

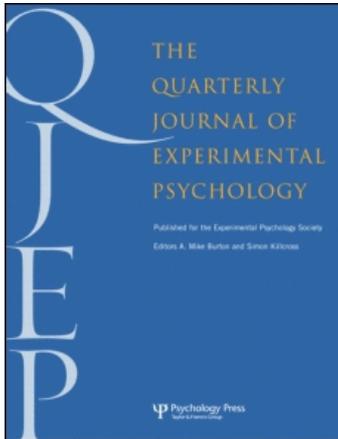
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# Analysis of an ambiguous-feature discrimination

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An autoshaping experiment with pigeons and three appetitive Pavlovian conditioning experiments with rats investigated the course of an ambiguous-feature discrimination in which trials with stimuli A and BC were followed by food, and trials with B and AC were not. The discrimination between A and B was acquired more rapidly than the discrimination between BC and AC in all experiments. Furthermore, the acquisition of conditioned responding with A was faster than that with BC for the three rat experiments. The results of these experiments are discussed in terms of elemental and configural theories of associative learning.

*Keywords:* Conditioning; Configural; Discrimination learning; Elemental.

Animals can solve discriminations in which the outcome of a trial is indicated not by the presence or absence of a particular stimulus, but by the presence of a particular combination of stimuli. For example, using a negative patterning discrimination, Woodbury (1943) gave dogs food after trials in which two stimuli, either A or B, were presented alone, but not after trials in which these stimuli were presented together, A+ B+ AB-. By focusing on either A or B alone it would not be possible to solve this discrimination. Instead, its solution rests on an appreciation that A and B signal food when they are presented separately, but not when they are presented together. In contrast to the relative ease with which such a configural discrimination can be solved, it has proved rather difficult to find a satisfactory

theoretical explanation for how this class of problem is learned. To illustrate this predicament we focus on what has been called the ambiguous-feature discrimination (Holland & Reeve, 1991).

The ambiguous-feature discrimination involves three stimuli and four trials: A+ B- AC- BC+ . An unconditioned stimulus (US) is presented after trials with A alone and the compound BC, but not after B alone or the compound AC. It should be apparent that the three stimuli by themselves are ambiguous as signals for whether or not the US will be delivered. Instead, as for the foregoing patterning discrimination, the solution of the discrimination is revealed by the overall pattern of stimulation on each of the four trials. The reason for being interested in this problem is that different

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theories of discrimination learning make contrasting predictions about the manner in which it will be solved.

According to the Rescorla–Wagner model (Rescorla & Wagner, 1972; Wagner & Rescorla, 1972), when a compound consisting of two or more stimuli is presented a unique configural cue is generated that participates in the associative learning process in the same way as normal stimuli. With the ambiguous-feature discrimination, therefore, compounds AC and BC will create two different cues, say, X and Y, respectively, which will be effective only when the appropriate compound is present. According to Rescorla and Wagner (1972), the discrimination will result in some of the stimuli gaining excitatory associative strength and some gaining inhibitory associative strength. The magnitude of change in associative strength of a stimulus on any trial is determined by the discrepancy between a value set by the magnitude of the reinforcer and the combined associative strength of all the stimuli present on that trial. This relationship is expressed by an equation presented in Rescorla and Wagner (see also, Wagner & Rescorla). The top and centre panels of Figure 1 show computer simulations based on this equation for the ambiguous-feature discrimination assuming that each compound creates its own unique configural cue. For the simulation, the magnitude of the reinforcer was set at 1 for reinforced trials and 0 for nonreinforced trials. The learning-rate parameter for reinforced trials was .2, and for nonreinforced trials it was .1. In addition to incorporating a learning-rate parameter that reflects the properties of the reinforcer, the equation also has a learning-rate parameter that reflects the salience of the stimulus whose change in associative strength is being calculated. The top panel of Figure 1 shows the predicted effects of discrimination training on the associative strengths of A, B, AC, and BC when the salience of all stimuli, including the configural cues, is .2. The centre panel shows the results from a simulation in which the associability was .2 for stimuli A, B, and C and .05 for the configural stimuli. A common feature of these figures is that responding during the compounds is predicted, initially, to be stronger than that to the elements. Indeed, throughout the

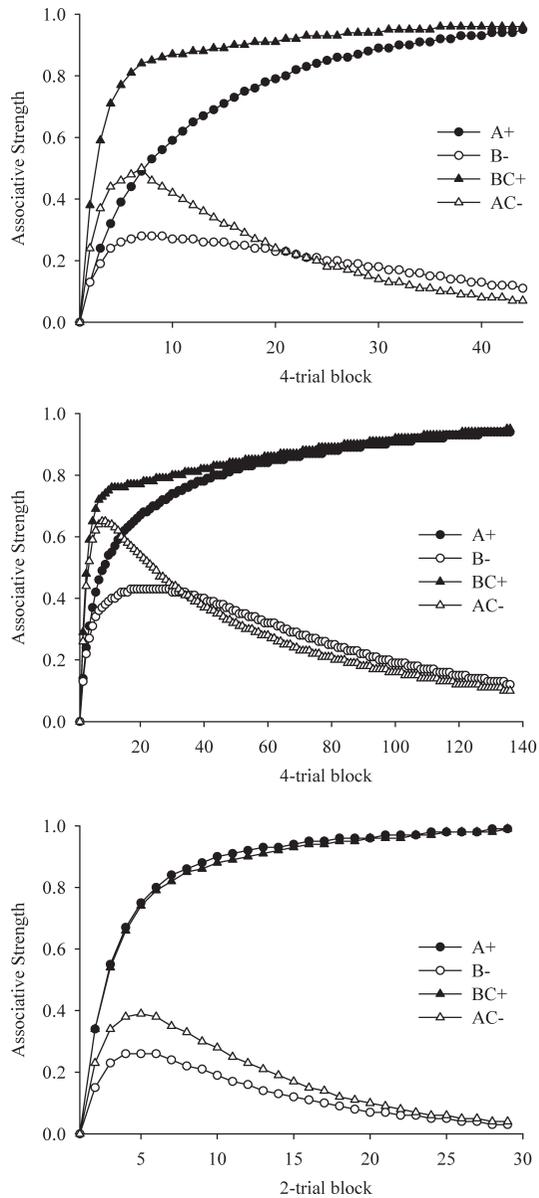


Figure 1. Simulations of the ambiguous-feature discrimination with the Rescorla–Wagner (1972) model—top and centre panels—and the theory of Pearce (1987, 1994)—lower panel. Note different scales on the abscissae. See text for the details of the simulations.

discrimination, responding is predicted to be stronger to BC than A. In addition, for both simulations, the discrimination is eventually predicted to be more

pronounced between AC and BC than between A and B. Thus the Rescorla–Wagner theory is able to predict that the ambiguous-feature discrimination can be solved, provided the existence of configural cues is allowed, and the acquisition of the discrimination is predicted to follow a reasonably consistent course despite substantial variations in the salience of the configural cues relative to the actual cues.

