

# Interval duration effects on blocking in appetitive conditioning

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## Abstract

Three experiments examined absolute (Experiment 1) and relative (Experiments 2a and 2b) duration effects on blocking. In Experiment 1, rats were pretrained with a short or long conditioned stimulus (CS1) followed by food, after which they were given reinforced short–short or long–long CS1–CS2 simultaneous compounds. Compared to overshadowing control groups, both pretrained groups displayed blocking, and there was no clear effect of absolute stimulus duration on the magnitude of blocking. In Experiments 2a and 2b, the rats received partially overlapping short–long CS1–CS2 compounds. In both experiments, a long CS1 blocked a short CS2, but not vice versa. This was the case when the long CS1 was nine times (Experiment 2a) or only 1.5 times (Experiment 2b) the duration of the short CS2. The pattern of results is most consistent with a real-time model of conditioning, such as the Sutton and Barto [Sutton, R.S., Barto, A.G., 1990. Time derivative models of Pavlovian reinforcement. In: Gabriel, M.R., Moore, J.W. (Eds.), *Learning and Computational Neuroscience: Foundations of Adaptive Networks*. MIT Press, Cambridge, MA, 497–537] temporal difference model.

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## 1. Introduction

The blocking paradigm (Kamin, 1968, 1969) is one of several forms of cue competition that have been reported in basic conditioning tasks. A typical procedure consists of presentations of a conditioned stimulus (CS1), usually followed immediately by an unconditioned stimulus (US). After a number of such trials, simultaneous compounds consisting of the previously conditioned CS1 and a novel CS2 are given. Presentation of CS2 alone typically produces little responding – the classic blocking effect.

Blocking experiments are nearly always conducted with fixed duration CSs that are presented in a simultaneous compound. Therefore, one factor that has received relatively little attention is the potential importance of the temporal relationship between the pretrained CS1 and subsequently added CS2. While it is virtually certain that animals learn the CS1 onset-US interval in the initial training phase, whether or not this contributes to the blocking effect is still largely unknown.

Only a few studies have examined the importance of temporal intervals in blocking, and these have produced equivocal results. The maintenance of CS1 duration between phases appears to be important, with shifts in CS1 duration between pretraining and compound training resulting in an attenuation of blocking (Barnet et al., 1993; Schreurs and Westbrook, 1982), but this effect has not always been observed (Kohler and Ayres, 1979, 1982; Maleske and Frey, 1979). Nonetheless, some researchers have argued that the temporal information acquired in the initial training phase must remain intact for blocking to occur (Barnet et al., 1993; Goddard and Jenkins, 1988; Savastano and Miller, 1998).

Even fewer investigations have examined the importance of CS1 and CS2 durations in blocking. Kehoe et al. (1981) conducted an investigation of blocking of the nictitating membrane response (NMR) in the rabbit with 400- and 800-ms CSs. They found that an 800-ms CS1 blocked acquisition of associative strength by a 400-ms CS2, and that the magnitude of the blocking effect was comparable to that of a simultaneous compound where both CSs were 800 ms in duration. Gaioni (1982), employing a conditioned emotional response procedure with rats, found essentially the same results as Kehoe et al. (1981). In Gaioni's experiment, a 30-s white noise CS2 was blocked by prior training with a 3-min light CS1, leading him to suggest that blocking with non-simultaneous CSs has considerable generality across

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species, research paradigm, and CS durations. Neither of these experiments, however, tested blocking of a long CS2 by a short CS1, but this was examined by Kehoe et al. (1987). They found only a weak blocking effect when the two CSs were presented in a sequential serial compound and no evidence of blocking when the CSs partially overlapped. Somewhat different findings were uncovered by Barnett et al. (1993), using a lick suppression procedure. They found that blocking was most robust when the novel CS2 shared the same temporal relationship with the US as CS1 had in pretraining, indicating that co-occurrence of the two stimuli (in terms of their temporal relationship with the US) is important for blocking. Thus, again the results are inconsistent.

The observation of blocking of a short CS by a long CS are most readily explained by a real-time model of conditioning such as the Sutton–Barto temporal difference model (the TD model, Moore and Choi, 1997; Sutton and Barto, 1990). Specifically, this model proposes that a CS is represented by a complete serial compound that is composed of a series of time-tagged units that develop associative strength independently based on their strength of activation at the time of US occurrence. Individual units fire at equally spaced intervals (e.g., 1 s) and decay exponentially; the decay rate is a free parameter in the model.

