which may cause differences in amplitude of the two frequencies. Thus R_c is used only if it is desired to equate the amplitudes of the different frequencies. (One-ohm-per-inch

resistive wire serves well as R_c .) To vary amplitude in discrete steps within one or more frequencies, additional relays and resistors (not shown) can be added.

A convective thermal controller for behavioral experiments

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The Convective Thermal Controller (CTC) is designed to provide rapid and precise control of a thermal stimulus for application to behavioral experiments with small animals. Subjects are bathed in one of two continuously recirculating air systems; two valves determine which of the systems play on S. When the systems are stabilized at different temperatures, actuation of the valves can produce an abrupt and stable temperature change in .3 sec. Behavioral observations indicate that escape learning occurs readily; latency decreases monotonically with drive intensity and increases monotonically with reinforcement duration.

The most general requirement of any device designed to control temperature is that it allow the rate of temperature exchange at the surface of an experimental organism to be varied with speed and precision. Most devices fail to meet this requirement in several ways. The first is speed of action. When a heat lamp or heating coils are used to heat an animal in a refrigerated environment (Weiss & Laties, 1960; Carlton & Marks, 1958), the termination of the radiant energy may be sufficiently abrupt when the heat source is turned off, but the air surrounding the animal has also been heated and it therefore will slow the return of the environmental temperature to the cold condition. A slowly changing thermal stimulus may have some application, but for most conditioning situations, a rapid acting system would be preferred. Another problem arises with the mode of application of a thermal stimulus. Several means of transferring heat to and from an animal have been used: convection with hot and cold air (Thorpe & Corbit, 1968), forced convection cooling (Matthews, 1968), radiant heating, and even evaporative cooling by showering a heated animal with a water spray (Epstein, 1968). Radiant heating and evaporative cooling are useful for changing temperature in one direction, but not in the other. A S can be heated but not effectively cooled by radiant energy. Similarly, it would be impractical to attempt to maintain a cool environment by continuous evaporative cooling. The result of this asymmetry is that comparisons of behavior in the presence of hot and cold conditions are confounded by procedural differences. Furthermore, it is difficult and sometimes impossible to calibrate the cold and hot stimuli on the same scale. A third difficulty involves the stability of the stimulus. A radiant lamp directed at a rat heats not only the rat but the air surrounding him. There is, therefore, an instantaneous and stable effect of the radiant heat, an; a slow increasing convective heating effect through the air. A more serious difficulty, however, is that radiant heat transfer occurs only at exposed surfaces, so that portions of the animal not directly exposed to the lamp will not be heated, except through conduction and convection.

Recently we have developed an apparatus to circumvent these difficulties. Although it is more complicated than previous devices, it satisfies the important requirements of thermal control.

THE APPARATUS

The Convective Thermal Controller (CTC) is essentially a forced convection system in which the animal is bathed in air of a controlled temperature. The application of this principle was suggested by John D. Corbit who found that rats will turn off a fan which circulates cold air around them (Matthews, 1968). In the present application, air circulates continuously over the animal but the temperature of the air is varied. Two continuously circulating enclosed air systems are arranged so that one system is circulating over the animal while another is circulating through a shunt. This arrangement is presented schematically in Fig. 1. When the valves are actuated, the air stream which had been flowing over the animal is directed through the shunt, and conversely, the system which had been circulating through the shunt is rerouted through the chamber. The function of the lower valve is to redirect the air emerging from the chamber and the shunt back into the correct source. The systems are enclosed so that there is neither mixing of temperatures, nor contamination of the room temperature with that of the system. In addition, greater maximum and minimum temperatures can be maintained. When the two systems are at different temperatures, the temperature surrounding the animal can be altered from one stable value to another in the time it takes the valves to change position, and the air to pass from the valve to the animal.

The overall design has several useful features. (1) The rate of change of temperature of the air is independent of the temperatures being presented and is only a function of the wind velocity and valve action time. (2) The temperature surrounding the animal is stable almost immediately after a switch is made and remains so indefinitely. (3) Under all conditions the mode of heat transfer is convection which produces more uniform exchange of heat at the surface of the animal. (4) All stimulus conditions are measured on the same scale, the temperature of the air in degrees. (5) The system is essentially modular. If it is desirable to present more than two temperatures to the animal, this is accomplished by adding an additional pair of valves for each new temperature condition.

