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## Instrumental Learning of Vasomotor Responses by Rats: Learning to Respond Differentially in the Two Ears


Abstract. *Curarized and artificially respirated rats were rewarded by electrical stimulation of the brain for changes in the balance of vasomotor activity between the two ears. They learned vasomotor responses in one ear that were independent of those in the other ear, in either forepaw, or in the tail, or of changes in heart rate or temperature. In addition to implications for learning theory and psychosomatic medicine, these results indicate a greater specificity of action in the sympathetic nervous system than is usually attributed to it.*


In previous studies from this laboratory, we have discussed the importance of the instrumental learning of visceral responses for theories of learning and psychosomatic medicine, and have summarized the literature; we have presented evidence that the instrumental learning of cardiac, gastrointestinal, and renal responses can occur in curarized rats, with the use of either the onset of rewarding brain stimulation or the offset of mildly painful electric shock to the tail as reinforcement (*1*).

DiCara and Miller (*2*) have shown that vasomotor responses in the tail of the rat can be modified by instrumental learning. The purpose of the experiment we now report was to determine whether such vascular learning can be made specific to a given structure, such as one ear. In order to accomplish this, individual measures of vasomotor responses in the ears of the curarized rat were fed into a bridge circuit so that the differences in vasomotor activity between the two ears could be detected. The output of the bridge circuit was then fed in parallel into two pens of a Grass polygraph. One pen, the tip of which was constructed of a brass ballpoint, traced the between-ear difference over the surface of a plate constructed of 25 strips of brass, each 1.7 mm wide, inlaid into a flat piece of Plexiglas and separated from each other by 0.3 mm. When these strips were appropriately connected to programming equipment, reward consisting of electrical stimulation of the brain (ESB) could be delivered whenever the pen tracing the difference between the two ears was on or beyond a specified "reward criterion" strip. The second pen traced an ink record of the exact movements of the first pen. Other pens recorded the separate responses of each ear.

Subjects were 12 male rats of the Sprague-Dawley strain (394 to 558 g), implanted with permanent monopolar electrodes aimed at the medial forebrain bundle with Krieg stereotaxic coordinates of 1.5 mm posterior to bregma, 8.5 mm below the surface of the skull at 1.5 mm lateral to midline. Subsequent histologic examination showed that all of the electrode tips were located in the medial forebrain bundle at the level of the ventromedial nucleus [for details of general method, see (*3*)].

During vasomotor conditioning, the subject lay prone in a harness-supported cloth sling, placed in a soundproof, ventilated enclosure equipped with a loudspeaker delivering a 1000-hz tone at 82 db. The sling was cut so as to allow the subject's forepaws to hang down through the opening and rest on a small platform support. Grass photoelectric plethysmograph transducers were used to measure the vasomotor activity in the ears, forepaws, and tail. Recordings were taken at a sensitivity of 0.1 mv/cm for the ears, and 1.0 mv/cm for the forepaws and tail. The transducers were rigidly mounted on swivel arms attached to the metal frame of the harness so that the arms could be adjusted in all directions to place the photocells in homotopic positions on the ears (bisecting the central artery) and forepaws. The photocell used to measure vasomotor activity in the tail was placed at the base of the tail, and the tail was elevated about 3 cm to allow excreted boluses to pass without disturbing the position of the photocell. Heart rate was measured with previously implanted stainless steel electrodes, and temperature was measured by a thermistor probe inserted 4 cm into the rectum. A Grass Model 5 polygraph was used for all recordings.

Three to 4 days before vasomotor training, and approximately 2 weeks after electrode implantation, a current ranging from 30 to 100 $\mu$a was adjusted for each subject in order to elicit maximum rates of bar pressing for 0.5 second of 60-cycle a-c ESB. Current was then held constant, and on the next 2 days each subject was trained on fixed-interval schedules. During this training, a 1000-hz tone was turned on whenever bar pressing would secure ESB, and turned off during the time-out intervals (lengthened progressively: 5, 10, 20, 30 seconds), at which time the subject was in silence and ESB was not available.

The day after the above training, subjects were injected intraperitoneally with 3 mg of *d*-tubocurarine chloride per kilogram of body weight in a solution containing 3 mg/ml; the animals were fitted with a specially constructed face mask and artificially respirated, with the ratio of inhalation to exhalation being 1:1 (70 cycle/min, and a peak pressure of 20 cm-water). Addi-

tional *d*-tubocurarine was infused intraperitoneally at 1.0 mg per kilogram of body weight per hour throughout the experiment.

At the end of a 60-minute habituation period, vasomotor training began. Of the 12 rats used in this experiment, six were rewarded for relatively greater vasodilatation in the right ear (which could also be relatively less vasoconstriction), and the other six were rewarded for relatively greater vasodilatation in the left ear. Assignment to groups was random except for the last two subjects, that had to be assigned to the group rewarded for left-ear dilatation. All subjects had ESB electrodes located on the right side of the brain.

