

A test of Rescorla and Wagner's (1972) prediction of nonlinear effects in contingency learning

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Published online: 28 March 2012
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Abstract According to most theories, in a simple contingency learning situation, excitatory learning occurs when the probability of the unconditioned stimulus in the presence of the conditioned stimulus (p_1) is higher than the probability of the unconditioned stimulus in the absence of the conditioned stimulus (p_2). In Rescorla and Wagner's (1972) model, this prediction varies, depending on the parameters used. In the following experiments, we evaluated whether the difference between p_1 and p_2 that is required to produce excitatory conditioning is the same, independent of the specific value of p_1 , or whether this difference varies proportionally to p_1 's value. To do so, an appetitive procedure of Pavlovian conditioning with rats was used. In four experiments, we compared different levels of contingency (low, medium and high) and found that the difference between p_1 and p_2 that is required to produce excitatory conditioning increases when the value of p_1 is higher. The possibility of analyzing contingency learning as a discrimination between p_1 and p_2 is also discussed.

Keywords Contingency learning · Associative learning · Excitatory conditioning · Psychophysics · Discrimination · Rescorla and Wagner's (1972) model

Electronic supplementary material The online version of this article (doi:10.3758/s13420-012-0070-x) contains supplementary material, which is available to authorized users.

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Introduction

In many situations, organisms need to learn about the relationships between cues and their consequences. In the simplest case, a cue is paired with a significant outcome and can be used to predict the occurrence of that outcome. In non-human animal experiments, the cue is a conditioned stimulus (CS), and its relevant consequence is the unconditioned stimulus (US). If both of them were binary, there would be four possible presentations of the stimuli. At a given trial, the CS and the US can appear together, the CS can appear alone, the US can appear alone, or neither of them may be present. We call the frequencies of each of these possible combinations a , b , c , and d (see Table 1, e.g., Crump, Hannah, Allan, & Hord, 2007). Using the frequencies of each type of trial, the conditional probabilities of the US given the CS (p_1), and of the US given the absence of the CS (p_2), can be calculated. The value of p_1 is $a/(a + b)$, and the value of p_2 is $c/(c + d)$.

Learning the relationship between a CS and a US is the basis of the conditioning, and many theories and models have been proposed to explain such contingency learning. In 1968, Rescorla reported a series of conditioned suppression experiments in which the difference between p_1 and p_2 determined whether learning was observed or not. According to Rescorla, a CS will produce an excitatory conditioned response if it is an informative predictor of an increase in the probability of the appearance of the US.

Rescorla and Wagner's (1972) model had, among others things, the objective of explaining these results. The model is usually expressed using two formulas, $\Delta V = \alpha\beta_1(\lambda_1 - \sum V_{X_i})$ and $\Delta V = \alpha\beta_2(\lambda_2 - \sum V_{X_i})$. Parameters α and β are associated to the CS and US salience, respectively. The parenthesis formulation represents the difference between the asymptotic level of associative strength that a

Table 1 Trial types in contingency learning

	CS	\overline{CS}
US	<i>a</i>	<i>c</i>
\overline{US}	<i>b</i>	<i>d</i>

CS and US indicate the presence of the conditioned and unconditioned stimuli, respectively, and \overline{CS} and \overline{US} indicate their absence. The frequencies of each trial type are represented with the letters *a*, *b*, *c*, and *d*

US is able to support (λ) and the total associative strength that is governed by the stimuli on the present trial (V_{Xt}). The first formula is applied when the US is presented in that trial, the second when it is absent. Parameters β_1 and β_2 represent, respectively, the salience of the US and of its absence. In a similar fashion, λ_1 would be the maximum associative strength supported by the US, and λ_2 by the absence of the US.

Rescorla and Wagner (1972) ran several simulations of their model, showing that, through trial-by-trial learning, it can predict phenomena such as contingency learning and blocking (e.g., Kamin, 1969). In the years that followed, evidence of new phenomena predicted by the model, such as superconditioning (e.g., Rescorla, 2004) and overexpectation (e.g., Lattal & Nakajima, 1998), was found. Rescorla and Wagner's model, and other models that share with it many features (e.g. Mackintosh, 1975; Pearce & Hall, 1980; Van Hamme & Wasserman, 1994) had been found relevant to not only animal associative learning but also to fields such as artificial intelligence, neuroscience, or categorization (e.g., Gluck, 1991; Luque, López, Marco-Pallares, Cámara, & Rodríguez-Fornells, in press; Schultz, 2002; Soto & Wasserman, 2010).

Many other models and rules were developed to study contingency learning. One of the most used is Δp (Allan, 1980; Jenkins & Ward, 1965). It is a normative model of covariation between events. In this case, the events would be the CS and the US. It states that $\Delta p = p_1 - p_2$. Positive values of Δp indicate an excitatory relationship between the CS and the US, whereas negative values indicate an inhibitory relationship. A value of 0 indicates that they are independent; that is, the presence or the absence of the CS gives no information about the occurrence of the US. As can be seen, it is equivalent to the rule proposed by Rescorla (1968). Following Δp , other rules were developed (see Allan, 1993, for a review in humans, and Hammond & Paynter, 1983, for nonhumans). Chapman and Robbins (1990) showed that the asymptotic predictions of Rescorla and Wagner's (1972) model for a partially reinforced CS were equivalent to those of Δp if two assumptions were made. The first one was to assume that a contextual stimulus was present in every trial. The second was that the salience

of the presence and absence of the US was equal. That is, β_1 and β_2 should have the same value.

The assumption about the values of β_1 and β_2 is theoretically relevant, because using different values can change the predictions of the model in some circumstances. An example of this comes from the relative validity phenomenon (Wagner, Logan, Haberlandt, & Price, 1968). Wagner et al. (1968) reinforced two compounds (AX and BX) differentially in two groups. In the first group, the correlated group, AX was reinforced 100% of the trials, whereas BX was never reinforced. In the second group, the uncorrelated group, both compounds were reinforced on 50% of the trials. In both groups, X was reinforced half of the times it was presented, and according to Δp , it should show the same level of conditioning. Contrary to this prediction, the uncorrelated group showed a higher level of X conditioning than the correlated group. This result is predicted by Rescorla and Wagner's (1972) model only if β_1 is higher than β_2 . When β_1 and β_2 have the same value, the model predicts that X should have the same associative strength in both the correlated and the uncorrelated groups. On the other hand, if β_1 is higher than β_2 , it predicts correctly that X in the uncorrelated group should have more associative strength than in the correlated group (see Murphy, Baker, & Fouquet, 2001, for an extensive discussion). In their original work, Rescorla and Wagner used values of 0.2 for β_1 and 0.1 for β_2 , which would lead to a correct prediction. These same values are very often used when this model is used in animal learning literature (e.g., Miller, Barnet, & Grahame, 1995).

Rescorla (1968), Rescorla and Wagner's (1972) model, when β_1 and β_2 have the same value, and Δp all predict the same result: If a difference between p_1 and p_2 were enough to provoke excitatory conditioning, this should happen independently of the specific values of p_1 and p_2 . For example, a group of rats trained with $p_1 = 0.1$ and $p_2 = 0$ would have a $\Delta p = 0.1$, and the CS should have an asymptotic associative strength of 0.1. The same would be true for a group with $p_1 = 0.9$, $p_2 = 0.8$, or a third that had $p_1 = 0.5$ and $p_2 = 0.4$. If excitatory conditioning were found in one of them, it should be found in all three.