Fig. 1. Schematic view of CTC. Solid line arrows indicate flow of hot system, dashed line arrows indicate cold system flow.

Air Propulsion

The air in each system is impelled by 100-cu ft/min squirrel cage blowers fixed at the input and output ports of the upper and lower valves, respectively. When measured at the chamber, the velocity of the wind in each system was approximately 1500 ft/sec or 17 mph. The wind itself, however, was not aversive. This point was established by training a rat to turn off the wind with a bar press. When the temperature of the moving air was adjusted to between 30 deg C and 35 deg C (the skin temperature of rats), animals stopped pressing. Thus, when the effect of an increase in rate of temperature exchange induced by air motion is removed the wind itself is not aversive. Rohles (1965) has shown that wind speeds as low as 5 mph are aversive to the monkey (temperature of the wind and the still air were not manipulated independently). Our finding suggests that this aversiveness may be accounted for in terms of the thermal loss induced by air motion, rather than the air motion itself.

Ducting

The components of each system are connected together by Micro-lok fiberglass tubular duct (3.5-in. inside diam, 1-in. thick). This material is easy to work with and is an effective insulator.

Temperature Control

The temperature of the air in each system is altered from room temperature by one of two interchangeable source chambers; a "hot box" and a "cold box." The hot box consists of electrified nicrom wire coil suspended in an insulated fiberglass cylinder (14 in. inside diam, 18 in. high). A baffle at the exit port of the chamber produces turbulence which allows convective exchange to even the temperature in the system. In the cold box, the heating coils are replaced by a heat exchanger which consists of copper tubing surrounded by thin aluminum fins. Air flows around the coils and fins and gives off heat to a cold water anti-freeze solution circulated through the coils. Seventy gallons of the cooling fluid are contained in a conventional floor model home freezer. The temperature of the fluid is maintained at 4 deg C by allowing a layer of ice to form on the surface of the liquid so that the fluid temperature remains locked at the freezing point while heat is added during testing. The air temperature of the system is controlled by a thermostat located near the entrance to the upper valve. In the hot box, the thermostat turns the heating coil on and off which allows the temperature to range ± 0.05 deg C from the set point. The cold temperatures are regulated by thermostatic control of the pump which forces the cooling fluid through the heat exchanger. This results in accuracy of ± 0.15 deg C around the set point.

The Valve

The valve is designed to minimize the amount of time required to change temperature of the air in the chamber from one stable value to another. (Note Fig. 2, top view.) When the vane is in Position 1, air enters Port A and exits through the adjacent Port B. When the vane is changed to Position 2, the air entering Port A is then directed out of Port D. Likewise, air entering Port C passes out Port D during Position 1 and out Port B during Position 2. In the case of the upper valve, A and C might be the hot and cold ports, and B and D the chamber and shunt. When the vane is in Position 1, the hot air is directed into the chamber and cold into the shunt. When the valve is thrown to Position 2, cold air goes into the chamber and the hot air is circulated through the shunt.

The amount of time required for the air temperature to change at the location of the animal is a function of the time required to change the vane position, the air velocity, and the distance between the upper valve and the animal. The delay

Fig. 2. Top and side views of four-way valve used to direct the flow of the separate temperature systems.

between the command to the valves and the temperature change is approximately .3 sec.

The valves now in use were machined from a 4 x 4 x 4-in. aluminum stock. The vane was made from 1/2-in. acrylic plastic and is connected to the valve by two vane shafts seated in ball bearings. One shaft is connected to a 72-rpm Slo-Syn motor which turns the vane through 90 deg in .2 sec; the other is fixed with an eccentric to actuate two limiting switches which regulate the throw of the vanes.

The Test Chamber

The chamber was designed to minimize air turbulence. It is constructed of a Plexiglas cylinder (8 1/2-in. inside diam) connected to the inlet tube by a conical ceiling. The chamber is insulated by expanded dyerlite material approximately 2 in. thick. Air is removed through a trap in the bottom of the chamber which prevents excrement from passing into the lower valve. The animal is supported on a 5/8-in. mesh plastic screen and most of the fixtures within the chamber are constructed of plastic materials. This was done to prevent the rapid heat exchange that would occur at surfaces of the animal exposed to more conductive materials.

