A Novel Contextual Dimension for Use With an Operant Chamber: From Simple to Hierarchical Forms of Learning

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A novel procedure is described in which the floor temperatures (warm and cool) in an operant chamber are used as contextual cues in 2 experiments with rats. Experiment 1 demonstrated that rats learn the relationship between these thermal contexts and auditory stimuli that have been paired with them. Experiment 2 showed that thermal stimuli can serve a conditional function that (a) reflects the operation of a mechanism that is common to conventional, visual contexts and (b) is bound to these contexts' ability to retrieve the nature of the relationship between the auditory stimuli and food.

The experimental study of rodent behavior within psychology and neuroscience has been dominated by the use of the operant chamber. Even in its basic form, this apparatus provides the opportunity to present animals with a range of stimuli, manipulanda, and events of motivational significance. Moreover, the ambient or contextual cues that accompany being placed in such a chamber (its visual characteristics, odor, and so on) are also cues that animals readily learn about (see Bouton, 1991). As versatile as this apparatus is, it remains the case that the number of stimulus dimensions that are both available and readily controlled (principally, the auditory and visual dimensions) serves as a constraint on the experiments that can be conducted. For example, when an additional stimulus dimension is required, different odor cues have been used that require procedures designed to minimize contamination between them. These procedures can be either expensive or inconvenient (e.g., Hall & Honey, 1989). At a practical level, therefore, the study of rodent behavior in the laboratory would be facilitated by the development of a system that allows another dimension to be presented. Moreover, many of our conceptual models of animal learning and memory (e.g., Gluck & Myers, 1993; McLaren, Kaye, & Mackintosh, 1989; Pearce, 1994; Rescorla & Wagner, 1972) assume that the principles that underlie them will be as likely to operate in one (sensory) domain as another. Use of an additional dimension would provide a way of assessing the generality of those effects on which our understanding of learning and memory has developed.

With these practical and theoretical considerations in mind, we describe the development and use of a novel addition to an operant chamber that allows thermal contexts to be presented to rats in a simple, economical and effective manner (see below). This investigation begins with an examination of associative learning using thermal contexts (Experiment 1). We then used these contexts in a conditional learning task and examined whether or not our thermal contexts and more traditional, visual contexts operate through a shared, hierarchical associative learning system (Experiment 2). The results of these experiments should enable us to establish that our novel procedure is effective and allow us to assess what is learned about thermal stimuli.

Experiment 1

Changes in temperature exert a dramatic influence on the everyday behavior of animals, and yet the use of thermal cues in the study of animal learning, in general, and in rodents, in particular, has been sporadic. In Pavlov's laboratory, the use of thermal conditioned stimuli in studies of salivary conditioning in dogs (see Pavlov, 1928, p. 90) appears to have been limited because of the peculiar tendency for these stimuli to induce drowsiness in the dogs (Pavlov, 1928, pp. 132 and 158). This observation, however, should not be taken to undermine the suggestion that thermal stimuli might be effective under other circumstances. For example, thermal stimuli have been used in an appetitive conditioning procedure with squirrels (Yoakum, 1909), as discriminative stimuli in shock avoidance conditioning in cats (e.g., Kenshalo, 1964), and a transient increase in temperature has been used as an unconditioned stimulus (US) in visual discrimination procedures with chicks (e.g., Honey, Bateson, & Horn, 1994; Wasserman, 1973). Finally, it has been established that rats acquire an aversion to the temperature of a liquid (Nachman, 1970) and associate the temperature of a liquid with its flavor (Heth, 1981). Taken together, the results described in this brief survey indicate that although thermal stimuli appear to be effective both as CSs and USs in a variety of species, the use of these stimuli has neither become commonplace nor has it been investigated in a systematic fashion in rats.

The alterations that we have made to an operant chamber that allow thermal contexts to be presented to rats are straightforward and consist of replacing the standard grid floor with an aluminum floor with a bracket fixing below that can hold two Thermos picnic

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blocks. These blocks can be heated in a microwave or frozen in a freezer. Once held in place by the bracket, the heated blocks result in a relatively constant floor temperature of 35 °C (henceforth, warm) over a period of 30 min, and the frozen blocks result in a floor temperature of 10 °C (henceforth, cool) over a period of 2 hr. Given that the duration of exposure to these floors was 3 min in Experiment 1 and 15 min in Experiment 2, the scope for changes in the floor temperature during the course of a session were limited (see below).