But, what would be the prediction if β_1 were higher than β_2 ? In this situation, from a psychological point of view, trials in which the US is present would be more salient and relevant than those in which the US is absent. From the point of view of the model, because of the difference between β_1 and β_2 , in those trials in which the US is presented, the change of the associative strength would tend to be higher than in those in which the US does not appear. As the proportion of trials in which the US is presented changes, this might lead to a change in the predictions.

To answer this question, a simulation with Rescorla and Wagner's (1972) model was run (for details of the simulations, see Appendix 1), using values of 0.2 for β_1 and 0.1 for

β_2 . The results of the simulation for the CS and the context are presented in Fig. 1. The pattern of predictions for the conditioning of the CS with these parameters is very different to that mentioned before (context conditioning will be discussed below). If β_1 is higher than β_2 , then the same difference of $p_1 - p_2$ leads to different asymptotic associative strengths of the CS, depending on the specific values of p_1 and p_2 . A group trained with $p_1 = 0.1$ and $p_2 = 0$ is now predicted to have a higher asymptotic associative strength than those trained with $p_1 = 0.9$ and $p_2 = 0.8$, or $p_1 = 0.5$ and $p_2 = 0.4$. When p_1 is 0.9, p_2 should be 0.6 to predict the level of conditioning obtained in the case of $p_1 = 0.1$ and $p_2 = 0$. When p_1 is 0.5, a p_2 of 0.3 would be required to obtain an equivalent level of conditioning. Therefore, with these parameters, Rescorla and Wagner's model predicts that as the value of p_1 increases, the difference between p_1 and p_2 that is necessary to produce excitatory learning will increase. It should be noted that this is a robust prediction that occurs whenever β_1 is higher than β_2 , independent of their specific values and of the values of the salience of the CS

and of the context (see the [Supplemental Data](#) for additional simulations).

The aim of the present study was to test that prediction using an appetitive procedure in rats. The objective of the series of experiments presented was to see whether the difference between p_1 and p_2 needed to produce an increase in the conditioned responding to the CS is the same for all the values of p_1 , or whether this difference becomes higher as the value of p_1 increases. In [Experiment 1a](#), we tested whether a group with contingency $p_1 = 0.1$ and $p_2 = 0$ has a higher rate of responding to the CS than a control group receiving a training in which $p_1 = 0.1$ and $p_2 = 0.1$. In [Experiment 1b](#), we explored whether that same difference would be enough to produce an increase in the conditioned response when p_1 and p_2 have much higher values, $p_1 = 0.9$ and $p_2 = 0.8$ in the case of the experimental group, and $p_1 = 0.9$ and $p_2 = 0.9$ for its control group. In [Experiment 2](#), a difference between p_1 and p_2 that was high enough to produce conditioning when p_1 was 0.9 was investigated. In [Experiment 3](#), the effect was tested at a medium contingency level not used before, $p_1 = 0.5$. Finally, in [Experiment 4](#), we replicated the findings of [Experiments 1a](#) and [1b](#) in the same experiment, with a different procedure that allowed better measuring of context conditioning (see [Table 2](#) for all the frequencies employed in the four experiments).

Experiment 1

Experiment 1a

The aim of this [Experiment 1](#) was to test the extent to which a magazine training procedure in rats was able to show contingency learning at a low contingency level. To do this, in the experimental group, p_1 had a value of 0.1, and p_2 of 0. Note that for all of the comparisons in this experiment, and in the following ones, a group in which the value of p_2 is the same as that of p_1 is used as the control. In previous studies, researchers have shown that control groups can show some change of performance (e.g., Kirkpatrick & Church, 2004; see Papini & Bitterman, 1990, for a review). In our procedure, excitatory conditioning will be understood as a differential increase in responses during the presence of the CS in the experimental groups as compared with the control group (using an elevation ratio, which will be explained later in more detail, as a dependent measure). Thus, the presentation of a salient CS might increase the arousal of rats so that the CS would have an elevation ratio over 0.5, even although no learning has been acquired. Such problems are obviated by making a comparison with the control group described. Baker, Murphy, Vallee-Tourangeau, and Mehta (2001) discussed extensively the advantages of using this kind of control instead of normative ones.

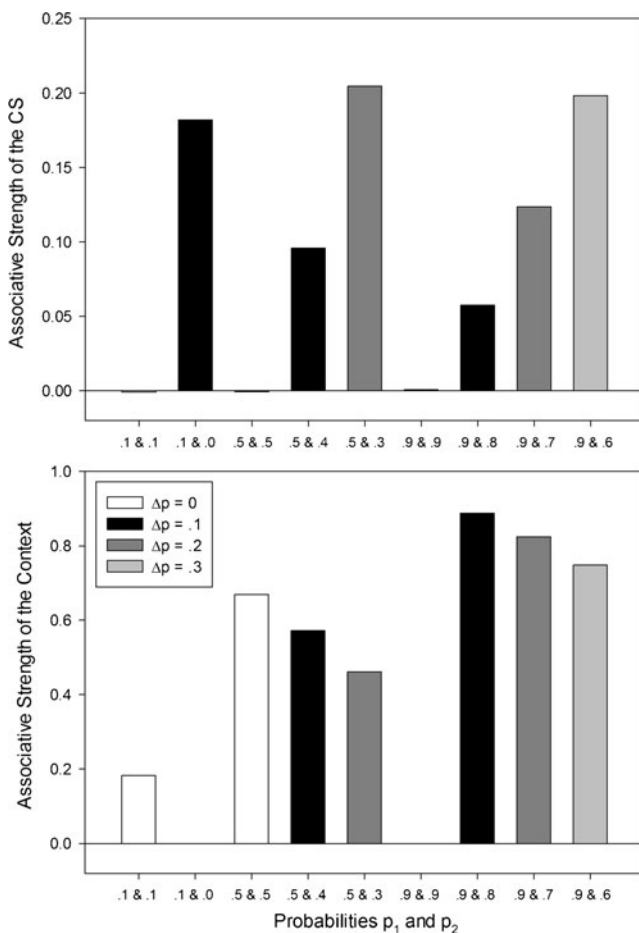


Fig. 1 Predictions of asymptotic associative strength of the CS (top panel) and the context (bottom panel) by the Rescorla and Wagner's (1972) model when $\beta_1 = 0.2$ and $\beta_2 = 0.1$. The color of the bars represents the value of Δp for that combination of p_1 and p_2

Table 2 Probabilities and frequencies of reinforcement

Experiment	Group	p_1	Reinforced and total CS trials	p_2	Reinforced and total non-CS trials
1a	Control: 0.1 & 0.1	0.1	1/10	0.1	8/80
	Experimental: 0.1 & 0.0	0.1	1/10	0.0	0/80
1b	Control: 0.9 & 0.9	0.9	9/10	0.9	72/80
	Experimental: 0.9 & 0.8	0.9	9/10	0.8	64/80
2	Control: 0.9 & 0.9	0.9	9/10	0.9	72/80
	Experimental 1: 0.9 & 0.75	0.9	9/10	0.75	60/80
	Experimental 2: 0.9 & 0.7	0.9	9/10	0.7	56/80
	Experimental 3: 0.9 & 0.6	0.9	9/10	0.6	48/80
3	Control: 0.5 & 0.5	0.5	5/10	0.5	40/80
	Experimental 1: 0.5 & 0.4	0.5	5/10	0.4	32/80
	Experimental 2: 0.5 & 0.3	0.5	5/10	0.3	24/80
4	Control 1: 0.1 & 0.1	0.1	3/30	0.1	3/30
	Experimental 1: 0.1 & 0.0	0.1	3/30	0.0	0/30
	Control 2: 0.9 & 0.9	0.9	27/30	0.9	27/30
	Experimental 2: 0.9 & 0.8	0.9	27/30	0.8	24/30