A rather different explanation for the way in which the ambiguous-feature discrimination is solved is provided by the configural theory of Pearce (1987, 1994, 2002). Training is assumed to result in the growth of a single association between the reinforcer for that trial and the entire pattern of stimulation that preceded it. The strength of responding on any trial is then determined by the associative strength of the pattern that is presented, together with the associative strength generalizing to that pattern from similar patterns. Pearce (1994) provides a set of equations that specify the degree of generalization from one pattern to another and that also specify the change in associative strength that will take place to a given pattern on a training trial. The lower panel of Figure 1 shows the outcome of a computer simulation for the ambiguous-feature discrimination based on these equations. For this simulation the salience of A, B, and C was set at .2. The values of the learning-rate parameters for the reinforced and nonreinforced trials were the same as those for the previous simulations. In contrast to the predictions derived from the Rescorla–Wagner (1972) theory, the discrimination between A and B is predicted to be consistently more marked than that between AC and BC. Moreover, responding to the reinforced compound BC is never predicted to be stronger than that to the reinforced element, A. Thus by comparing the course of acquisition predicted by these different theories to that found when animals are trained on the ambiguous-feature discrimination, it should be possible to assess the relative merits of these accounts for how it is solved.

A number of experiments have used an ambiguous-feature discrimination, but for a variety of reasons their results are of rather little

value for choosing between the two theoretical accounts that have just been described. Nakajima (1997; see also Rescorla, 1993) reports a series of autoshaping experiments using an ambiguous-feature discrimination, but the components of the compounds were presented serially, with C preceding A and B, rather than simultaneously as considered above. Pigeons learned the discrimination, and the course of acquisition was more similar to that predicted by the theory of Pearce (1987, 1994, 2002) than the Rescorla–Wagner (1972) theory. However, because of the uncertainty about how a simulation of the theories under consideration should be performed for stimuli presented serially, it is difficult to draw any clear theoretical conclusions from these experiments. Other demonstrations of an ambiguous-feature discrimination are even less informative for the issue considered here. Many of these studies have again used serial compounds, and their results are reported in terms of difference scores based on the rate of responding during reinforced trials with either A or BC, less the rate of responding during the nonreinforced trials. (Han, Gallagher, & Holland, 1998; Holland, 1991; Holland & Reeve, 1991; Nakajima & Kobayashi, 2000). It is thus not possible to appreciate the course of acquisition of the discrimination with respect to each of the four different trials. There are several reports of experiments using an ambiguous-feature discrimination with simultaneous compounds. However, for some of these the data are again presented in the form of difference scores (e.g., Holland, 1991), and for the others reinforced A+ trials were administered before the complete discrimination was introduced (Alvarado & Rudy, 1995a, 1995b). In the latter circumstances the theories of Pearce and of Rescorla and Wagner make broadly similar predictions, and the outcome of the experiments is of little value of choosing between them. For instance, both theories predict that once the discrimination is initiated, responding will be weaker to B than to the AC compound, which is how the subjects performed. Nakajima (1992) reports an autoshaping experiment in which pigeons solved an ambiguous-feature discrimination with stimuli

that were presented as part of a simultaneous compound. Unfortunately, all but one of the birds in this experiment were pretrained on an ambiguous-feature discrimination with serial compounds. Again, without knowing how to simulate the theories under consideration with stimuli presented in a serial compound, it is difficult to know how the effects of this pretraining on the ambiguous-feature discrimination are to be interpreted.

## EXPERIMENT 1

In order to examine the manner in which an ambiguous-feature discrimination is acquired with simultaneous, rather than serial compounds, pigeons received an A+ B- BC+ AC- discrimination in which coloured triangles, presented upon a television screen, served as A, B, and C. Food was delivered after presentations of A and BC, and it was anticipated that autoshaped keypecking would eventually be more vigorous during these trials than during the nonreinforced trials with B and AC. The question of interest was whether the acquisition of the discrimination would resemble more closely the course predicted by the Rescorla-Wagner (1972) theory or the theory of Pearce (1987, 1994).

## Method

### *Subjects*

The subjects were 8 adult homing pigeons. The pigeons were housed in pairs and had free access to water and grit in their home cages. They were maintained at 80% of their free-feeding weights by being fed a restricted amount of food after each experimental session. They were maintained in a lightproof room in which the lights were on for 14.5 hr each day. The subjects had previously participated in an autoshaping experiment, conducted in different apparatus, with small coloured squares and vertical and horizontal stripes as stimuli, but were naïve with respect to the current stimuli.

### *Apparatus*

The experimental apparatus consisted of eight pigeon test chambers (30.0 × 33.0 × 35.0 cm). Each contained an 8.3-cm high × 6.5-cm wide clear acrylic panel, which was hinged at the top. Pecks on the panel were detected by a reed relay that was operated whenever a magnet attached to its lower edge was displaced by a distance greater than 1 mm. The midpoint of the panel was 24 cm above the floor of the chamber and 6.0 cm to the right of the midline of the chamber. A Sony colour television with a 10 × 7.5-cm screen was located 2.0 cm behind the acrylic panel. Food was delivered by operating a grain feeder (Colbourn Instruments, Lehigh Valley, PA) with an opening that measured 5.0 cm × 6.0 cm located in the same wall as the response key. The midpoint of the opening was 9.0 cm above the chamber floor and 7.0 cm to the left of the midline of the wall. The feeder was illuminated whenever grain was made available. The chambers were permanently lit during all experimental sessions by a 2.8-W incandescent bulb, operated at 24 V, located 2.5 cm above the top of the acrylic panel. A RISC PC microcomputer (Acorn Computers Ltd., Cambridge, UK), which was programmed in Arachnid (Paul Fray Ltd., Cambridge, UK), was used for the control of events, recording of responses, and generation of stimuli on the TV screens.