A 10-s CS will be comprised of 10 units, assuming that each unit is 1-s in duration. To illustrate the workings of the model, one can look at the activation of CS components that precede the US occurrence by differing amounts of time. The final unit, N, fires in the last time step prior to US delivery; for simplicity it will be assumed that this unit fires during the last second of the CS occurrence. This unit will be at full strength. The previous unit, N-1, will have fired 2 s prior to US delivery and will have decayed slightly. Thus, the activation of a unit at the time of US occurrence is a function of the amount of time between the unit firing and US occurrence.

Each unit independently acquires strength, if it has fired prior to US occurrence and has not fully decayed. Units that fire at close temporal proximity to the US receive the greatest weight. Cue competition is accomplished with a modified Rescorla–Wagner rule (Rescorla and Wagner, 1972), thereby allowing the model to explain basic conditioning phenomena such as blocking, overshadowing, conditioned inhibition, etc. in the same fashion as the Rescorla–Wagner model. However, because the TD model is a real-time model, competition occurs at the level of the individual unit rather than at the level of the stimulus or trial. Thus, unit N of CS1 will compete for strength against unit N of CS2. This assumption allows the TD model to predict differences in competition based on the temporal aspects of different CSs.

The TD model predicts that a long CS will block a short CS, even though the short CS occurs in a closer temporal relationship with US occurrence. If pretraining occurs with a 30-s CS1, units N to N-29 will become conditioned. Following this, if a novel 10-s CS2 is added in compound with CS1, so that CS1 onset occurs 20 s prior to CS2 onset and both terminate at the time of US, the short CS will not become conditioned. Blocking occurs because units N to N-9 (which are the units that com-

prise the 10-s CS2 as well as the last 10 s of the 30-s CS1) will have already been fully conditioned in the pretraining phase and thus there will be no available strength remaining for CS2 to acquire.

A second prediction of the model is that a short CS1 should fail to block a long CS2 because the novel long CS possesses units that the short CS does not and these become conditioned. If pretraining occurs with a 10-s CS1, units N to N-9 will become conditioned. If a novel long CS2 is added in compound with CS1, the long CS2 will possess units that will not come into competition with CS1. Unit N-10 will not have been conditioned previously and there will be no basis for competition. This unit can now become conditioned, if its eligibility trace has not decayed to zero before the US occurs. This specific prediction of the model has only been tested once (Kehoe et al., 1987), but the results were generally in accord with the model predictions. However, it seems that further tests are warranted.

The present set of experiments was designed as a systematic investigation of the effects of CS1 and CS2 duration and the nature of the CS1/CS2 compound on blocking using an appetitive Pavlovian procedure in rats. Experiment 1 examined absolute interval duration effects in simultaneous compounds, whereas Experiments 2a and 2b looked at blocking in partially overlapping short–long compounds using different long duration stimuli. In addition, measures of both the magnitude and timing of responding were analyzed to determine whether there was any relationship between timing accuracy and blocking. A focus of the experiments will be to test the specific predictions of the TD model, which are outlined below in relation to each experiment.

## 2. Experiment 1

### 2.1. Introduction

Experiment 1 examined the blocking effect using compounds that were simultaneously presented. Separate groups of rats were given training with either a short (10 s) or long (30 s) CS1 followed by food. They then received simultaneous short–short or long–long compound presentations. The purpose of Experiment 1 was to determine whether short or long CSs were both capable of robust blocking in simultaneous compounds. This is an important prerequisite prior to the introduction of short–long serial compounds in Experiment 2 because any asymmetries in blocking in the serial compounds could possibly be due to differences in the efficacy of short versus long CSs in blocking.

The TD model, a real-time implementation of the Rescorla–Wagner model (Rescorla and Wagner, 1972), predicts robust blocking in simultaneous compounds (both short–short and long–long), if initial training with CS1 results in the achievement of asymptotic strength. When CS2 is added in the second phase and it shares the same temporal space (i.e., same units) as CS1, the units of CS2 should be unable to garner any strength. This is because the units of CS1 during the corresponding temporal position in the compound CS will already be fully conditioned.

## 2.2. Methods and materials

### 2.2.1. Animals

Twenty-four male Sprague–Dawley rats (Harlan, UK) were housed in pairs in a colony room on a 12:12 light:dark cycle (lights on at 8:00 a.m.). The rats were fed a daily ration that consisted of 45-mg Noyes pellets (Improved Formula A) that were delivered during the experimental session, and an additional 15 g of food given in the home cage shortly after the daily sessions. Water was available ad libitum in both the home cages and experimental chambers. Rats were handled daily in the colony room beginning three days after arrival from the supplier. The experiment began two weeks after the rats arrived to the laboratory.