Frequencies of reinforcement delivered in each session are summarized in Table 2. For every group, the probabilities p_1 and p_2 and Reinforced and total CS trials Reinforced and total non-CS trials are shown

In **Experiment 1a**, the control group received 0.1 and 0.1 as p_1 and p_2 , respectively. If experimental animals are able to show significantly more responding to the CS than are control animals, at low levels of contingency, then a difference between p_1 and p_2 of 0.1 would be enough to produce an increase in responding, and the paradigm with the parameters employed would have shown to be suitable for the investigation of other levels of contingency.

Method

Subjects Subjects were 16 experimentally naive male Wistar rats that were about 120 days old and that had an ad libitum weight of 502 (range 397–580 g.). They were housed in cages, each of which containing four rats. They had free access to water. One hour after each session, they were fed to maintain them at 80% of their ad libitum weight. Each day, there were 12 hours of light, beginning at 8 a.m. The experiment was run during this light phase.

Apparatus The apparatus consisted of eight identical operant chambers measuring $24 \times 29 \times 38$ cm. The front and the back walls were made of aluminium, the side walls and the ceiling of transparent methacrylate, and the floor was composed of 0.4 cm stainless steel rods, spaced 1 cm apart. The center end of the front wall contained a recessed food magazine measuring $6 \times 3.5 \times 6$ cm that was located 0.5 cm above the floor. Each chamber was enclosed in a sound- and light-attenuating shell. A speaker that produced a 600-Hz and 76-dB SPL tone, which was used as the CS, was mounted on the front wall,

8 cm over the food magazine. A fan included in the shell produced a background noise of 62 dB SPL. A pellet dispenser mounted behind the food magazine dispensed 45 mg pellets (type Test Diet-MLab Rodent Tablet) through a tube connecting the magazine and the dispenser. Photocells located in the magazine recorded entries into the food magazine in both presence and absence of the CS.

Procedure Rats were randomly assigned to two groups of eight subjects each and then received two days of magazine training and 22 sessions of conditioning.

Magazine training On Days 1 and 2, subjects received a 20-min session of magazine training during which pellets were delivered according to a variable-time 120-s schedule. Four pellets were placed in the magazine before the beginning of these sessions.

Conditioning Conditioning began on Day 3 and continued through Day 24 (a total of 22 sessions). Conditioning sessions were designed to be an appetitive procedure equivalent to that used by Rescorla (1968). Each session lasted 960 s. The first and last 30 s had no event scheduled. The remaining 900 s were divided into 10-s. bins. In 10 of these bins, the tone used as the CS was presented for the duration of the bin. In the remaining time bins, the CS was absent. The mean interval between CS trials was 90 s, the minimum was 70 s, and the maximum was 110 s. (Bueno & Álvarez, 2001; Holland, 2000). A food pellet, the US, could be delivered during the last second of each time bin. Whenever the CS was present, the probability of this happening was

p_1 , as set in the experiment, and in those bins in which the CS was absent, the probability was p_2 (Table 2 shows the exact number of trials reinforced and nonreinforced). In **Experiment 1a** these values were $p_1 = 0.1$ for both the Experimental group and the Control group. The value of p_2 for the Experimental group was 0, and for Control group, 0.1. This means that for the Experimental group, on average, a US would appear once every 10 CS trials, but no USs would be presented in absence of the CS. On the other hand, the Control group would receive food, on average, once every 10 CS trials and also once every 10 no-CS trials.

The conditioned response controlled by the CS was computed as an elevation ratio. The value of this ratio was the number of magazine entries during the presentation of the CS divided by the sum of this number, and the number of magazine entries in the previous 10 s. Therefore, higher values of the ratio reflect more excitatory conditioning of the CS. To ensure that the effects found were asymptotic, only the last eight sessions were analyzed.

Data analysis SPSS 14 was used to analyze the data. Sphericity was tested in every repeated measures ANOVA and, when needed, degrees of freedom were adjusted using the Greenhouse–Geisser correction. The level of significance used was $\alpha = 0.05$.

Results

The mean elevation ratios for the two groups of **Experiment 1a** during the last eight sessions (from the fifteenth to twenty-second) are presented in Fig. 2. As can be seen in Fig. 2, animals in the Experimental group showed higher elevation

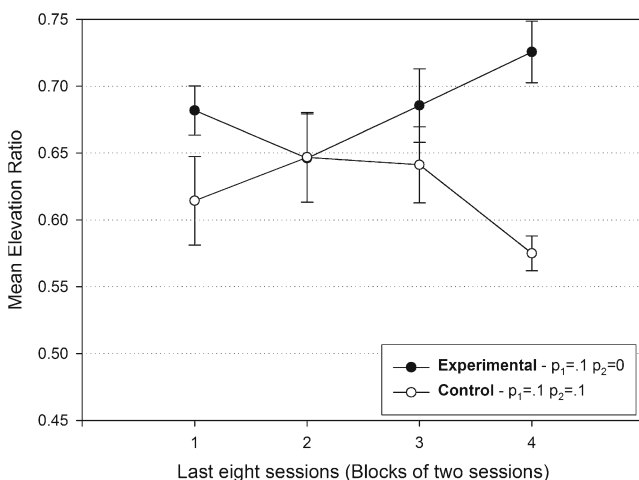


Fig. 2 Mean elevation ratio of the responses to the CS of the experimental and control groups of **Experiment 1a** in the last eight conditioning sessions. Error bars represent the standard errors of the means

ratio scores than controls, especially in those blocks that represent sessions 19 to 22 (blocks 3 and 4).

A repeated measures ANOVA of the last eight sessions, using group and session as factors, showed a statistically significant effect of the factor group, $F(1, 14) = 5.74, p < .05$. There was no effect of session, $F(7, 98) = 0.60, p > .05$, or of interaction between both factors, $F(7, 98) = 2.00, p > .05$. The mean pre-CS responding of the Control group was 0.69 ($SD = 1.14$), and the mean of the Experimental group was 1.04 ($SD = 1.97$). Another ANOVA showed that there were no statistical differences in the levels of responding previous to the CS, $F(1, 14) = 1.62, p > .05$, indicating that groups did not differ in its CR to the context. A difference of 0.1 between p_1 and p_2 was enough to show more excitatory conditioning with low values of p_1 than in a control group trained with no difference between the two probabilities.

Experiment 1b

In **Experiment 1a**, we showed that with the current procedure, a value of $\Delta p = 0.1$ is enough to produce excitatory conditioning when $p_1 = 0.1$. If the difference between p_1 and p_2 that is needed to produce excitatory conditioning is absolute and constant for every value of p_1 , then a group with $\Delta p = 0.1$ having $p_1 = 0.9$ and $p_2 = 0.8$ should show a higher level of responding to the CS than a control group trained with p_1 and p_2 equal to 0.9. On the other hand, according to Rescorla and Wagner's (1972) model with different values for β_1 and β_2 , the difference between these two groups should be very small. To test this prediction, these two groups were used in **Experiment 1b** as experimental group and control group, respectively.