### *Stimuli*

The stimuli were presented on the TV screen, which was otherwise dark. Stimuli for A and B were counterbalanced as cyan or yellow right-angled triangles, the hypotenuse of which travelled from the top-left to the bottom-right hand corner of the screen. The dimensions of the triangles were 12.5 × 10.0 × 7.5 cm (hypotenuse, horizontal side, vertical side). Stimulus C was a magenta right-angled triangle that had the same dimensions. For half of the trials with A and AC, A was presented in the top-right half of the screen; on the remaining trials A was presented in the bottom-left half of the screen. Similarly, for half of the trials with B and BC, B was presented in the top-right half of the screen; on the remaining

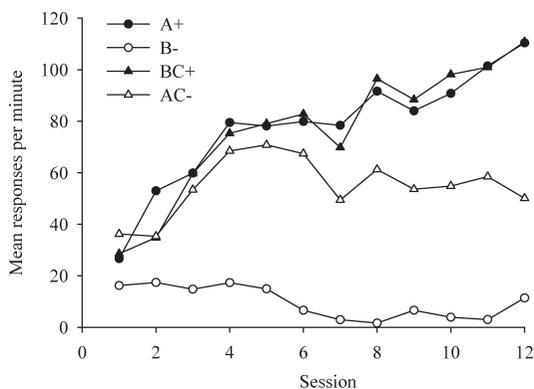
trials B was presented in the bottom-left half of the screen.

### Procedure

Because of their experimental history, the subjects required neither magazine training nor autoshaping. On each of 12 daily sessions of discrimination training there were 14 trials each with A, BC, B, and AC. The order of stimulus presentation was block randomized with the constraint that no more than three trials of the same kind (either reinforced or nonreinforced) could occur in succession. All stimuli were presented for 10 s, and following the termination of trials with A and BC, food was delivered, and the hopper was illuminated for 4 s. There were no programmed consequences following trials with B and AC. The mean intertrial interval, which was measured as the interval between the termination and onset of each trial, was 60 s (range: 35–85 s).

### Results and discussion

A Type I error rate of  $p < .05$  was adopted for all statistical tests. The course of the ambiguous-feature discrimination can be seen in Figure 2. By the end of the experiment, responding was more frequent during trials with A and BC than during trials with B and AC indicating that the discrimination was solved. Furthermore, the discrimination between A and B was solved sooner than the discrimination between BC and AC, and there was no difference in the rate of responding to A and BC. These observations were confirmed by a three-way analysis of variance (ANOVA) of individual responses per minute with the factors of session (1 to 12), number of elements (1 or 2 elements presented on a trial), and reinforcement (trials with or without food). The analysis revealed a significant effect of session, and significant Session  $\times$  Number of Elements and Session  $\times$  Reinforcement interactions,  $F_s(11, 77) > 2.90$ . There were also significant effects of number of elements and reinforcement and, crucially, a significant Number of Elements  $\times$  Reinforcement interaction,  $F_s(1, 7) > 7.84$ . The three-way interaction between the factors was not significant,



**Figure 2.** The mean response rates (responses per minute) during the ambiguous-feature discrimination training of Experiment 1. Visual stimuli A and B (counterbalanced as cyan and yellow triangles) were presented both alone and in compound with an ambiguous feature (C), which was a magenta triangle. Food was delivered on termination of A and BC but not of B and AC.

$F(11, 77) = 1.39$ . Simple main effects analysis was conducted to explore the Number of Elements  $\times$  Reinforcement interaction in more detail. This analysis revealed that, pooled over the 12 sessions, there was a difference between the nonreinforced stimuli, as responding to AC was faster than that to B,  $F(1, 14) = 15.69$ . There was, however, no difference in the rate of responding between the reinforced A and BC stimuli,  $F < 1$ . In addition, the discrimination between A and B was significant,  $F(1, 14) = 30.93$ , but the difference between BC and AC was not,  $F(1, 14) = 3.37$ ,  $p = .09$ . This is not to say, however, that the discrimination between BC and AC was not solved. The mean number of responses to BC and AC during the final two sessions of training were 110.85 and 50.10, respectively. The difference between these means was significant,  $t(7) = 3.30$ .

The results of this experiment do not accord well with the account of ambiguous-feature discrimination derived from the Rescorla–Wagner (1972) model. As the top and centre panels of Figure 1 reveal, this theory predicts that conditioning with BC should progress faster than that with A. There was no indication at any point during training that this was the case. From the relatively low levels of responding at the outset of training, to the rather

higher levels of performance towards the end, responding to A was much the same as that to BC. The notable feature of this experiment, however, was that the discrimination between AC and BC was substantially more difficult to solve than the discrimination between A and B. It is less clear whether this feature of the results can be accommodated by the Rescorla–Wagner model. On the one hand, the simulation in the top panel of Figure 1 shows that, contrary to our results, the discrimination between AC and BC should progress more rapidly than the discrimination between A and B. On the other hand, the simulation of the Rescorla–Wagner model shown in the centre panel of Figure 1 does show, at least early in training, a greater difference between A and B than between AC and BC. However, accompanying this difference should also be stronger responding during A than during BC, which, as we have already noted, was not a feature of our results. Furthermore, at the time when the discrimination between A and B is predicted to be greater than that between AC and BC, the model also predicts that responding to the nonreinforced AC compound should be stronger than that to the reinforced stimulus, A. This experiment provided rather scant support for this prediction.

In contrast to the failings of the Rescorla–Wagner (1972) model, the configural theory proposed by Pearce (e.g., 1987, 1994) fares rather better, at least qualitatively. The prediction that can be derived from Pearce’s theory for the course of the ambiguous-feature discrimination is shown in the lower panel of Figure 1. The ordering of the associative strengths of the stimuli shown in the figure corresponds with the ordering of the rate of responding to the stimuli shown in Figure 2, but the observed difference between the rates of responding during B and AC is considerably larger than that predicted.