Training consisted of the presentation of trials signaled by the onset of the 1000-hz tone, during which the subject could obtain ESB for making the proper vasomotor response, and time-out or intertrial intervals during which the subject remained in silence and ESB was not available. A total of 300 trials was presented on a variable-interval schedule with a mean intertrial interval of 30 seconds (range: 10 to 50). The fifth trial and every tenth trial thereafter were test trials during which ESB could not be obtained for the first 7.5 seconds of the trial, so that vasomotor performance could be measured without contaminating effects from having the tone turned off or ESB turned on. On the tenth trial and every tenth one thereafter, subjects received so-called blank trials each lasting 7.5 seconds, during which vasomotor activity was recorded, but the subjects remained in silence and could not achieve reward. Throughout training, each block of 20 trials was analyzed, and the criterion level (that is, the difference in vasomotor activity between the two ears required to obtain ESB) was made more difficult if the time to achieve reward fell below an average of 5 seconds and easier if it was above 10 seconds.

The results are presented in Fig. 1. Since the resistance of the photocell in the photoelectric transducer depends on the amount of light reaching it, changes in vasomotor activity have been expressed as changes in resistance of the photocell. The subjects rewarded for relatively greater vasodilatation in the right as compared to the left ear showed significant increases in dilatation of the right ear ($P < .01$) and significant decreases in vasodilatation of the left ear ($P < .01$), with the difference between the two ears at the end of training being

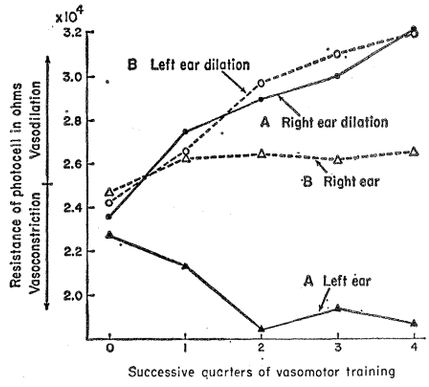


Fig. 1. Learning a difference between the vasomotor responses of the two ears. Group A was rewarded for relatively more dilatation of the right ear; Group B was rewarded for relatively more dilatation of the left ear.

highly significant ($t = 10.12$, $P < .001$). Subjects rewarded for relatively greater vasodilatation in the left as compared to the right ear showed significant vasodilatation of the left ear ($P < .01$) but did not show a significant change in vasomotor activity in the right ear. However, despite the lack of significant vasomotor changes in the left ear in this group, the increase in the difference between the ears during training, as well as the difference at the end of training ($t = 5.18$, $P < .001$), was highly significant.

During training, the between-paw difference in vasomotor response was not significantly correlated with the between-ear difference ($\rho = -.22$), and at the end of training there was no significant difference between the paws ($t = .32$).

These results indicate that the learned differences between the vasomotor responses of the two ears were specific to the ears and not to the entire right or left side of the rat's body. Analyses of heart rate, vasomotor activity in the tail, and temperature did not indicate any significant overall changes either between groups at the end of training or within groups during training; however, both groups showed slight increases in vasoconstriction of the tail and in body temperature. In previous experiments on heart rate, rats learned the discrimination of changing their heart rate during the time-in stimulus, when such a response would be rewarded, rather than during the time-out intervals between trials, when it would not. However, analyses of vasomotor responses on blank and test trials in the present experiment did not indicate any evidence of discrimination learning.

The experiment described here adds to an increasing list of successful attempts to secure instrumental learning of visceral responses mediated by the autonomic nervous system, and represents a striking example of the specificity of the learning which can be achieved. Since the vasomotor innervation to the ear of the rat is primarily, if not wholly, sympathetic, the results indicate that the sympathetic nervous system has a greater capacity for specific local activity than usually has been attributed to it. The specificity of visceral learning is further supported by the finding that changes in either heart rate or intestinal contraction can be learned without changes in the other response (*4*). Furthermore, Miller and DiCara (*5*) have secured instrumental learning of changes in urine formation, accompanied by changes in renal blood flow but independent of heart rate and blood pressure, and of vasomotor responses in the tail. The specificity of learning of a variety of visceral responses demonstrated in these experiments makes it difficult to salvage the strong traditional belief that the instrumental learning of visceral responses is impossible by trying, as Black (*6*) has done, to explain the visceral changes produced by training as the indirect effects of somatic learning mediated by the cerebrospinal nervous system.

Finally, if changes in the blood flow to organs other than the kidney can be learned, and if these changes have the specificity that our experiment has demonstrated for the vasomotor responses of the ears, such changes could have significant consequences for psychosomatic medicine.

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