Method

The experimental subjects were 16 naive male Wistar rats that at the beginning of the experiment were 120 days old and had an ad libitum weight of 499 g (range 432–561 g). All of the maintenance details were the same as in **Experiment 1a**. The procedure used was the same as in **Experiment 1a**, and only the contingencies of the groups were changed (see Table 2).

Results

The mean elevation ratios for the groups of **Experiment 1b** are presented in Fig. 3. As can be seen in the figure, both groups showed similar levels of CR in the last eight sessions.

A repeated measures ANOVA of the last eight sessions showed no statistically significant effect of the group factor, $F(1, 13) = 0.01, p > .05$. There was a significant effect of

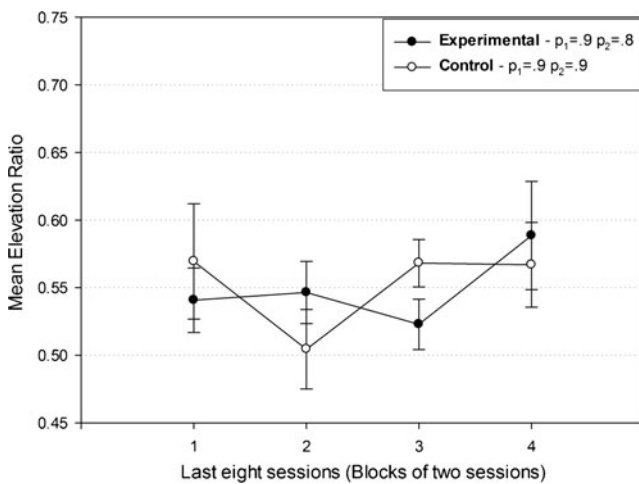


Fig. 3 Mean elevation ratio of the responses to the CS of the experimental and control groups of Experiment 1b in the last eight conditioning sessions. Error bars represent the standard errors of the means

session, $F(2.5, 32.6) = 3.12, p < .05$ but no interaction between the factors, $F(2.5, 32.6) = 0.89, p > .05$. The mean pre-CS responding was 7.55 ($SD = 4.91$) in the Control group and 6.88 ($SD = 4.60$) in the Experimental group. No statistical differences between the groups were found in the levels of responding previous to the CS, $F(1, 13) = 0.65, p > .05$.

The difference between the probabilities of the US in the presence and absence of the CS, which produced an increase in responding to the CS when p_1 value was low (Experiment 1a), was not enough to produce a similar effect when p_1 value was high (Experiment 1b).

Experiment 2

The difference between p_1 and p_2 that produced an increase in conditioned responding as compared with its control when p_1 was 0.1 did not produce it when p_1 had a value of 0.9. Experiment 2 was designed to determine a difference between p_1 and p_2 that was high enough to produce more excitatory conditioning than a control when $p_1 = 0.9$. To do this, four groups were used: a Control group ($p_1 = 0.9$ and $p_2 = 0.9$) and three experimental groups that had increasing values of Δp . They were Experimental 1 ($p_1 = 0.9$ and $p_2 = 0.75$), Experimental 2 ($p_1 = 0.9$ and $p_2 = 0.7$), and Experimental 3 ($p_1 = 0.9$ and $p_2 = 0.6$). They had Δp values of, respectively, 0.15, 0.2, and 0.3 (see Table 2).

Method

The experimental subjects were 32 naive male Wistar rats that were 90 days old and had an ad libitum weight of 437 g

(range 378–508 g) at the beginning of the experiment. All of the maintenance details were the same as in Experiments 1a and 1b. The procedure used was the same as in previous experiments, and only the contingencies of the groups were changed.

Results

The mean elevation ratios for the groups of Experiment 2 during the last eight sessions are presented in Fig. 4. It can be seen that group Experimental 3 ($p_1 = 0.9$ and $p_2 = 0.6$) showed higher levels of CR than the other groups.

By conducting a repeated measures ANOVA of the last eight sessions, we found a statistically significant difference among the groups, $F(3, 28) = 3.71, p < .05$, a significant effect of the sessions, $F(4.8, 135.7) = 4.13, p < .05$, and a significant interaction between these factors, $F(14.5, 135.7) = 2.43, p < .05$. A post hoc Tukey of the means of those last eight sessions test showed that only the difference between the Control group ($p_1 = 0.9$ and $p_2 = 0.9$) and the Experimental group 3 ($p_1 = 0.9$ and $p_2 = 0.6$) was statistically significant. The mean number of responses during the pre-CS period of the Control group and Experimental Groups 1, 2, and 3 was, respectively, 6.91 ($SD = 3.34$), 8.87 ($SD = 4.44$), 9.62 ($SD = 5.34$), and 6.36 ($SD = 3.16$). No statistical differences were found in the levels of responding previous to the CS, $F(3, 28) = 1.15, p > .05$.

Therefore, when p_1 value was high, a difference between p_1 and p_2 of 0.3 was enough to produce an increase in conditioned responses to the CS, but differences of 0.2 and 0.15 were not.

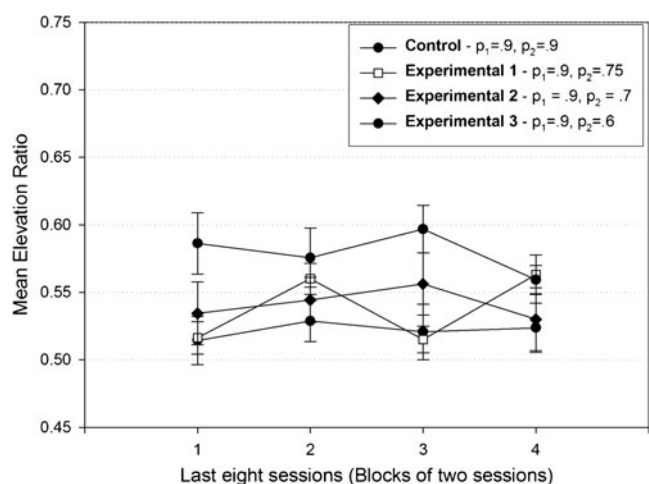


Fig. 4 Mean elevation ratio of the responses to the CS of the experimental and control groups of Experiment 2 in the last eight conditioning sessions. Error bars represent the standard errors of the means

Experiment 3

In **Experiment 3**, a similar design to those of **Experiments 1** and **2** was used, but this time the value of p_1 was medium, 0.5. The objective was to extend the findings of **Experiments 1** and **2** to another level of p_1 value, and to test the predictions of Rescorla and Wagner's (1972) model also under those conditions. By doing so, a potential problem of **Experiment 1a** was solved. In **Experiment 1**, the experimental group p_2 had a value of 0. It might be argued that this value might have a special psychological significance and be more salient than other values in the continuum of probabilities. Then, the results of **Experiment 1a** might not be applicable to the whole contingency space, preventing a correct test of the discussed predictions of Rescorla and Wagner's model. In **Experiment 3**, therefore, we investigated the effects produced by $\Delta p = 0.1$, but in a procedure without values of p_1 or p_2 , that might be of special relevance. One group was trained with $\Delta p = 0.1$ ($p_1 = 0.5$ and $p_2 = 0.4$); a second experimental group was trained with $\Delta p = 0.2$ ($p_1 = 0.5$ and $p_2 = 0.3$). Would these show excitatory conditioning as compared with a control group with $\Delta p = 0$ ($p_1 = 0.5$ and $p_2 = 0.5$)? (See Table 2).