## EXPERIMENT 2

The purpose of Experiment 2 was to replicate the results of Experiment 1, in a different species, rats, and using a different experimental procedure,

conditioned magazine approach. If the results of Experiment 1 have any generality then the course of the ambiguous-feature discrimination should progress in a manner more akin to that predicted by the theory proposed by Pearce (1987, 1994) than that predicted by the Rescorla–Wagner (1972) model. For Experiment 2 stimuli A and B were counterbalanced as a tone and a clicker, and C was the presentation of a light.

## Method

### *Subjects*

The subjects were 16 experimentally naïve, male, hooded-Lister rats (*Rattus norvegicus*) supplied by Charles Rivers UK Ltd. Rats were housed in pairs in a colony room illuminated from 0800 to 2000 and were permitted free access to water throughout the experiment. Before the experiment began, record was made of the rats’ weights (range: 420–515 g); thereafter, access to laboratory chow (which was, until this point, freely available) was restricted to allow their weights to reduce gradually to 80% of their free-feeding levels. Rats were maintained at this weight throughout the experiment and were fed one hour after each daily experimental session.

### *Apparatus*

All experimental procedures were performed in eight identically specified operant boxes supplied by Campden Instruments Ltd., Loughborough, UK. The boxes were individually housed in light- and sound-attenuated chambers that were equipped with an exhaust fan serving to ventilate the boxes and to provide a background noise level of 67 dB (Scale A). Each box had three aluminium walls and an aluminium ceiling; a transparent plastic door served as the fourth wall. The floor was made from stainless steel rods. The internal dimensions of a box were: 24.5 cm wide; 23.0 cm deep; 21.0 cm high. The boxes were equipped with a concave, recessed tray to which 45-mg food pellets could be delivered (Formula P, P. J. Noyes, Lancaster, NH). The tray was covered by a sprung, transparent plastic flap (6 cm high, 5 cm wide). Pushing this flap actuated

a microswitch, which was recorded as a response. Each box had four, 2.8-W incandescent lamps covered by 1.5-cm diameter plastic discs. One lamp was located centrally in the ceiling, and three were located on the wall that housed the food tray. Only two of the wall lamps were used. They were located symmetrically either side of the midline of the wall, 12.5 cm apart (centre to centre), and 15 cm above the floor. The ceiling lamp was also used but, unlike the wall lamps, its current was passed through a 120 $\Omega$  resistor, which resulted in a dim illumination of the box. A loudspeaker, located in the ceiling, could be used to present a 2-kHz tone and broadband white noise. A heavy-duty relay located on the top of the box could be operated at 10 Hz to produce a train of clicks. Auditory stimuli were approximately 10 dB (Scale A) above the background noise. A Risc PC micro-computer (Acorn Computers Ltd., Cambridge, UK), which was programmed in Arachnid (Paul Fray Ltd., UK, England), was used for the control of the experimental events and the recording of responses.

### Procedure

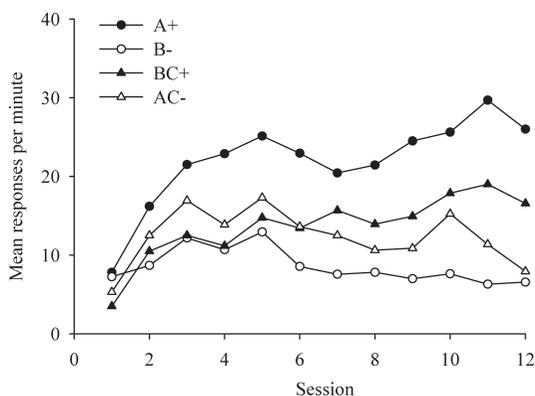
Rats were first trained to retrieve pellets from the food tray. In each of two sessions, pellets were delivered to the tray on a 1-min, fixed-interval schedule. In the first session the flaps that cover the food tray were held open with masking tape; in the second session, as in the rest of the experiment, the flap was not held open.

On the following day, the subjects began 12 sessions of ambiguous-feature training of the form: A+ B- AC- BC+. Two food pellets were delivered on the termination of A and BC but not following trials with B and AC. The tone and click served as A and B and were counterbalanced across subjects; illumination of the wall lamps served as C for all subjects. During compound presentations (AC and BC), C was presented simultaneously with A or B. There were a total of 32 trials in each session. The trial sequence was block randomized with the constraint that no more than three trials of the same type (reinforced or nonreinforced) could occur in succession. The

duration of the stimuli was 10 s, and trials were separated by a variable intertrial interval (ITI) that had a mean of 60 s (range: 30–90 s) measured from the termination of one stimulus to the onset of the next.

### Results and discussion

The results of the ambiguous-feature discrimination are summarized in Figure 3. The discrimination was eventually solved with responding on the reinforced trials with A and BC being faster than that on the nonreinforced trials with B and AC. Moreover the discrimination between the individual stimuli, A and B, was mastered more readily than that between the compounds BC and AC. An unexpected result was that responding on the reinforced trials was consistently stronger during A than during BC. The individual rates of responding for the four different types of trial for each of the 12 sessions of training were analysed using a three-way ANOVA with the factors of reinforcement, number of stimuli, and session. There was no significant effect of number of stimuli,  $F(1, 15) = 2.95$ , but there was an effect of reinforcement,  $F(1, 15) = 30.16$ ,



**Figure 3.** The mean response rates (responses per minute) during the ambiguous-feature discrimination training of Experiment 2. Auditory stimuli A and B (counterbalanced tone and click) were presented both alone and in compound with a visual, ambiguous feature (C), which was the illumination of wall lamps (in normally dark chambers). Food pellets were delivered on termination of A and BC but not of B and AC.

and a significant effect of session,  $F(1, 15) = 4.38$ . There was also a significant Session  $\times$  Reinforcement interaction,  $F(11, 165) = 6.79$ , and, in confirmation of the observation that the discrimination between A and B was mastered more readily than that between AC and BC, a significant interaction between reinforcement and the number of stimuli,  $F(1, 15) = 16.54$ . Subsequent tests of simple main effects revealed that responding on reinforced trials was more frequent during A than during BC,  $F(1, 30) = 17.39$ . The equivalent comparison for the nonreinforced trials fell short of statistical significance,  $F(1, 30) = 3.49$ . Simple main effects tests further revealed that responding during the reinforced trials was faster than that during the nonreinforced trials for the discrimination between A and B,  $F(1, 30) = 44.85$ , but not between BC and AC,  $F < 1$ . The remaining interactions from the three-way ANOVA were not significant,  $F_s(11, 165) < 1.46$ . Again, this is not to say that the discrimination between BC and AC was not solved. The mean number of responses to BC and AC during the final two sessions of training were 17.78 and 9.66, respectively. The difference between these means was significant,  $t(15) = 2.24$ .