### 2.2.2. Apparatus

All experimental procedures were conducted in 12 identical chambers (25 cm × 30 cm × 30 cm), each of which was situated within a ventilated, noise-attenuating box (74 cm × 38 cm × 60 cm) supplied by Med Associates. The 12 chambers were located in two rooms with six chambers per room. Each chamber was equipped with a speaker for delivering auditory stimuli, a houselight, a food cup, and a water bottle. The speaker was located on the right side of the back wall of the chamber, on the opposite wall from the food cup. The houselight (Model ENV-227M) was situated on the top-center of the wall above the food cup, and provided diffuse illumination of the chamber of approximately 200 lx. A magazine pellet dispenser (Model ENV-203) delivered 45-mg Noyes (Improved Formula A) pellets into the food cup. Each head entry into the food cup was transduced by an LED-photocell. The water bottle was mounted outside the chamber; water was available through a tube that protruded through a hole in the lower-center of the back wall of the chamber. Med-PC for Windows (Tatham and Zurn, 1989), running on two Pentium III 800-mHz computers (one for each set of six chambers), controlled experimental events, and recorded the time at which events occurred with 2-ms resolution.

### 2.2.3. Procedure

Rats were randomly assigned to one of four groups ( $n=6$ ): P10-10, P30-30, C10-10, and C30-30, where P indicates that CS1 was pretrained in Phase 1 and C indicates that CS1 was not pretrained. The two numbers (10-10 or 30-30) indicate the durations of CS1 and CS2, respectively.

**2.2.3.1. Pretraining (Sessions 1–6).** Groups P10-10 and P30-30 received pretraining with a houselight or a 70-dB white noise CS1 that lasted for 10 or 30 s; at CS termination, a food pellet was immediately delivered into the food cup. Each session comprised 48 trials that were separated by an exponentially distributed random intertrial interval (ITI) with a mean of 120 s and a minimum of 60 s. The chambers were dark except when the houselight CS was present. During pretraining, the overshadowing control groups, C10-10 and C30-30, were placed in the experimental chambers for the same duration as the experimental groups. They received no stim-

uli or reinforcers and were kept in darkness throughout the session.

**2.2.3.2. Compound training (Sessions 7–14).** Following pretraining, eight sessions with a compound of light and noise were delivered to all four groups. All groups received 48 trials comprising 40 trials of compound training involving two CSs of the same duration followed by US delivery, four reinforced CS1-only, and four reinforced CS2-only. The CSs were always presented for their normal duration, either 10 or 30 s. The eight probe trials were distributed randomly in the session. During compound training, data from three rats were lost from Session 14 due to an intermittent fault in the Med-PC software. The fault did not appear to have affected the delivery of stimuli, but due to the loss of data, we pooled responding in two-session blocks for analysis.

### 2.2.4. Data analysis

The time of occurrence of each stimulus onset, stimulus termination, food delivery, and head entry response was recorded with a time stamp, with a resolution of 2 ms. The raw data were analyzed in MatLab v 6.1 (The Mathworks, Natick, MA) to assess conditioning and timing during the two stimuli. Statistical analysis of the various summary measures was conducted in SPSS v12.

Conditioning was measured by determining the mean response rate over the second half of the CS, when response rates were at their highest and blocking effects were most apparent (see Section 2.3.2). Conditioning of CS1 in the experimental groups was assessed in the pretraining phase during normal training trials, and in the compound conditioning phase during CS1-only probe trials. Conditioning of CS2 was assessed in all groups during compound conditioning on CS2-only probe trials. In all instances, the mean response rates were analyzed in two-session blocks. There were significant main effects of block during pretraining and compound training in all experiments that only occasionally interacted with other variables. Because the effect of blocks of training was of little interest in the absence of an interaction, we only report effects in these instances.

Analyses of temporal control over behavior were conducted by determining the number of head entry responses occurring in successive 1-s time bins since CS1 (pretraining) or CS2 (compound training) onset across all sessions in a phase.

In order to conduct statistical analysis of timing accuracy, the response functions were normalized to factor out differences in overall response rate. The number of responses in each time bin was divided by the total number of responses and multiplied by 100 to give the percentage of total responses in each bin. The slope of the normalized response rate functions was determined by fitting a linear function. Linear fits were used because these provided a simple but adequate characterization of the response rate functions. Analyses were conducted separately for short versus long CSs because normalizing the response rate functions will necessarily result in lower slopes for longer durations due to the larger number of bins.