Method

The experimental subjects were 24 naive male Wistar rats that, at the beginning of the experiment, were 90 days old and had an ad libitum weight of 430 g (range 363–506 g). All of the maintenance details were the same as in previous experiments. The procedure used was the same as in **Experiment 1a**, and only the contingencies of the groups were changed.

Results

The mean elevation ratios of the groups of **Experiment 3** during the last eight sessions of training are represented in Fig. 5. As can be seen in the figure, Experimental Group 2 ($p_1 = 0.5$ and $p_2 = 0.3$) showed the highest level of CR.

A repeated measures ANOVA of the last eight sessions found statistically significant differences between the groups, $F(2, 21) = 25.77$, $p < .05$, a significant effect of the sessions, $F(7, 147) = 3.64$, $p < .05$, but no significant interaction between the factors, $F(14, 147) = 1.06$, $p > .05$. A post hoc Tukey test of the means of the eight sessions showed that the only difference that was statistically significant was between the Control group ($p_1 = 0.5$ and $p_2 = 0.5$) and Experimental Group 2 ($p_1 = 0.5$ and $p_2 = 0.3$). The mean number of responses during the pre-CS period of the Control group and Experimental Groups 1 and 2 was, respectively, 6.89 ($SD = 4.19$), 6.17 ($SD = 3.89$), and 4.72 ($SD = 4.96$). Another ANOVA found no statistical differences in responding previous to the CS, $F(2, 21) = 2.24$, $p > .05$.

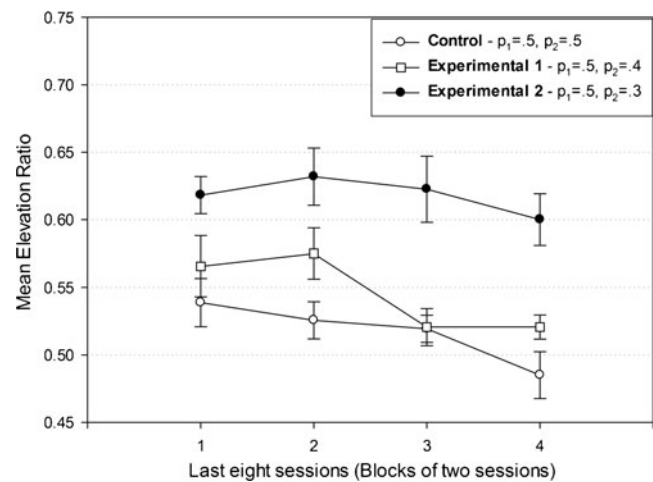


Fig. 5 Mean elevation ratio of the responses to the CS of the experimental and control groups of **Experiment 3** in the last eight conditioning sessions. Error bars represent the standard errors of the means

Experiment 4

In **Experiment 1a**, we showed that a difference of 0.1 between p_1 and p_2 was enough to produce an increase in conditioned responding to the CS when p_1 had a value of 0.1. This difference did not produce the same effect in **Experiment 1b**, where p_1 was 0.9. In **Experiment 4**, we tried to replicate these two results in a single experiment. Also, the simulations presented in Fig. 1 show that Rescorla & Wagner's (1972) model predicts that in each of the previous experiments, experimental and control groups should have differed in their level of context conditioning. For example, according to the predictions presented in Fig. 1, the associative strength of the context in a group with $p_1 = 0.1$ and $p_2 = 0$ should be zero, whereas one with $p_1 = 0.1$ and $p_2 = 0.1$ would be 0.2. However, this was not found, although differences in responding to the CS were detected. This could have been because of the fact that the measure of context conditioning was less sensitive than that used to assess the CR. Responding to the CS was measured as an elevation ratio, to control a possible effect of context conditioning. This kind of measure allows additional advantages, because it also reduces the influence of additional factors such as general activity of the animal. Since the index of context responding was the number of responses while the CS was absent, it did not have this feature. Because of this, a different procedure was used in this experiment, in order to try to measure responding to the context in a situation equivalent to the CS. In this procedure, every trial was signaled with a discrete stimulus. Therefore, this stimulus appeared in all trials and functioned as a contextual cue that indicated that a trial was taking place. This stimulus could appear on some of the trials alone, followed or not by the US (these trials were used to calculate p_2), whereas in

others, it appeared with the CS, followed by the US or not (to calculate p_1). As a result of this training, these types of trials defined the probabilities assigned to each group. Thanks to this change, an elevation ratio equivalent to that of the CS could be calculated for all of the trials, those that included the CS and those that did not, allowing a better comparison between these two situations. Therefore the basic analysis used in Experiments 1–3 was also applied to the modified procedure. Also, as can be seen in Fig. 6, the predictions of Rescorla and Wagner's model for this training are identical to those shown in Fig. 1 that were calculated for the training used in Experiments 1 to 3 (see Appendix 1).

Four groups were used; two of them were experimental groups with the same $\Delta p = 0.1$, but with different values of p_1 ($p_1 = 0.1$ and $p_1 = 0.9$). There were two equivalent control groups with the same p_1 as the experimental groups and $\Delta p = 0$.

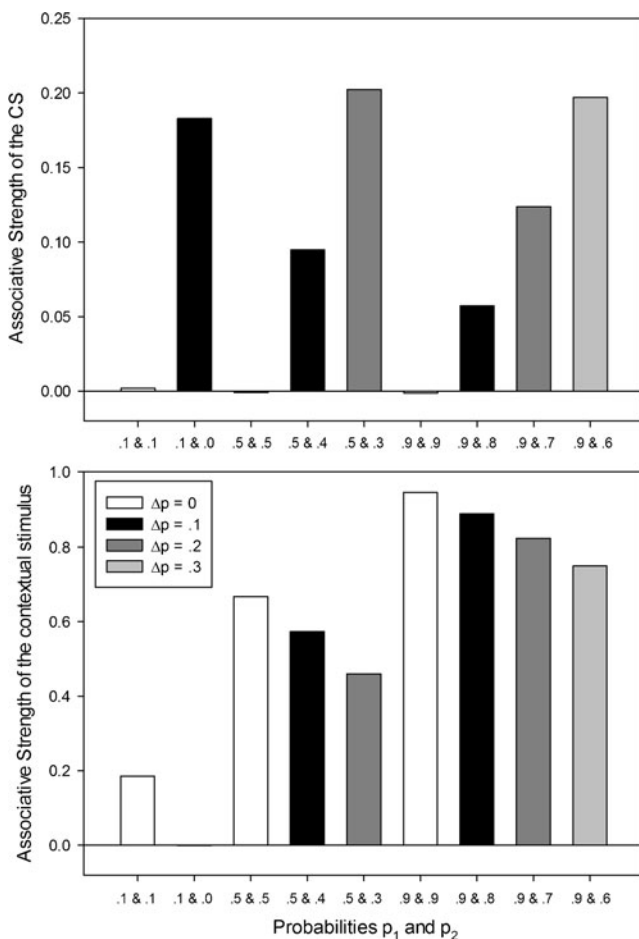


Fig. 6 Predictions of asymptotic associative strength of the CS (top panel) and the contextual stimulus (bottom panel) by Rescorla and Wagner's (1972) model for a contingency training in which a contextual cue is used to mark each trial. The value of the parameters used were $\beta_1 = 0.2$ and $\beta_2 = 0.1$. The color of the bars represents the value of Δp for that combination of p_1 and p_2 (see Appendix 1 for more details)

Method

Subjects Subjects were 32 experimentally naive male Wistar rats about 120 days old that had an ad libitum weight of 383 g (range 347–411 g). All of the maintenance details were the same as in previous experiments.