The current experiment replicated some of the findings of Experiment 1. Again, the discrimination between AC and BC was acquired more slowly than that between A and B, a result that is more consistent with the theory proposed by Pearce (1987, 1994) than with that by Rescorla and Wagner (1972). The failure to confirm again this prediction of the Rescorla–Wagner model might be attributed to insufficient training, but there is scant evidence in Figure 3 to encourage the view that with further training the discrimination between BC and AC would ultimately be more marked than that between A and B. In addition, there was no hint at the outset of the discrimination of responding being faster during the nonreinforced trials with AC than during the reinforced trials with A, whereas this effect is predicted by each of the simulations of the Rescorla–Wagner model shown in Figure 1. A surprising result of the current experiment was that the acquisition of conditioned responding

was more rapid to A than it was to BC—a result that was not observed in Experiment 1. This outcome is particularly damaging for the Rescorla–Wagner model, simulations of which reveal that the opposite outcome should occur (see Figure 1). However, this result is also difficult for the theory of Pearce to account for. Recall that according to this theory, there should be rather little difference in the rate of acquisition between A and BC: To the contrary, and as a glance at Figure 3 reveals, responding was substantially stronger to A than to BC even from a relatively early stage of training.

### EXPERIMENT 3

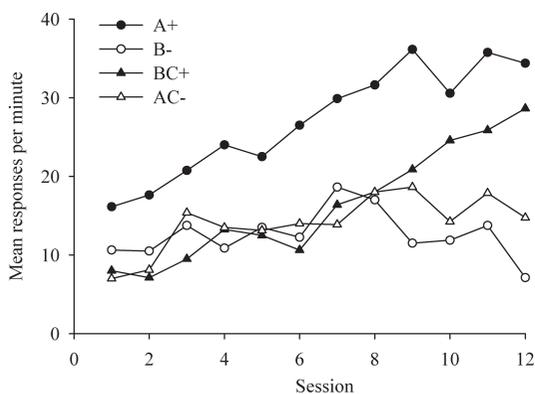
It is possible that conditioned responding was stronger to A than to BC in the previous experiment because of a peculiarity of the stimulus used as C. For Experiment 2 this stimulus was the presentation of a light; it is therefore conceivable that C interfered with the expression of conditioned responding during the trials with BC by, for example, evoking orienting responses away from the food magazine (e.g., Honey, Good, & Manser, 1998; Kaye & Pearce, 1984). The implication is that the associative properties of A and BC in Experiment 2 were in fact rather similar—in line with the results of Experiment 1—but a difference was observed between A and BC because the expression of the associative properties of BC was hindered. For Experiment 3, rats were again required to solve an ambiguous-feature discrimination; however, the identity of Stimulus C was changed. Now, the conditioning chambers were normally illuminated throughout the experimental session, but this illumination was turned off during trials with AC and BC. Thus darkness, rather than light, served as Stimulus C in the current experiment. If the results of Experiment 3 were a consequence of a peculiarity of the light serving as Stimulus C, then the outcome of Experiment 3 should resemble more closely that of Experiment 1, and conditioning to A and BC should progress at a similar rate.

## Method

The subjects were 8 experimentally naïve, male, hooded Lister rats, which were of a similar age, were obtained from the same supplier, and were maintained in the same way as the rats of Experiment 2. The apparatus was that used in Experiment 2. The conditioning boxes were normally illuminated by the operation of the wall lamps that were used for the stimulus C in the previous experiment. Stimulus C in the present experiment was produced by turning these lamps off. Stimuli A and B were the same as those for the previous experiment. The procedure was the same as that for Experiment 2.

## Results and discussion

The acquisition of the ambiguous-feature discrimination is shown in Figure 4. Despite the change made to stimulus C, the pattern of responding during the 12 sessions of training is remarkably consistent with that seen in Experiment 2. A three-way ANOVA similar to the one for the previous experiment revealed significant effects of reinforcement,  $F(1, 7) = 7.67$ , number of stimuli,  $F(1, 7) = 6.82$ , and session,  $F(11, 77) = 5.23$ . The Session  $\times$



**Figure 4.** The mean response rates (responses per minute) during the ambiguous-feature discrimination training of Experiment 3. Auditory stimuli A and B (counterbalanced tone and click) were presented both alone and in compound with a visual, ambiguous feature (C), which was darkness (in normally illuminated chambers). Food pellets were delivered on termination of A and BC but not of B and AC.

Reinforcement  $F(11, 77) = 4.15$ , and, crucially, the Reinforcement  $\times$  Number of Stimuli,  $F(1, 7) = 6.32$ , interactions were also significant. Tests of simple main effects for the latter interaction revealed that responding during A was faster than that during BC,  $F(1, 14) = 12.77$ , but the difference between the response rates during B and AC was not significant,  $F < 1$ . These tests also revealed that responding during A was significantly faster than that during B,  $F(1, 14) = 13.94$ , but responding during BC was not significantly faster than that during AC,  $F < 1$ . None of the remaining interactions from the three-way ANOVA were significant,  $F_s(11, 77) < 1.54$ .

Despite a substantial change in the nature of the stimulus that served as C between Experiments 2 and 3—from light to dark—the overall pattern of results remained the same. In particular, the acquisition of conditioned responding to A was again more successful than it was to BC during an ambiguous-feature discrimination. It would seem, therefore, that our appeal to the peculiarities of the light serving as Stimulus C in Experiment 2 were misguided. It is worth reiterating that these results pose a serious challenge to the account of the ambiguous-feature discrimination that can be derived from both the Rescorla–Wagner (1972) model and the theory proposed by Pearce (1987, 1994, 2002).