Experiment 1 examined whether rats represent the fact that a given floor temperature (e.g., warm) has been presented in conjunction with a specific auditory stimulus (e.g., a tone). The design of the experiment was based on that used by Rescorla and Cunningham (1978). In the first stage, rats were placed in an operant chamber for 3-min periods, and on some occasions the floor was warm and on others it was cool. When the floor was one temperature (A), one auditory stimulus (X; e.g., a tone) was presented, and when it was the other temperature (B), another auditory stimulus (Y; e.g., a clicker) was presented. To assess whether the rats had represented these relationships, we then placed them in a different operant chamber with a standard grid floor, and they received trials on which X was paired with footshock and other trials on which Y was presented but was not followed by footshock. Finally, we videorecorded the rats’ activity when placed on the two types of floor, A and B. If the rats represented the (AX and BY) relationships from the first stage of training, then changing the value of X by pairing it with footshock should be reflected in their behavior when they were placed on Floor A but not when they were placed on Floor B. We supposed that the rats would be less active when placed on Floor A than on Floor B (see Honey & Watt, 1999).

Method

Subjects. The subjects were 8 naive adult male hooded Lister rats (Rattus norvegicus; supplied by Harlan Olac Ltd., United Kingdom) maintained at 80% of their ad-lib weights (M = 458 g; range = 440–505 g). The colony room used to house the rats was illuminated between the hours of 0800 and 2000. Training and testing started at, approximately, 1100.

Apparatus. Four operant chambers (internal dimensions: 24.5 cm wide × 23.0 cm deep × 21.0 cm high; supplied by Campden Instruments Ltd., United Kingdom) arranged in a 2 × 2 array were used during the initial stage of training and the final test. Each chamber had three aluminum walls and an aluminum ceiling and floor. A Perspex door served as the fourth wall. The gauge of the aluminum used in the construction of the floors was, approximately, 1 mm, and the surface of the floor was 24.5 cm wide and 23.5 cm deep. The bottom surface of the aluminum floor had a bracket fixing with the following internal dimensions: 19.0 cm wide × 3.7 cm deep × 14.5 cm long. Two Thermos picnic blocks (model no. IP400; 9.0 cm wide × 3.7 cm deep × 16.0 cm long) could be inserted in the space between the bracket and the bottom surface of the floor. The size of the bracket was such that it resulted in the Thermos block being in contact with the aluminum floor that was immediately above it. The temperature of the floor, measured at the center of the floor’s surface, was 20 °C, and the temperature of the air, measured at the center of chamber, was 24 °C. Inserting two heated Thermos picnic blocks in the space below the floors for 10 min resulted in an increase in temperature of the floor to 35 °C and an increase in the ambient air temperature to 28 °C. The temperature of the floor declined to 32 °C over the course of 30 min, and the air temperature remained relatively constant over the same period. The blocks were heated in an 800-W Kenwood Simplicity Microwave (model no. KM2901T) for 3 min. If the blocks were heated for much longer than this, then they became inflated and would not fit in the space below the floor. Inserting two frozen Thermos picnic blocks in the space below the floors for 10 min resulted in reductions of the floor temperature to 10 °C and the air temperature to 22 °C. The floor temperature increased over a period of 2 hr to 12 °C, and the air temperature remained relatively constant over the same period. In both of the experiments reported in this article, the heated blocks were replaced every 30 min, and the frozen picnic blocks were replaced every 2 hr. The floors were kept clean using a damp cloth.

The doors of the sound-attenuating boxes for each of the chambers remained open throughout the experiment to allow rats’ behavior during the final test to be recorded using a Panasonic VHS movie camera (model no. NV-M40). All chambers received ambient illumination through their Perspex doors from the brightly lit experimental room in which the chambers were located and local illumination from a single, 15-V, 24-W jewel light in the center of the ceiling. The auditory stimuli were a 2-kHz tone and a 10-Hz click presented at an intensity of, approximately, 78 dB(A), from a speaker mounted above the aluminum ceiling. In an effort to avoid auditory contamination between the four chambers, the auditory stimulus presented at any point in time was the same in each of them. The chambers were equipped with a food well into which 45-mg food pellets could be delivered (P. J. Noyes, Lancaster, NH). There was a transparent plastic flap (6 cm high × 5 cm wide) hinged along the uppermost edge of the opening to the food well. A movement of this flap of, approximately, 2 mm could be automatically recorded as a single response or magazine entry. Although no food pellets were delivered and no magazine entries were recorded in Experiment 1, both of these facilities were used in Experiment 2.