Apparatus The apparatus was the same as before, except for a new speaker that was added in Skinner boxes. It generated a new auditory stimulus: a 3,000-Hz and 82-dB SPL intermittent click that lasted for 10 s. This stimulus was used as a CS.

Procedure Rats were randomly assigned to four groups of eight subjects each and then received 2 days of magazine training and 16 sessions of conditioning. The procedure used was similar to that employed by Murphy and Baker (2004). Each session was composed of trials in which only a 10-s tone was presented (no-CS trials) and trials in which the tone and a click, also 10 s long, were presented simultaneously (CS trials). Therefore, the click was used as a CS, and the tone served as a discriminative stimulus that indicated that a trial was taking place. This ensured that CS and no-CS trials were signaled in the same way.

Conditioning Conditioning began on Day 3 and continued until Day 18. Each session lasted 60 min. In each session, 60 trials were presented, 30 with the presentation of the tone alone (non-CS trials), whereas in the other 30, the tone and a click were presented (CS trials). The mean interval between trials was 60 s, and the order of the trials was random. A food pellet, the US, could be delivered at the end of the trial. Each trial had a probability of reinforcement determined by the values of p_1 and p_2 of the group (Table 2 shows the exact number of reinforced and no reinforced trials). Four groups were established: Control Group 1 ($p_1 = 0.1$ and $p_2 = 0.1$), in which both probabilities were the same and fixed in a low value; Experimental Group 1 ($p_1 = 0.1$ and $p_2 = 0.0$), which was trained with a $\Delta p = 0.1$ and a low p_1 value; Control Group 2 ($p_1 = 0.9$ and $p_2 = 0.9$), which worked as control with an equal value of probabilities fixed in a high value; and, finally, Experimental Group 2 ($p_1 = 0.9$ and $p_2 = 0.8$), which was a group trained with a $\Delta p = 0.1$ and a high value of p_1 . In each session, the click was conditioned according to the probabilities stated. In Control Group 1 ($p_1 = 0.1$ and $p_2 = 0.1$), 10% of tone and click (p_1) and tone-alone trials (p_2) were reinforced. Experimental Group 1 ($p_1 = 0.1$ and $p_2 = 0.0$) received a food pellet on 10% of the 30 tone and click trials (p_1), but none of the 30 tone-alone trials was followed by food (p_2). In Control Group 2 ($p_1 = 0.9$ and $p_2 = 0.9$), 90% of both types of trials was reinforced. Finally, 90% of tone and click trials and 80% of the tone trials were reinforced in Experimental Group 2 ($p_1 = 0.9$ and $p_2 = 0.8$).

This method generated faster conditioning than that used in previous experiments, which is why the number of sessions was reduced as compared with those in previous experiments.

Data analysis Elevation ratios, similar to those explained before, were used for the analysis. The elevation ratio of the non-CS trials, in which the tone was presented alone (ER_{tone}), and of the CS trials, in which both the tone and the click were presented ($ER_{\text{click+tone}}$), were calculated using the magazine entries recorded during the presentation of the stimuli and those registered in a previous period of the same duration, 10 s. The dependent variable employed to analyze the conditioning data was the difference of elevation ratios of the two types of trials ($Dif_{ER} = ER_{\text{click+tone}} - ER_{\text{tone}}$). By doing so, the conditioning of the CS was estimated. The final six sessions were analyzed, to avoid possible pre-asymptotic effects.

Results

In Fig. 7, we present the results of the last six conditioning sessions (collapsed in blocks of two) and show that Experimental Group 1 ($p_1 = 0.1$ and $p_2 = 0.0$) had the highest asymptotic level of conditioned responses. To analyze the data, a repeated measures ANOVA was used. It had a within-subjects factor, session, and a between-subjects factor, group. No interaction effect between session and group, or a main session effect was found, $F < 1$. However, the main effect of group was significant, $F(3, 28) = 18.897$, $p < .05$. A Tukey post hoc analysis showed significant differences in their CR between Experimental Group 1 ($p_1 = 0.1$ and $p_2 = 0.0$) and the other three groups. No other difference was statistically significant.

To test for a possible difference in context conditioning, elevation ratios on CS and no-CS trials were analyzed separately. The results are presented in Fig. 8. Experimental Group 1 showed a higher ER on the CS trials, whereas the four groups showed a similar level of conditioning on no-CS trials. Another ANOVA was run, now with two within-subjects factors, session and trial Type (CS vs. no CS). There was a significant interaction between trial type and group factors, $F(3, 28) = 23.57$, $p < .05$. Additional tests showed that there was no significant difference among groups in mean elevation ratio on no-CS trials ($F < 1$), but a significant difference was present in CS trials, $F(3, 28) = 3.04$, $p < .05$. A Tukey test showed that this result was due to differences between Experimental Group 1 ($p_1 = 0.1$ and $p_2 = 0.0$) and the other three groups.

These results replicated those of Experiments 1a and 1b. A difference of Δp of 0.1 was enough to produce an increase in responding to the CS in a group with a low value

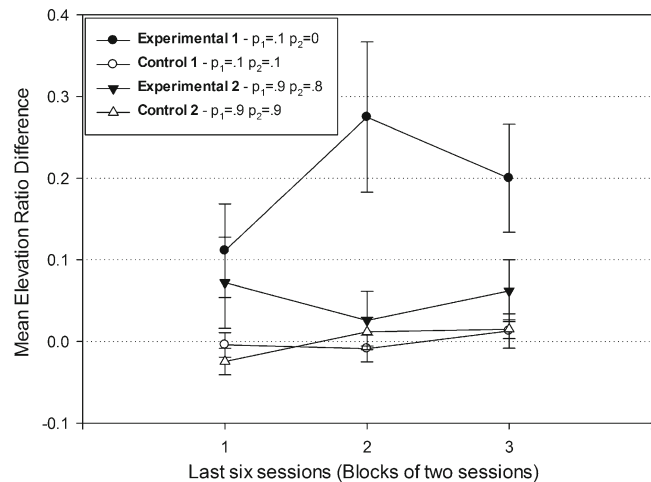


Fig. 7 Mean difference of elevation ratio of CS trials minus the elevation ratio of non-CS trials of the groups of Experiment 4 in the last six conditioning sessions (collapsed in blocks of two). Error bars represent the standard errors of the means

of p_1 as compared with its control group with $\Delta p = 0.0$. The same difference was not enough to produce a significant increase of responding in the experimental group, with a high value of p_1 . As in previous experiments, context-conditioning differences were not found.