## EXPERIMENT 4

The results of Experiments 2 and 3 revealed that when either the onset or the termination of a light served as C in an A+ B- AC- BC+ discrimination, conditioned responding acquired more rapidly to A than to BC. It is possible that any change in the illumination of the conditioning chamber, be it a shift from darkness to light or vice versa, interfered with the expression of conditioned responding, thus generating the pattern of responding seen in Experiments 2 and 3. Although the results of these experiments do not allow us to refute this possibility with certainty, we have some reason to treat it with doubt. If the presence of C interfered with the

expression of conditioned responding then one would expect this effect to be present not only to BC, but also to AC. Thus, any tendency to evoke a conditioned response that AC acquires should be hindered by the presence of C, and consequently one would expect weaker responding during AC than during B, all else being equal. Contrary to this expectation, in both Experiments 2 and 3 the mean rate of responding was greater during AC than during B, and in fact the results of Experiment 2 indicate that this difference only just failed to reach statistical significance. Despite this doubt, Experiment 4 was conducted to examine an A+ B- AC- BC+ discrimination, in rats using entirely auditory cues. Under these circumstances, there is little reason to believe that C will elicit responses that will interfere with conditioned responding during A and B. Experiment 4 should therefore provide the opportunity to examine the course of an ambiguous-feature discrimination, untainted by the potentially interfering effects of a visual stimulus.

**Method**

The subjects were 16 experimentally naïve, male, hooded Lister rats, which were of a similar age, were obtained from the same supplier, and were maintained in the same way as the rats of Experiment 2. The apparatus was that used in Experiment 2. The conditioning boxes were normally dark, and a 10-s presentation of white noise served as Stimulus C. Stimuli A and B were the same as those for the previous experiment. The procedure was the same as that for Experiment 2 with the exception that discrimination training continued for 16 days.

**Results and discussion**

The acquisition of the ambiguous-feature discrimination is shown in Figure 5. The pattern of responding during the 16 sessions of training is similar to that seen in Experiment 2, except that the difference between the response rates during A and BC was smaller and eventually disappeared. A three-way ANOVA similar to the

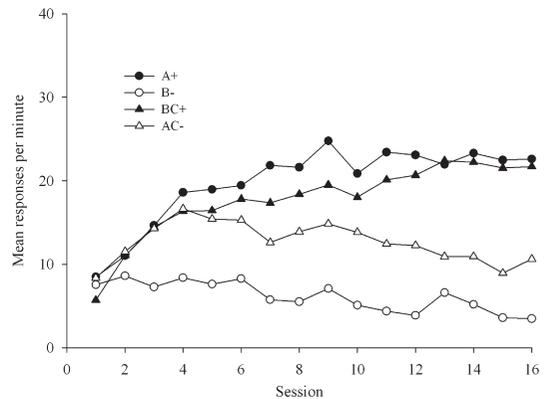


Figure 5. The mean response rates (responses per minute) during the ambiguous-feature discrimination training of Experiment 4. Auditory stimuli A and B (counterbalanced tone and click) were presented both alone and in compound with an auditory, ambiguous feature (C), which was white noise. Food pellets were delivered on termination of A and BC but not of B and AC.

one for the previous experiment revealed significant effects of reinforcement, number of elements, and a significant Reinforcement × Number of Elements interaction,  $F_s(1, 15) > 7.53$ ; there was also a significant effect of session, an interaction between Session × Reinforcement, and a significant three-way interaction,  $F_s(15, 225) > 3.66$ . Simple effects analysis of the three-way interaction revealed significant Reinforcement × Number of Elements interactions from Session 3 onwards,  $F_s(1, 24) > 4.23$ . Further simple effects analysis revealed that the difference between A and B was significant from Session 3 onwards,  $F_s(1, 480) > 14.40$ , but the difference between BC and AC was only significant from Session 7 onwards,  $F_s(1, 480) > 4.68$ . Responding to A was more frequent than that to BC on Sessions 7 to 9 and Session 11,  $F_s(1, 480) > 4.57$ , and responding to B was less frequent than that to AC from Session 3 onwards,  $F_s(1, 480) > 21.62$ .

The results of the current experiment replicated those of Experiments 2 and 3 using stimuli that were all drawn from the auditory modality. The discrimination between A and B was solved sooner than the discrimination between BC and AC. In addition, as conditioned responding emerged,

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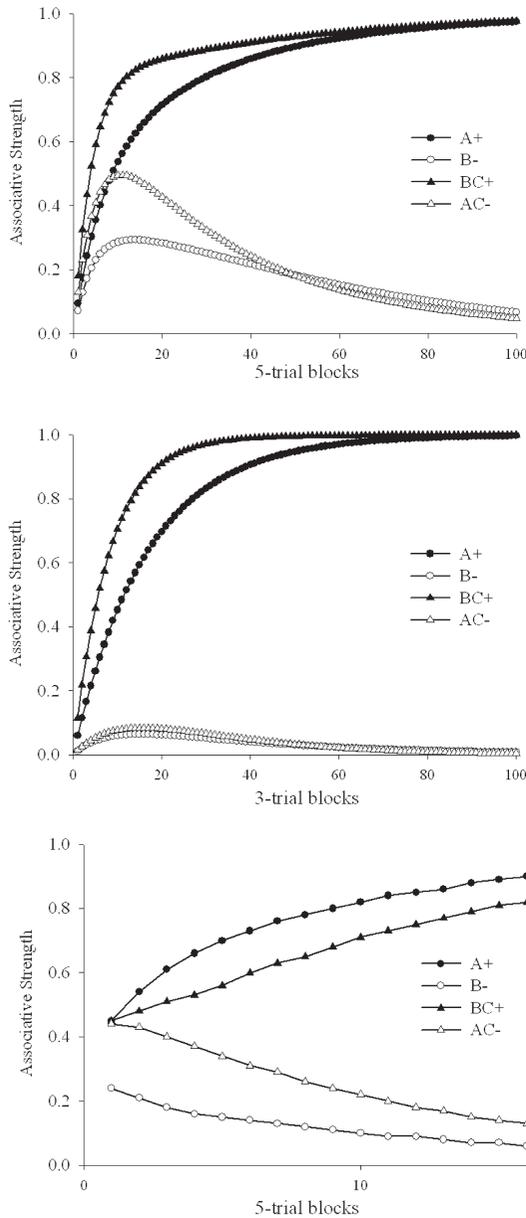
performance was stronger to A than to BC. The statistical analysis of Experiments 1 to 3 revealed significant Number of Elements  $\times$  Reinforcement interactions in each case, and simple-effects analysis of these interactions revealed successful solutions of the A versus B discrimination, but not of the BC versus AC discrimination. In contrast, the present experiment revealed a significant discrimination between BC and AC. Training in the present experiment continued for more sessions than in the previous studies, and it thus possible that insufficient training was responsible for the negative outcome concerning the statistical analysis of the results for the trials with BC and AC in the first three experiments.

