
c. 3.0 sec.[b]	9	
Rate		−.21
Off-time		.30
2. With preferred interval		
a. Ad lib. rate vs. 0.4-sec. rate	11	−.48*
b. Ad lib. rate vs. 3.0-sec. rate	9	−.58*

[a] Because the distributions of raw scores were positively skewed, all statistics are based on logarithmic transformations of the raw scores.

[b] Two animals could not be given the 3.0-sec. test. Both *S*s had chosen short preferred intervals and learned to escape in the T maze. They took one bar-press with the 3.0-sec. schedule and went into a wild panic of squealing and jumping about, invariably landing on the bar again in their frantic movements. Under these conditions no meaningful measure of bar-pressing performance could be obtained. However, had we been able to include them, they would have increased the correlations in the expected direction.

* One-tailed *p* significant at .05 level.

** One-tailed *p* significant at .025 level.

Bar-Pressing Measures

The bar-pressing measures were total number of responses and total stimulation time during the 10 min. that ESB was available in the tests. From these two basic quantities we derived two other measures: average off-time and preferred interval. Average off-time was calculated by dividing total off-time (10 min. minus total time on the bar) by the number of responses. Preferred interval (average on-time) was calculated by dividing total stimulation time by the total number of responses given over the 10 min. in the ad lib. test. This measure is of no interest in the fixed-interval tests since the stimulation interval was independent of the holding time. For reward-aversion rats the preferred interval measure ranged between 0.15 and 0.8 sec., while for *S*s showing reward effects only it ranged from 0.33 to 5.19 sec.

With respect to bar-pressing, we reasoned that reward-aversion rats would learn to choose short intervals of stimulation in the ad lib. test because longer intervals hurt them. The converse of this statement, namely, all rats choosing short intervals are reward-aversion rats, does not necessarily hold. However, in a group of rats which includes a sizable proportion of reward-aversion animals, this correlation should be relatively high. Therefore, for animals preferring short intervals, we predicted (*a*) that prolonged stimulation would probably be aversive and motivate the learning of an escape response, and (*b*) that they were likely to show a large decrement in rate of bar-pressing when switched to the long fixed interval.

To check Prediction *a*, the *S*s were dichotomized into those which met the escape-learning criterion (9 of 10 correct) and those which did not. A point biserial correlation was obtained between this dichotomized variate and the *S*s' preferred interval measure. The negative correlation of −.61 in Section 1 of Table 1 means that *S*s with short preferred intervals were more likely to meet the escape learning criterion, which supports the prediction. The point biserial correlations of other bar-pressing measures are included for comparison. Preferred interval is the only bar-pressing measure that correlates significantly with escape learning. The mean preferred interval for escape learners and nonescape learners was 0.36 sec. and 2.03 sec., respectively. These means differ significantly ($p <$ .05) by a t test.

To test the validity of Prediction *b*, each animal was given two change scores: one represented the difference in rate of bar-pressing under ad lib. and the 0.4-sec. fixed-interval condition; the other represented rate difference under ad lib. and the 3.0-sec. condition. Product-moment correlations were obtained between these difference scores and the *S*s' preferred interval. The negative correlations in Section 2 of Table 1 mean that *S*s having short preferred intervals, as defined by the ad lib. test, were more likely to show greater decrements in response rate when switched to the fixed-interval conditions. These correlations support Prediction *b*.

Since the preferred-interval measure seemed to be the only good predictor variable in our bar-pressing results, we thought it necessary to show that it is a consistent measure of an S's ad lib. bar-pressing performance. To this end, an analysis of variance was performed on the preferred-interval measures obtained from the first and second ad lib. tests. The differences between *S*s were significant ($p < .01$) while the F for replications variance was less than one. The retest reliability coefficient of the measure was .97. This shows that it is a consistent measure.

We are presently conducting a study of ESB parameters (current intensity, pulse frequency, and pulse duration) which appear to affect the aversive component, and hence the preferred-interval measure, of reward-aversion rats.

To obtain further information about bar-pressing under the various stimulation schedules, separate analyses of variance were performed using rate and average off-time as dependent variables. For both measures, there was significant variance contributed by subject differences ($p < .01$) and by the different stimulation schedules ($p < .01$). The group mean rate of responding is about the same for the ad lib. and 0.4-sec. conditions, but is significantly lower in the 3.0-sec. condition. The subjects by conditions interaction was significant ($p < .05$), supporting the expectation that the pure reward and the mixed reward-aversion rats would differ in their over-all pattern of responding to the three stimulation schedules.

Histology[2]

The histology reveals that animals showing both reward and escape learning had electrodes in the middle to anterior portion of the medial forebrain bundle, and it is possible that the fornix was involved. To show that the fornix is not necessary, we operated six additional rats and obtained the reward-aversion effect from electrodes in the medial forebrain bundle, anterior to the columns of the fornix. To show that the fornix is not sufficient, five other animals with electrodes implanted in the body of the fornix, just above the branching of the fornical columns, showed neither reward nor aversion.[3] Finally, animals with electrodes placed far posteriorly in the medial forebrain bundle showed reward but not escape learning. A considerable number of rats with electrode placements in other parts of the hypothalamus have not showed the reward-aversion effect. Thus, it seems that the middle to anterior portions of the medial forebrain bundle are responsible for producing the reward-aversion effect. It is possible, however, that reward-aversion effects (perhaps with somewhat different properties) may be obtained from stimulating other structures which we have not investigated.

[2] The histology was done by Burton Rosner and Judith Levine.

[3] We are grateful to Burton Rosner for suggesting these placements to delimit the critical structures.

SUMMARY

Thirteen reward rats were given bar-pressing tests with varying stimulation schedules and were tested in a T maze for aversive effects of prolonged stimulation at the same electrode and at the same intensity. Twenty-one additional rats with implanted electrodes were used in further tests of specific subhypotheses. The major findings are: first, there are structures in the rat's brain where the onset of electrical stimulation is reinforcing, but if stimulation continues, it becomes aversive and its termination is reinforcing; second, such reward rats will show escape learning but not ordinary avoidance learning; third, animals that show an aversive effect from prolonged stimulation will prefer relatively short intervals of brain stimulation; and, finally, the reward-aversion effect was obtained from electrodes in the middle to anterior portions of the medial forebrain bundle.

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