A fifth chamber was used for aversive conditioning. This chamber was identical to the other chambers with the exception that the floor of the chamber was made from stainless steel rods (0.5 cm in diameter and mounted 1.5 cm apart) that could be electrified using a shock generator coupled with a shock scrambler (Campden Instruments Ltd., Models 521C and 521S, respectively). This chamber was positioned below the other four chambers.

Procedure. The experiment was conducted over the course of 5 days. On each morning of the first 4 days of the experiment, rats received four 3-min training trials. On two of these trials, rats were placed in a chamber in which the floor was one temperature (A) and an auditory stimulus (X) was presented for the duration of the trial; on the remaining trials, the rats were placed on a floor with a different temperature (B), and a second auditory stimulus (Y) was presented for the duration of the trial. The auditory stimulus was turned on immediately prior to the rats’ placement in the chambers and was turned off at the end of the trial. The rats were then placed in a holding cage for approximately 1 min before the next designated trial began. The identities of the floor (warm or cool) that were designated as A and B and those of the auditory stimuli (tone or clicker) that served as X and Y were fully counterbalanced: For half of the rats, the warm floor was paired with the tone and the cool floor with the clicker, and for the remaining rats this arrangement was reversed. Half of the rats in each of the counterbalanced subgroups received the trial order AX, BY, AX, BY on Days 1 and 4 and the trial order BY, AX, AX, BY on Days 2 and 3, and the remaining rats received the order BY, AX, AX, BY on Days 1 and 4 and AX, BY, BY, AX on Days 2 and 3. On Days 1 and 4, the top chambers had warm floors and the bottom chambers had cool floors, and on Days 2 and 3, the top chambers had cool floors and the bottom chambers had warm floors. This arrangement (a) allowed the experimenter to simply exchange rats between different trials within a session without having to change the temperature of a given chamber, and (b) resulted in any characteristic of a particular chamber, with the exception of its temperature, being irrelevant with respect to the auditory stimulus that was presented. Within each day of the experiment, half of the rats received training in the top chamber first and training in the bottom chamber second, and for the remaining rats this arrangement was reversed.

In the afternoon of the final day of initial training, rats received aversive conditioning in the fifth operant chamber. The training session included...
two 30-s presentations of X that were both followed by a .5-s .5-mA footshock and two 30-s presentations of Y that were not reinforced. For all rats, the order of trials was X,Y,Y, X, and the intertrial interval (ITI) was 2 min. On the fifth day of the experiment, all rats received two 3-min test trials on which they were placed on Floors A and B. These trials were separated by, approximately, 1 hr. For half of the rats in each subgroup, the order in which the trials was presented was A, B and for the remainder it was B, A. For each animal, the top chamber was warm, and the bottom chamber was cool. Although we video-recorded rats' behavior during the entire 3-min test trials, our analysis focused on the first minute of each test trial because rats became generally less active toward the end of each trial. We began scoring each test trial when the door closed following the experimenter's exit from the experimental room.

Video scoring. The scoring of videotapes was conducted in the way described in Honey and Watt (1999) by an observer (R. C. Honey) who was blind with respect to the treatment received by the rats. A brief auditory stimulus (200 ms) was presented at the end of every 2-s period, and the observer judged whether the rat had been active at any point during the 2-s period that had just elapsed. Activity was defined as any behavior with the exception of that necessary to maintain breathing. A score of 1 was given for a 2-s period in which activity was noted, and a score of 0 was given for a 2-s period in which no activity was noted. We assumed rats would be less active in a chamber in which they were more fearful. This method of scoring produces a high level of interobserver agreement (see Honey and Watt, 1999). The level of agreement between the individual scores from 120 observations (comprising the behavior of 2 rats on an A test and a second pair of rats on a B test) made by a second unaware observer (Jasper Ward-Robinson) and R. C. Honey was 88%. The level of agreement between the overall rates of responding (with a maximum of 30 rpm) was also high; R. C. Honey scores are with corresponding Jasper Ward-Robinson scores in brackets: 22 (19), 16 (15), 22 (21), and 24 (23).