General Discussion

The results of the present experiments have shown that the difference between p_1 and p_2 that is required to produce excitatory conditioning in an experimental group, as compared with a control group trained with the same p_1 and p_2 , was not absolute, but that its value increased as the value of p_1 increased. Specifically, the experiments have shown that a small difference between p_1 and p_2 ($\Delta p = 0.1$) can be enough to produce increased responding to the CS when p_1 has a low value, 0.1 (Experiment 1a), but not when p_1 has a

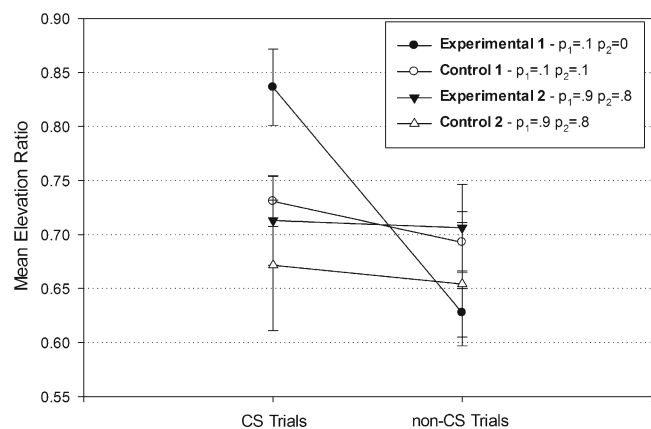


Fig. 8 Mean elevation ratios of CS and non-CS trials of the groups of Experiment 4 in the last six conditioning sessions. Error bars represent the standard errors of the means

high value, 0.9 (Experiment 1b). In this case, when p_1 is 0.9, the difference has to be bigger, $\Delta p = 0.3$, with this procedure (Experiment 2). When p_1 has a value of 0.5, a difference of $\Delta p = 0.2$ was enough to produce excitatory conditioning, whereas a difference of $\Delta p = 0.1$ was not (Experiment 3). The results of Experiments 1a and 1b were replicated in a single experiment (Experiment 4). This result is contrary to the widely accepted idea that whenever p_1 is bigger than p_2 , excitatory conditioning will occur (Rescorla, 1968).

A potential problem of Experiments 1b, 2, and 4 would be the existence of a ceiling effect. Given that a high magnitude of reinforcement was used, it might be possible that a maximum level of responding was reached. This, in turn, could have masked possible differences between high magnitude groups. If this had happened, it might explain to some extent the results found in those experiments, but it cannot explain the whole pattern of results obtained, and therefore does not invalidate the conclusions discussed before. Specifically, in Experiment 3, the probabilities of reinforcement were approximately half of those used in Experiment 1b; the mean response rate of all of the groups of Experiment 1b during the CS in the sessions analyzed was of 0.975 responses per second, whereas in Experiment 3, this rate was only 0.722, 25% less. It seems unlikely, therefore, that a ceiling level was reached in both experiments. But in neither experiment was a difference between p_1 and p_2 of 0.1 enough to produce an increase in conditioned response with a medium magnitude.

The asymptotic values predicted by some models applied to contingency learning for each particular contingency explored in these experiments are given in Table 3. Six different representative models were used. They are Rescorla and Wagner's (1972) model and Δp (already explained); an adaptation of the Weber–Fechner rule (see below for an extended discussion); and three additional correlational models, ΔD (White, 2003), PowerPC (Cheng, 1997), and Φ (Hammond & Paynter, 1983). The algebraic expressions of those models not described before can be found in Table 4. As is true for Delta Δp , these three models are correlational and are usually described as rule-based models because they do not incorporate a trial \times trial learning mechanism. Instead, they calculate their contingency index on the basis of the frequency of trials and the probabilities derived from them (see Table 4), each one proposing a different contingency rule.

The experimental results that were obtained are incompatible with rule-based models such as Δp , ΔD , PCi (White, 2003), and others (see Allan, 1993, for a review in humans and Hammond & Paynter, 1983, for nonhumans), but can be explained by the Rescorla and Wagner (1972) model, as long as the value of the parameter β_1 is higher than the value of the parameter β_2 . For instance, a simple inspection of Table 3 shows that Δp predicts the same level

of conditioning in the group with $p_1 = 0.1$ and $p_2 = 0$, as in the group with $p_1 = 0.9$ and $p_2 = 0.8$. However, Experiments 1a, 1b, 2, and 4 revealed a greater increase of excitatory conditioning in the former group than in the latter, as compared with their respective controls. Similarly, ΔD predicts a similar level of learning in a group with $p_1 = 0.5$ and $p_2 = 0.3$, and another in which p_1 is 0.9 and p_2 is 0.7. The first group showed significant greater levels of response than its control group, whereas the second did not (Experiments 2 and 3). Something similar happens with PowerPC and Φ predictions about these groups. Only the Rescorla and Wagner model, when β_1 is higher than β_2 , accommodates the results of these experiments.

The effect shown in these experiments is compatible with the density effect, but it cannot be explained by this effect. The density effect (Allan, 1993) is an increase in CR due to an increase in the general probability of appearance of the outcome, but it does not imply a relative difference in discrepancy between p_1 and p_2 . Density effect has been explained in terms of context conditioning, which could be present in present experiments, but its contribution to the kind of modulation reported here, if any, has been controlled by using elevation ratio as a measure of CR. What is more, no differences in contextual conditioning were found between groups in any of the experiments. In Experiments 1 to 3, direct responses to the context, in absence of the CS, were recorded. This might have reduced the sensitivity of this measure as compared with the CS conditioned response measure, which was an elevation ratio that takes into account the general level of activity of the animal and controls for it. In order to have the same sensitivity in both cases, in Experiment 4, we used a procedure in which contextual conditioning could be measured using an elevation ratio, making its measure equivalent to that of the CS. Even under these conditions, no difference in context conditioning was found between groups that should have differed according to the predictions of Rescorla and Wagner's (1972) model and the rest of the models. Although this finding was not the main objective of the present study, and taking into account that additional experiments focused mainly on exploring it with different procedures and measures are necessary, so far it seems that Rescorla and Wagner's model explains only partially the data obtained.

Another way to conceptualize contingency learning is as a discrimination between p_1 and p_2 . When this discrimination is solved, and p_1 is perceived as higher than p_2 , subjects would show an increase in responding as compared with a situation in which p_1 and p_2 are perceived as equal. Using this simple idea as theoretical framework, it is possible to analyze contingency learning in terms of theories and models that come from perception and psychophysics. This would allow us to look for some effects that are commonly found in psychophysics in contingency learning. For instance, the effect that has been described in the present experiments could

Table 3 Empirical results and simulated predictions of contingency learning models

	0.1–0.0	0.5–0.3	0.5–0.4	0.9–0.6	0.9–0.7	0.9–0.8
Results	Yes	Yes	No	Yes	No	No
ΔP	0.1	0.2	0.1	0.3	0.2	0.1
ΔD	0.1	0.4	0.2	0.6	0.4	0.2
ϕ	0.05	0.1	0.04	0.12	0.6	0.2
Power PC	0.11	0.29	0.17	0.75	0.67	0.5
RW ($\beta_1/\beta_2 = 1$)	0.10	0.20	0.10	0.30	0.20	0.10
RW ($\beta_1/\beta_2 = 0.5$)	0.05	0.16	0.08	0.39	0.28	0.15
RW ($\beta_1/\beta_2 = 2$)	0.18	0.21	0.10	0.20	0.12	0.06
Weber–Fechner	<i>0.10</i>	<i>0.20</i>	<i>0.20</i>	<i>0.30</i>	<i>0.30</i>	<i>0.30</i>