BEHAVIORAL OBSERVATIONS

The Ss were adult male albino rats, Charles River CD strain, obtained from Charles River Breeding Laboratories. All were shaved before use in the experiment.

Many animals were trained on an escape procedure with either cold or hot air as the aversive stimulus (the drive temperature). Room temperature air served as reinforcement; the response was a bar press. Training was usually rather rapid but sometimes required shaping. Certain behaviors occasionally emerged during shaping which competed with the bar pressing responses, e.g., huddling in the cold or sprawling in the hot. These interfering responses did not usually occur early in a session, so we terminated a session when they appeared, and resumed training later.

Rat D22 was used to test the effects of the duration of the reinforcement temperature. In this case the drive temperature was 45 deg C and the reinforcement temperature durations tested were 4, 10, and 20 sec, presented in Fig. 3 (left panel); mean latency increases monotonically with an increase in the duration of the reinforcement temperature. Although these results are in good agreement with the findings of many Es (Weiss & Laties, 1960; Satinoff, 1964; Carlisle, 1966), they seem paradoxical when compared to the usual findings of reinforcement magnitude studies with other reinforcers. Commonly, when food is used, greater response strength is associated with larger quantities of food (Crespi, 1942).

Fig. 3. Left Panel: Mean latency of the escape response for Rat D22 as a function of the duration of the response produced temperature condition. Right Panel: Mean latency of the escape response for Rat S91 as a function of the intensity of the drive stimulus.

Similarly, greater response strength is observed when ICS reinforcement train duration is increased (Hodos, 1965). A simple explanation, however, is that when a short duration reinforcer is used in the thermal situation, the thermal deficit induced by the previous drive stimulus would carry over into the following drive stimulus. This accumulation of drive over trials would result in short latency responding. However, when the reinforcer duration is long enough so that thorough reduction of drive can occur before the onset of the next drive stimulus, latency should be unaffected by the previous drive stimulus. Trial independence and reinforcement magnitude would affect latency oppositely from the point of view of reinforcement theory; this paradoxical result seems to be an artifact of trial nonindependence. However, in the context of behavioral thermoregulation, these results are easily resolved in terms of the animal's tendency to minimize thermal deficit.

Rat S91, with comparable previous training, was used to determine the effects of drive temperature on the latency of the escape response. The duration of the reinforcement temperature was 15 sec and the temperatures tested were, in order, 3 deg, 10 deg, 16 deg, 10 deg, 8 deg, and 3 deg C. Figure 3 (right panel) shows that latency increases monotonically with an increase in the difference between the drive and room temperatures. These results are, again, consistent with the finding of earlier experiments (Weiss & Laties, 1960; Carlisle, 1966). The findings of both tests are easily reproduced in other animals and can be generalized to

drive temperatures different from room temperature, regardless of the direction of difference.

Other common aversive control procedures were tested also. But even with numerous modifications of procedures usually used with electric shock, we were unsuccessful in developing a method that would produce a punishment effect or a conditioned emotional response (Estes & Skinner, 1941). Although we were able to produce reliable avoidance behavior after serious modification of the usual avoidance procedures, correct avoidance never exceeded 50%. Rather, Ss were more likely to stabilize around 40% correct responding. We have not suspended efforts to train animals to respond well under these conditions. So far, it appears that several factors are playing a role in this situation that are not normally considered when electric shock is used as the UCS.

In summary, the present apparatus provides a solution to many of the problems of thermal stimulus control. The most obvious application is to the study of behavioral thermoregulation, although it might be of broader interest in the study of conditioning and learning. Here appetitive and painful stimuli have been used almost exclusively for the study of reinforcement and drive effects.

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NOTE

1. The author is indebted to Russell M. Church, who served as advisor and provided support for this research, and to Lawrence Morin, Carol Wooten, and Sylvia Thorpe for their assistance in the design and construction of this apparatus. This research was supported by a grant (MH 08123) to Russell M. Church from the National Institute of Mental Health.