Results and Discussion

The results of the test trials on the final day of Experiment 1 are shown in Figure 1. Inspection of this figure reveals that rats were less active when placed on Floor A than when they were placed on Floor B and that this effect was equally apparent when Floor A was warm and Floor B was cool as when Floor A was cool and Floor B was warm. Statistical analysis confirmed these impressions. Analysis of variance (ANOVA) with floor type (A or B) and counterbalancing (warm or cool) as factors revealed that there was an effect of floor type, F(1, 6) = 16.56, p < .01, no effect of counterbalancing and no interaction between these two factors, Fs < 1. These results show that rats readily learn that a given floor temperature is accompanied by a specific auditory stimulus. In doing so, our results both demonstrate the efficacy of our simple alterations to an operant chamber and extend the range of conditions under which sensory preconditioning can be observed. In Experiment 2, we investigate the use of our novel contexts in tasks that are more complex and theoretically interesting.

Experiment 2

Honey and Watt (1999) investigated the associative structures that are acquired during various conditional discriminations involving conventional stimuli. In one experiment, rats received a conditional discrimination in which two associative relationships (X → food and Y → no food) were in force in two visual contexts (A and C), and the complementary pair of relationships (X → no food and Y → food) were in force in a second pair of visual contexts (B and D). After this training, C was paired with footshock, and D was presented but was not paired with footshock. This revaluation stage resulted in rats being less active or more fearful in Context C than in Context D. It also resulted in rats being less active in Context A than in Context B. These results indicate that rats, in some way, represent the fact that Context A, like Context C, signaled the same associative relationships during conditional training and consequently treat A and C in a similar or equivalent manner. This view is consonant with hierarchical accounts of conditional learning (e.g., Holland, 1983). Experiment 2 examined whether or not such an acquired equivalence effect can be demonstrated between thermal and visual contexts that signal the same associative relationships. To demonstrate such an effect would indicate that our novel contextual dimension operates (a) in the same manner and (b) through the same hierarchical learning mechanism as visual contexts. Moreover, it would establish that this mechanism operates on stimuli that each come from a different modality (thermal, A and B; visual, C and D; and auditory, X and Y).

On each day of the first stage of Experiment 2, rats received four sessions of training. During two of the sessions, rats were placed in operant chambers that were undecorated and had floors that were either warm or cool (Contexts A and B) and in the remaining sessions rats were placed in operant chambers that had been decorated with distinctive wallpapers (check or dots) and that had standard grid floors (Contexts C and D). When the rats were placed in either Context A (e.g., warm) or Context C (e.g., check) presentations of one auditory stimulus, X, were followed by the delivery of food, whereas presentations of Y were not. When rats were placed in either Context B (e.g., cool) or Context D (e.g., dots), Y was followed by food and X was not. In the revaluation stage of the experiment, rats continued to receive food pellets in C but received no food pellets in D. We assumed that this procedure would result in rats approaching the food well more frequently in Context C than in Context D. Following this revaluation stage, rats were simply placed in Contexts A and B, and the rates of magazine entries were recorded. If the original stage of conditional training

![Figure 1](image-url)
Method

Subjects and apparatus. The subjects were 16 naive adult male hooded Lister rats (Rattus norvegicus) from the same source as those used in Experiment 1. The rats were maintained at 80% of their ad-lib weights (M = 346 g; range = 317–364 g) and housed in the same way as in Experiment 1. Four chambers were used that were arranged in a 4 × 1 column. The middle two chambers (2 and 3) were the same as those used in Experiment 1. The outer chambers (1 and 4) had grid floors, and their walls and ceilings were lined with Perspex. A different type of wallpaper was hung behind the Perspex lining sheets in each of the two chambers: the wallpaper in the top chamber (1) consisted of black dots (diameter, 1.5 cm; center-to-center distance, 2.5 cm) on a white ground, and the wallpaper in the bottom chamber (4) was black and white check (3.0 cm × 3.0 cm squares). An additional set of eight conventional operant chambers that had grid floors and were housed in a different experimental room were used for magazine training (see below).