The first row indicates the occurrence or not of a significant increase of CR in that group in the results of the experiments. The last row, whose values are in italics, represents the Weber–Fechner rule—that is, the difference needed for the occurrence of differences in the conditioned response given the p_1 level in the corresponding column. The intermediate rows symbolize the asymptotic values predicted by rules models and Rescorla and Wagner (1972) assigning three different values to β_1 and β_2 .

be explained in terms of the Weber–Fechner law, a formal descriptive rule for discrimination and perception. According to this rule, the difference necessary to perceive two stimuli as different (ΔS) is proportional to the magnitude of the stimuli (S) and is usually a constant (k), specific for each sensory modality. The generalized Weber–Fechner law (Laming, 1986) is expressed as $\Delta S = (S + b)k$ (it includes an additional parameter, b , to avoid numerical confusions between increments and absolute values of the stimuli). This generalized law is normally employed when the scale of the absolute values of the S are very close to the incremental values, as is the case in our experiments. Thus, the effects reported presently can be understood if we adopt a Weber–Fechner modulation of perception in contingency. Indeed, if contingency perception were similar to other perceptual tasks, it would be expected that the bigger the magnitude of the stimulus (in our case: the magnitude of the probability of the US in the presence of the CS), the bigger the difference necessary to perceive as different a new stimulus (in our case, to perceive as different the probability of the US in the absence of the CS). Other features of conditioning have been described using this law; they appear to be perceived according to a logarithmic function. For example, timing seems to follow the Weber–Fechner law; the scalar property of timing (Gibbon, 1991)

means that longer times are perceived with greater variance than shorter times, and this variance is proportional to the duration being timed.

In fact, the generalized Weber–Fechner law accommodates all of the results described. The results of Experiments 1a and 1b showed that a difference between p_1 and p_2 of 0.1 produces more excitatory conditioning than a control when p_1 is 0.1, but not when p_1 is 0.9. When p_1 is 0.9, that difference has to be of 0.3, according to the results of Experiment 2. Given these values, the parameters of the generalized Weber–Fechner law (Laming, 1986) can be calculated (see Appendix 2). This calculation leads to an estimation of parameters b having a value of 0.3 and k being 0.25. It is then possible to determine what difference between p_1 and p_2 , according to the model, will be high enough to produce an increase in conditioning (ΔS) for a given value of p_1 (S). For example, when $p_1 = 0.5$, the model predicts that only those contingencies with Δp equal or higher than 0.2 will produce excitatory conditioning. The results of Experiment 3 are consistent with the predictions of this rule.

This psychophysical interpretation allows linking two different fields in experimental psychology: learning and perception. This can lead to new ideas and ways to analyze learning situations, and some authors have done this in the past for other aspects of learning (e.g., Allan, Hannah, Crump, & Siegel, 2008; Boneau & Cole, 1967; Hack, 1963; Hirsch, 1979; Mason et al., 2003; Nevin, 1964; Schmajuk, 1987). This research has made use of classical psychophysics to deal with a paradigmatic learning issue (contingency). Allan et al. (2008) proposed a psychophysical account of contingency data in which they made use of an account of contingency learning in human subjects based on signal detection theory. Both research programs share a similar conceptual framework based on the usefulness of putting together theories from apparently independent fields such as perception and learning.

Table 4 Asymptotic algorithms used to generate the data in Table 3

Model	Asymptotic algorithm	Reference
Δp	$p_1 - p_2$	Jenkins and Ward, 1965
ΔD	$[p_1 + (1 - p_2)] - [p_2 + (1 - p_1)]$	White, 2003
PowerPC	$(p_1 - p_2) / 1 - p_2$	Cheng, 1997
ϕ	$\sqrt{(p_1 - p_2)(p_3 - p_4)}$	Hammond and Paynter, 1983

Finally, it is hard to overstate the influence that Rescorla and Wagner's (1972) model has had in associative learning. Both its theoretical aspects and mathematical formalization have been useful tools for researchers for 40 years now. The fact that novel predictions of this model are still being found and tested is a good proof of its longevity and strong predictive validity. Although it predicted correctly only part of the results, it is a powerful research tool and heuristic. Mathematical models of learning are essential research tools under constant development (see, e.g., Le Pelley, 2004; Stout & Miller, 2007; van Hamme & Wasserman, 1994; Wagner & Brandon, 2001).

Author note The present research was supported by a FICYT predoctoral scholarship awarded to S. C., Ficyt/BP07-020. Thanks to Beatriz Álvarez Diaz for her kind help.

Appendix 1

A MATLAB function was programmed to simulate the data presented in Fig. 1 and supplemental data. It implemented Rescorla and Wagner's (1972) model. The parameters used are presented below.

For the contingency learning simulation, the structure of the training used later in Experiments 1 to 3 was used. Each CS trial was followed by nine trials in which it was absent. The total number of trials was 2,200 in each replica. Each CS trial had a probability of having a US presentation of p_1 , and, each non-CS trial, of p_2 . For each condition 10 thousand replicas were run and the results averaged. The value plotted in Fig. 1 is the associative strength of the CS and the context after the last trial of the simulation. Parameter α of the CS was 0.2. Parameter α of the context was 0.1. Parameters λ_1 and λ_2 were 1 and 0, respectively. β_1 and β_2 were 0.2 and 0.1, respectively. An additional simulation using a wider range of values can be found as supplemental data.

The same function was used to simulate the data of Fig. 6 with a different training structure, in which 30 CS and 30 non-CS trials were ordered randomly. In each trial, the contextual stimulus was present. Each CS trial had a probability of having a US presentation of p_1 , and, each non-CS trial, of p_2 . For each condition, 10 thousand replicas were run and the results averaged. The value plotted in Fig. 6 is the associative strength of the CS and the contextual stimulus after the last trial of the simulation. Parameter α of the CS was 0.2. Parameter α of the contextual cue was 0.2. Parameters λ_1 and λ_2 were 1 and 0, respectively. β_1 and β_2 were 0.2 and 0.1, respectively.

Appendix 2

In Appendix 2, we include the calculations of parameters b and k of the generalized Weber–Fechner law (Laming, 1986) using the results of Experiments 1 and 2. In Experiment 1, we showed that when $p_1 = 0.1$, a difference $\Delta p = 0.1$ was enough to observe excitatory conditioning. In Experiment 2, a difference $\Delta p = 0.3$ produced excitatory conditioning when $p_1 = 0.9$. Given these two points ($p_1 = 0.1$ and $p_1 = 0.9$) for which the difference needed to produce excitatory conditioning is known ($\Delta p = 0.1$ and $\Delta p = 0.3$, respectively) and the equation of the generalized Weber–Fechner Law, $\Delta S = (S + b) * k$,

For $p_1 = 0.1$:

$$0.1 = (0.1 + b) * k$$

For $p_1 = 0.9$:

$$0.3 = (0.9 + b) * k$$

$$0.1 = 0.1k + bk$$

$$0.3 = 0.9k + bk$$

$$0.2 = 0.8k \text{ then } k = 0.25$$

and

$$0.3 = (0.9 * 0.25) + 0.25b \text{ then } b = 0.3$$

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