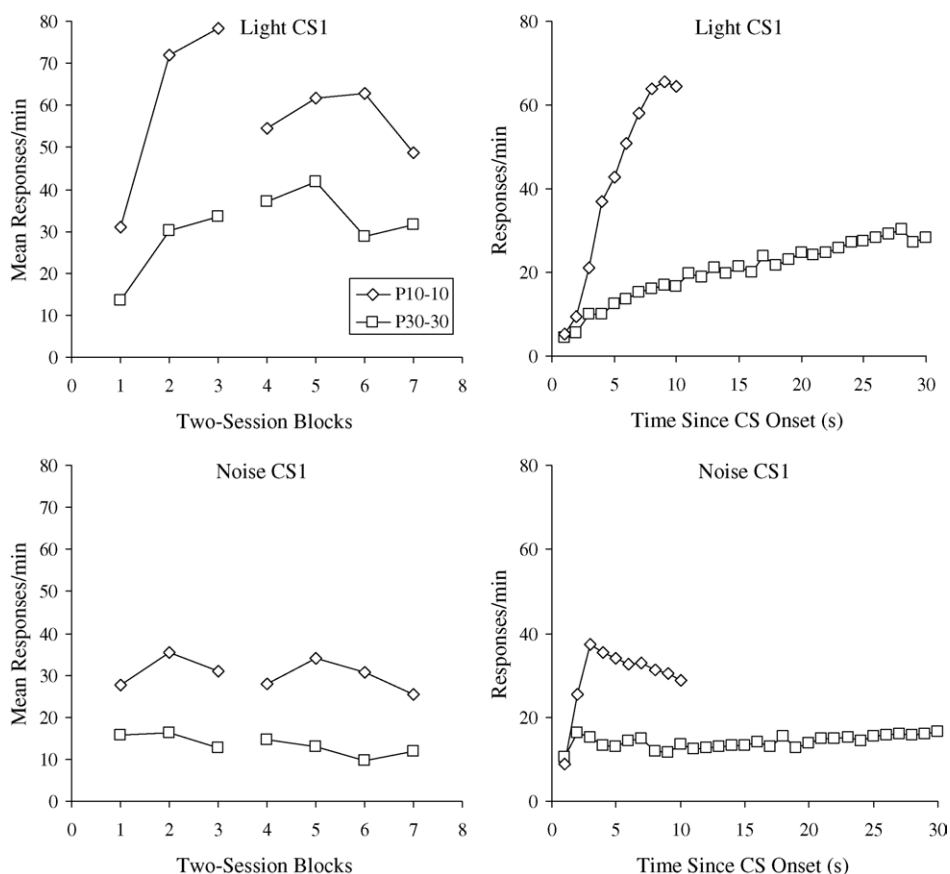


Fig. 1. Left column: the mean rate of responding (in responses/min) to the light (top panel) or noise (bottom panel) CS1 as a function of two-session blocks of pretraining (Blocks 1–3) and compound training (Blocks 4–7) in Experiment 1. The rate of responding during pretraining was obtained from reinforced CS1 conditioning trials, whereas the rate of responding during compound training was obtained from reinforced CS1-only probe trials. Right column: the local rate of responding during the light (top panel) or noise (bottom panel) CS1 as a function of time since CS onset over the six sessions of pretraining in Experiment 1. The timing functions were obtained during reinforced CS1 conditioning trials.

## 2.3. Results

### 2.3.1. Pretraining

Fig. 1 displays the mean response rate during light CS1 (top-left) or noise CS1 (bottom-left) trials as a function of two-session blocks of pretraining (Blocks 1–3) and compound training (Blocks 4–7). An analysis of variance, conducted on the pretraining data, revealed that there was a main effect of stimulus modality,  $F(1,8) = 8.7$ ,  $p < 0.05$ , that was attributed to greater responding during the light CS1 compared to the noise CS1. There also was a significant main effect of CS1 duration,  $F(1,8) = 14.3$ ,  $p < 0.01$ , that was due to greater responding to the 10-s CS1 compared to the 30-s CS1. There was no interaction between CS1 duration and modality,  $F(1,8) = 1.9$ , ns.