Procedure. On the first day of Experiment 2, rats were trained to retrieve food pellets from a food well in conventional operant chambers. On the first session of training, the plastic flaps in front of the food tray were fixed in a raised position and thereby allowed the rats ready access to the food pellets; on the second session of training, these flaps were lowered, and rats had to move the flaps in order to gain access to the food pellets. During both sessions, 20 food pellets were delivered on a variable time (VT) 60-s schedule. On each of the next 16 days of training, rats received one session in each of the four contexts: A and B (warm and cool) and C and D (check and dots). The interval between the sessions within each day was, approximately, 1 min. During this interval, rats were placed in a holding cage. When rats were placed in Contexts A and C, presentations of X were followed by two food pellets, and presentations of Y were nonreinforced, whereas when rats were placed in Contexts B and D, presentations of X were nonreinforced and presentations of Y were followed by two food pellets. The interval between the termination of the reinforced stimuli and the delivery of food pellets was 1 s. The auditory stimuli were both 10 s. In each session, there were 10 presentations of X and 10 presentations of Y. The ITI was 30 s, and X and Y were presented according to pseudorandom sequences that each had the constraint that no more than two trials of the same type occurred in succession. The identities of the thermal contexts (warm or cool) that served as A or B and that of the visual context (check or dots) that served as C and D were fully counterbalanced. Similarly, the identities of the auditory stimuli (tone or clicker) that served as X or Y were fully counterbalanced. On days 1, 4, 5, 8, 9, 12, 13, and 16, Chamber 2 was warm and Chamber 3 was cool, and on the remaining days, this arrangement was reversed. The order in which rats received the four context sessions (A, B, C, and D) changed from one day to the next. Within a 4-day block of training, each of the contexts was presented in the four possible positions within a day (first, second, third, and fourth), and placement in any one of the contexts (e.g., A) was equally likely to be immediately followed by or preceded by placement in any of the other three contexts (B, C, or D).

Scoring procedure. During each session, we recorded the overall rates of magazine entries during the reinforced and nonreinforced auditory stimuli. This scoring procedure has the advantage that it provides a relatively stable measure of the development of the discrimination across a series of days. However, it necessarily obscures changes in performance that might occur within a given session. Accordingly, some strategies that might contribute to the solution of contextual conditional discriminations will go undetected. For example, rats might appear to have solved the discrimination, but they are in fact simply responding on the basis of the reinforcement contingencies (e.g., X → food and Y → no food) that are in force within a given session of training. Although this strategy might contribute to differences observed during conditional discrimination training, it could not play any role in the subsequent stages of Experiment 2. In these stages, we assessed whether the rats have learned that a specific relationship (e.g., X → food) was operative in one context but not in another; and in these stages of training, the auditory stimuli (X and Y) were not presented.

Results and Discussion

To simplify the presentation of the results of conditional discrimination training, we have collapsed the rats' rates of responding during X and Y across the two types of thermal context and the two types of visual context. The mean rates of magazine entries during reinforced and nonreinforced presentations of X and Y in the thermal and the visual discriminations are shown in the left-hand panel of Figure 2. Inspection of this panel reveals that the thermal and the visual conditional discriminations were acquired—the rates of magazine entries on reinforced trials exceeded those on nonreinforced trials by an appreciable margin. It is also apparent, that the rate of magazine activity on nonreinforced trials was higher in the thermal discrimination than in the visual discrimination. This description of the left-hand panel of Figure 2 was supported by the results of an ANOVA with discrimination type (thermal or visual), trial type (reinforced or nonreinforced), and block as factors. This ANOVA revealed an effect of discrimination type, F(1, 15) = 5.80, p < .05, an effect of trial type, F(1, 15) = 85.94, p < .0001, and no effect of block, F(1, 15) = 6.63, p < .05. Analysis of simple main effects revealed that...
there was an effect of discrimination type on the level of responding on nonreinforced trials, $F(1, 15) = 15.43, p < .01$, but no corresponding effect on reinforced trials, $F < 1$; there was also an effect of trial type in both the thermal discrimination, $F(1, 15) = 54.10, p < .001$, and the visual discrimination, $F(1, 15) = 80.72, p < .001$. In addition, there was an interaction between trial type and block, $F(3, 45) = 9.52, p < .001$. Analysis of simple main effects revealed that there was no effect of block on the level of responding observed on reinforced or nonreinforced trials, largest $F(3, 45) = 1.46, p > .23$; and that there was an effect of trial type at each block, smallest $F(1, 15) = 15.43, p < .001$; largest $F(1, 15) = 72.76, p < .001$. Neither of the other possible interactions from the original ANOVA was significant, largest $F(3, 45) = 1.82$.