## GENERAL DISCUSSION

Four experiments examined the course of an ambiguous-feature discrimination in which trials with A and BC were paired with food, and trials with B and AC were not. The results of Experiment 1, conducted with pigeons, revealed two main properties of the discrimination: First, the discrimination between A+ and B- was solved more readily than the discrimination between BC+ and AC-, and, second, there was no difference in the rate of acquisition to A and BC. The results of Experiments 2 to 4, conducted with rats, replicated the first of these properties, but not the second. In the final three experiments, the rate of conditioning to A was substantially faster than that to BC. The first property of the ambiguous-feature discrimination can be likened to results that have been reported on a number of occasions from our laboratory, which show that the addition of an irrelevant stimulus to a discrimination interferes with its solution (e.g., Pearce & Redhead, 1993; Redhead & Pearce, 1995). These results have been taken as evidence to support a configural theory of learning (Pearce, 1987, 1994, 2002). However, as we have pointed out, the faster conditioning to A than to BC seen in Experiments 2 to 4 is a result that does not accord with the predictions of Pearce's theory.

The predictions for the course of the ambiguous-feature discrimination derived from

the Rescorla-Wagner model have been based, thus far, upon the representation of stimulus conjunction as it is presented in Rescorla and Wagner (1972) and Wagner and Rescorla (1972; see also, Rescorla, 1972, 1973). According to this model, when two or more stimuli are presented in compound, an internal cue (or element) is deployed that is unique to that particular trial. Consequently, this conception of stimulus conjunction has been termed an *added-elements* model (Brandon, Vogel, & Wagner, 2000; Wagner & Brandon, 2001; Wagner, 2003). Wagner and his colleagues, however, have suggested that a better way of conceiving of stimulus conjunction in Pavlovian conditioning is through a *replaced-elements* model (REM). From this framework, a stimulus, say A, is argued to have the capacity to activate both context-independent and context-dependent elements. Context-independent elements are activated by A whenever it is presented. Context-dependent elements are activated only when A is presented within a specific context. For example, when A is presented in compound with another stimulus, such as C, it will activate elements that are not activated when A is presented alone. Where the replaced-elements model differs from the added-elements model is with the additional assumption that when A and C occur together, some of the context-dependent elements normally activated by A alone will be replaced by other context-dependent elements that are specifically activated when A and C are presented together. Although this modification to the added-elements idea has proved successful (Wagner, 2003) REM cannot provide a complete account of the results from the experiments reported here. The top and centre panels of Figure 6 show simulations of REM based upon the equations provided by Wagner (2003). The parameters for these simulations were set to the same values as those shown in the top panel of Figure 1. In addition, Wagner (2003) proposed a further parameter ( $r$ ) that represents the extent to which the presence of one stimulus will replace the elements of another. For the simulation shown in the top panel of Figure 6, this value was set to the



**Figure 6.** Simulations of the ambiguous-feature discrimination with the theories proposed by Wagner (2003)—top and centre panels—and the Rescorla–Wagner model (1972) using an overlapping-elements conception of stimulus representation—lower panel. Note different scales on the abscissae. See text for the details of the simulations.

relatively low level of 0.2, for the simulation shown in the centre panel, it was set at 0.8. It is notable that, like our simulations of the Rescorla–Wagner model shown in Figure 1, the simulations show that REM predicts, incorrectly, that acquisition to A will never be higher than that to BC. The simulation shown in the top panel of Figure 6 shows that REM can predict that the discrimination between A and B will be solved sooner than the discrimination between AC and BC; however, it does so only whilst making the additional, incorrect, prediction that responding to BC should be higher than that to A. Further simulations of REM that we have conducted have explored other values of  $r$ ; they have also varied the saliencies of A, B, and C and have varied the parameters associated with reinforcement and nonreinforcement. In none of these simulations have we been able to generate an output that resembles our data. Specifically, we have not been able to show with this model either (a) that conditioning to A and BC can proceed at a similar rate whilst extinction to B is rather more rapid than to AC (as in Experiment 1), and (b) that the acquisition of conditioned responding to A can proceed more readily than that to BC (as in Experiments 2 to 4). At face value, therefore, REM does not appear to provide a particularly satisfactory account of the way in which animals solve an ambiguous-feature discrimination.

An alternative explanation for the way in which animals solve configural problems such as the ambiguous-feature discrimination is based on the assumption that any stimulus will excite a set of elements, some of which will also be activated by other stimuli (McLaren & Mackintosh, 2002; Rescorla, 1972; Rescorla & Wagner, 1972, p. 86; Williams, Mehta, & Dumont, 2004). When this overlapping-elements conception of stimulus representation is applied to an A+, B-, AC-, BC+ discrimination then the Rescorla–Wagner model is rather successful. The lower panel of Figure 6 shows the output of a simulation of an ambiguous-feature discrimination with the equations provided by Rescorla and Wagner. For this stimulation, Stimuli A, B, and C each activated elements a, b,

and c, which were unique to these stimuli. In addition, it was assumed that A, B, and C will each activate an element that it shares in common with one other stimulus (ab, ac, and bc) as well as activating an element that all three stimuli will activate (abc). For this simulation the learning-rate parameters for each element were set to 0.2, as was the learning-rate parameters for reinforcement and non-reinforcement. All the remaining parameters for this simulation were the same as those used in Figure 1. In contrast to the simulations shown in the top and centre panels of Figure 1, the theory now predicts that the discrimination between A and B should be solved faster than the discrimination between AC and BC. In addition, the theory now predicts that conditioning should be more effective with A than with BC, which is exactly what was observed in Experiments 2 to 4. Interestingly, further simulations that we have conducted reveal that the results of Experiment 1 can also be explained by an overlapping-elements approach to learning if it is assumed that the elements activated by C (c, ac, bc, and abc) are less salient than the remaining elements. Although it remains to be determined whether this final assumption can be fully justified, the results of these simulations of the Rescorla–Wagner model indicate that an overlapping-elements conception of stimulus representation provides a better account for how animals solve an ambiguous-feature discrimination than does either a unique-cue (Wagner & Rescorla, 1972) or replaced-elements conception (Brandon, Vogel, & Wagner, 2000; Wagner, 2003; Wagner & Brandon, 2001).