The local rate of responding (responses/min) as a function of time since CS1 onset during pretraining is shown in the right-hand panels of Fig. 1. There was a clear effect of CS duration on the gradients, with the 10-s CS1 resulting in steeper functions than the 30-s CS1. In addition, the light CS1 appeared to result in steeper gradients than the noise CS1. The temporal gradients were analyzed further by determining their slope (see Section 2.2.4). For the both CS durations, there was a sig-

nificant effect of modality [10 s:  $F(1,4) = 15.7$ ,  $p < 0.01$ , 30 s:  $F(1,4) = 67.4$ ,  $p < 0.01$ ] that was due to steeper slopes during the light CS1.

### 2.3.2. Compound training

The response during CS1 probe trials was examined during compound training to determine whether there were any changes due to the presentation of CS1–CS2 compounds. These data are displayed in the left-hand panels of Fig. 1, Blocks 4–7. An ANOVA on the mean response rates as a function of blocks of compound training revealed no main effect of block or any interaction of block with duration or modality, largest  $F(3,24) = 1.0$ , indicating that the response to CS1 did not change over the course of compound training. There were effects of duration,  $F(1,8) = 7.4$ ,  $p < 0.05$ , and modality,  $F(1,8) = 11.8$ ,  $p < 0.01$ , as in pretraining.

Fig. 2 displays the mean response rate as a function of two-session blocks of compound training for the four groups during noise (top-left) and light (bottom-left) CS2 probe trials. Because there were different patterns of results depending on whether CS2 was noise or light, the response rates were analyzed separately by modality. The mean rates dur-

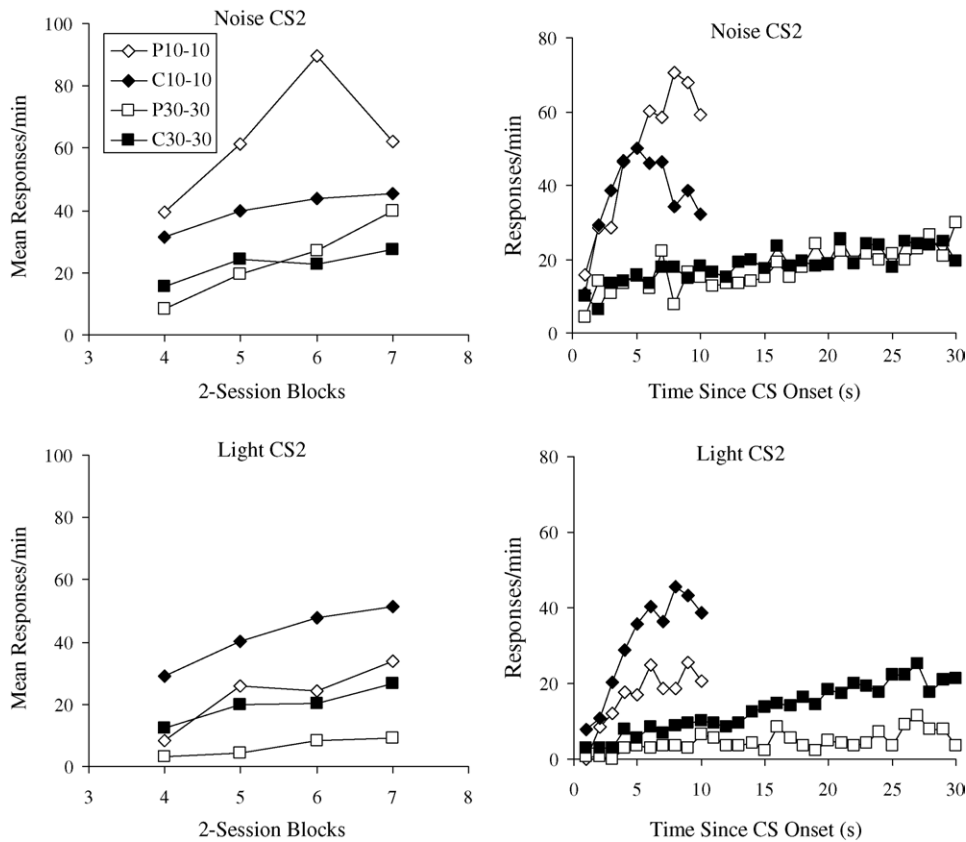


Fig. 2. Left column: the mean rate of responding (in responses/min) to the noise (top panel) or light (bottom panel) CS2 as a function of two-session blocks of compound training in Experiment 1. Right column: the local rate of responding during the noise (top panel) or light (bottom panel) CS2 as a function of time since CS onset over the eight sessions of compound training in Experiment 1. Both measures of responding were obtained during reinforced CS2-only probe trials.