The results of central interest from Experiment 2 are shown in the right-hand panel of Figure 2. The left-hand pair of bars show the mean rates of background responding when the rats were placed in Contexts A and B during the final block of conditional discrimination training. Inspection of this pair of bars reveals that, prior to the revaluation treatment, Contexts A and B did not support different levels of magazine activity. ANOVA confirmed that this was the case, $F < 1$. Inspection of the center and right-hand pairs of bars reveals that during both tests rats were more likely to approach the magazine in thermal Context A than in thermal Context B. ANOVA pooled across the two tests revealed an effect of context (A or B), $F(1, 14) = 5.32$, no effect of floor type (warm or cool), and no interaction between these factors, largest $F(1, 14) = 3.74$.

Experiment 2 shows that rats can acquire a conditional discrimination in which thermal contexts (A and B) and visual contexts (C and D) indicate the nature of the relationship between auditory target stimuli (X and Y) and their consequences (food and no food). The results from the critical test trials revealed an acquired equivalence effect between a thermal context and a visual context that had signaled the same relationships. This effect suggests that the solution of the two forms of contextual discrimination is bound to rats' capacity to encode the fact that Contexts A and C accompany one pair of relationships ($X \rightarrow$ food and $Y \rightarrow$ no food), whereas B and D accompany the complementary pair of relationships ($X \rightarrow$ no food and $Y \rightarrow$ food).

Summary and Conclusions

Changes in ambient temperature exert a dramatic influence over both our everyday behavior and that of other animals. Given this observation, it is noteworthy that there has been relatively little research using thermal cues within laboratory investigations of learning and memory in rodents. In this article, we described a simple system for presenting thermal cues within an operant chamber and documented their use in a variety of tasks. In general terms, the results of the experiments indicate that our thermal cues are quite effective in simple, associative learning tasks involving aversive conditioning and in more complex conditional tasks, involving appetitive conditioning. Experiment 1 used a simple procedure in which one floor temperature (e.g., warm) was paired with one auditory stimulus (e.g., a tone), and a second floor temperature (e.g., cool) was paired with a different auditory stimulus (e.g., clicker). Subsequently, revaluing one of the auditory stimuli (e.g., the tone) by pairing it with footshock resulted in rats being less active when placed on a floor with the temperature (warm) that had been paired with the tone during initial training. In Experiment 2, rats learned that when they were placed on one floor (e.g., warm), presentations of a tone would be followed by food and those of the clicker would not, whereas when they were placed on the other floor (e.g., cool), presentations of the clicker were reinforced whereas those of the tone were not. Finally, Experiment 2 demonstrated that the effective similarity of two quite different contexts (e.g., warm and check) is increased as the result...
of a training procedure in which both signaled a common relationship relative to when each signaled a different relationship. This finding is akin to other demonstrations of acquired relational equivalence (see Honey & Watt, 1999) and shows both that (a) this effect has some generality and that (b) common hierarchical learning processes underlie the way in which thermal contexts and visual contexts influence responding in conditional discriminations. The nature of these hierarchical processes, however, need not be particularly complex, and it is possible that the operation of at least some of them are obligatory rather than being restricted to the relatively complex procedures used in Experiment 2 (see Honey, 2000). The fact that our experiments have revealed parallels between the action of visual contexts and thermal contexts is interesting given that many of the physiological processes activated by changes in temperature are quite different to those activated by visual contexts. Indeed our thermal contexts, like pharmacological agents, could be regarded as stimuli that produce internal states (see, e.g., Eich, 1980). If this suggestion is correct, then the results of Experiment 2 can be taken to provide compelling evidence that the state dependence and context dependence of some forms of learning share a common origin.

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