The final theory to consider is that proposed by Pearce (1987, 1994, 2002). Recall that according to this theory, the acquisition of the discrimination between A and B should be acquired more readily than that between BC and AC, and that the rate of responding during A should be similar to that during BC. These predictions were confirmed in Experiment 1. As far as the remaining experiments are concerned, they confirmed that the discrimination between A and B is easier to master than that between BC and AC, but in each of them responding was, at least for some

of the trials, faster during A than during BC. There are at least two ways in which the theory of Pearce can explain this problematic finding. Computer simulations have revealed that predictions from this theory match reasonably well the results of Experiments 2 to 4 if it is assumed either that the salience of C was greater than of A or B, or that the learning-rate parameter (associability) on trials with the compounds AC and BC was less than that on trials with the elements A and B. As far as the first of these assumptions is concerned, the absence of appropriate counterbalancing of stimuli makes it possible that C was more salient than A or B but it would be unreasonable to assert that this was definitely the case. Another possibility is that the method of training resulted in more attention being paid to C than to A or B and thus effectively raising the salience of C relative to that of A or B. The obstacle facing this proposal is that it does not follow readily from current theories of attention (e.g., Mackintosh, 1975; Pearce & Hall, 1980). It is conceivable, however, that a rather different change in attention was responsible for our results. According to Kruschke (1996; see also Kruschke, 2001) exposure to complex discriminations will produce rapid shifts in attention that will lead to a stimulus receiving more attention in one context than another. Perhaps, therefore, our method of training resulted in more attention being paid to A and B on trials by themselves than on trials when they were accompanied by C. Although there is no precedent for assuming that this type of rapid attentional change occurs in animals, the complexity of the discrimination may have encouraged the use of more sophisticated attentional strategies than is normally considered possible. Furthermore, computer simulations of the theory proposed by Pearce have confirmed that attentional changes of this sort will result in a pattern of results that resembles the outcomes shown in Figures 3, 4, and 5. There is also no precedent for assuming that the associability of A and B when presented alone was greater than of the compounds AC and BC. However,

the fact that such an assumption enables configural theory to predict the results from our experiments with rats suggests it may be worth considering this possibility further. Thus it is possible for the theory of Pearce (1987, 1994, 2002) to explain the reported results, but it remains to be determined whether the assumptions on which this explanation is based are justified.

Thus far we have considered only the rate at which the discrimination between A and B was solved relative to the discrimination between BC and AC. However, it is useful to view the ambiguous-feature discrimination as simultaneous feature-negative (A+ AC-) and feature-positive (B+, BC-) discriminations. Interestingly, for Experiments 1 and 4, in which A, B, and C all shared the same modality, the feature-positive discrimination was solved more readily than the feature-negative discrimination. However, for Experiments 2 and 3, in which A and B were of a different modality to C, the opposite outcome was obtained: The feature-negative discrimination was solved more readily than the feature-positive discrimination.<sup>1</sup> A glance at Figures 1 and 6 reveals that in all our simulations of elemental (e.g., Rescorla & Wagner, 1972) and configural (Pearce, 1987, 1994) theories of learning, the feature-positive component of an ambiguous-feature discrimination is solved more readily than the feature-negative component. As we have already considered, it is possible that at least some of the features of Experiments 2 and 3 could have been a consequence of the change in illumination on trials with AC and BC interfering, at a peripheral level, with conditioned responding. If it could be demonstrated that the feature-negative component of an ambiguous-feature discrimination is solved more readily

than the feature-positive component when the effects of peripheral interference are minimized, then it would prove to be a major challenge to contemporary theories of discrimination learning.

Even though ambiguous-feature discriminations have been studied for more than 15 years, previous reports have failed to provide a clear description of how they are acquired. Some studies have involved the serial rather than simultaneous presentation of the stimuli, some have involved pretraining with the stimuli, and some have described performance in terms of the difference between the rates of responding during reinforced and nonreinforced trials. When the acquisition of this discrimination is studied using the simultaneous presentation of stimuli and by focusing on performance during each type of trial then it becomes clear that the manner in which it is solved poses a problem for current theories of learning. The results from all three experiments are hard to explain with unique-cue approaches to stimulus representation (e.g., Wagner, 2003; Wagner & Rescorla, 1972). Although configural theories (e.g., Pearce, 1987, 1994, 2002), and overlapping-elements models (e.g., McLaren & Mackintosh, 2000, 2002) of learning are able to explain the results from these experiments, the explanations offered rest on assumptions that remain to be fully justified. Future investigations into the manner in which ambiguous-feature discriminations are solved should therefore provide valuable insights into the mechanisms of discrimination learning.

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<sup>1</sup>A three-way ANOVA of individual mean responses per minute with the factors of session, reinforcement, and discrimination (feature positive vs. feature negative) reveal, for Experiment 1, a three-way interaction between these factors,  $F(11, 77) = 2.90$ . Simple effects analysis of this interaction revealed that the feature-positive discrimination was solved from Session 3 onwards,  $F_s(1, 168) > 8.70$ , whilst the feature-negative discrimination was not solved until Session 8,  $F_s(1, 168) > 3.98$ . An identical ANOVA performed upon the data from Experiment 3 revealed a significant Discrimination  $\times$  Reinforcement interaction,  $F(1, 7) = 6.82$ . Simple effects analysis of this interaction showed that, for this experiment, the feature-negative discrimination was solved,  $F(1, 14) = 13.81$ , but the feature-positive discrimination was not,  $F(1, 14) = 1.08$ .

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