ing the noise-only CS2 trials did not reveal any evidence of a blocking effect,  $F(1,14)=2.1$ , ns, but there were higher mean rates to the 10-s CS2,  $F(1,14)=13.8$ ,  $p<0.01$ . There was no condition  $\times$  duration interaction,  $F(1,14)=2.3$ , ns. The mean rates during the light-only CS2 trials revealed a blocking effect with greater responding exhibited by the control groups,  $F(1,14)=18.5$ ,  $p<0.01$ , as well as significantly higher response rates to the 10-s CS2 as compared to the 30-s CS2,  $F(1,14)=25.8$ ,  $p<0.001$ . There was no condition  $\times$  duration interaction,  $F(1,14)<1$ , indicating that there were no robust differences in blocking as a function of interval duration.

The timing functions are presented in Fig. 2 (right column) for the noise and light CS2 trials. The functions for the experimental and control groups appear similar in shape, but they diverged over time, with a maximal difference in the second half of the CS. As in pretraining, the short CS2 produced steeper response rate functions. The slopes of the timing functions were assessed to determine whether there was an effect of blocking on timing accuracy. For the 10-s CS2, there was no effect of condition on the slope during either the noise,  $F(1,7)=2.8$ , ns, or light,  $F(1,7)<1$ . Similar results were found with the 30-s CS2 in that there was no effect of condition on responding during either the noise,  $F(1,7)=1.6$ , ns, or light,  $F(1,7)<1$ .

#### 2.4. Discussion

The present experiment investigated blocking with simultaneous compounds, and revealed a similar blocking effect regardless of CS duration. However, blocking was only apparent when pretraining was with a noise CS1 and followed by adding a light CS2 in compound with the noise. Pretraining with a light failed to block responding to a noise, although this did not appear to be due to a failure of conditioning to the light because it actually produced higher rates of responding in pretraining. The problem of stimulus salience in blocking experiments is widely recognized. For instance, when the to-be-blocked stimulus is of high biological significance, or salience, the blocking effect is attenuated (e.g., Couvillon et al., 2001; Klein et al., 1984; Miller and Matute, 1996). The present results suggest that the light was relatively less salient than the noise, and thus was less able to produce blocking.

With both counterbalancing arrangements, there was a clear effect of duration on responding in both phases; shorter durations yielded higher rates and steeper temporal gradients. This pattern resembles interval duration effects on responding seen previously in appetitive conditioning (e.g., Holland, 2000; Kirkpatrick and Church, 2000). In addition, reasonably accurate temporal gradients were observed to both stimulus modalities and in both the experimental and control groups. Although

blocking occurred, this did not affect the accuracy of timing, indicating that the blocking effect was confined to a depression in mean response rate. This finding is consistent with Gaioni's (1982) observation of intact timing accuracy in groups that experienced a blocking effect.

While blocking and timing accuracy appeared unrelated, there was an indication that the blocking effected unfolded with time. The response rate functions began at similarly low levels, but the experimental and control groups diverged over time (Fig. 2). The observed pattern may simply be due to floor effects early in the CS. However, the TD model also expects this pattern because the units that occur late in the CS will be more strongly conditioned than early units, and thus blocking will be more robust. That is, the difference between the blocked group and the experimental group should be more easily observed late in the CS when CS1 has established a strong association with the US.

### 3. Experiment 2

#### 3.1. Introduction

Experiment 1 demonstrated that blocking in simultaneous compounds was similar in magnitude regardless of absolute CS duration, indicating that both short and long CSs are capable of producing robust blocking. Experiments 2a and 2b sought to investigate the blocking effect when CS2 onset was not contiguous with CS1 onset. Both experiments involved the delivery of short–long overlapping compounds with a short CS that was 10 s in duration. Experiment 2a implemented a 90-s long CS, and Experiment 2b used a 15-s long CS. Thus, blocking was assessed in a situation where the long CS was either much longer (nine times) or only slightly longer (1.5 times) than the short CS.

The present experiment attempted to address the disparity in the literature by determining whether blocking is only observed in simultaneous compounds (Barnet et al., 1993) or whether a long CS1 is capable of blocking a short CS2 (Gaioni, 1982; Kehoe et al., 1981). In addition, Experiment 2 expanded on the previous investigations by: (a) comparing blocking in short–long compounds when CS1 was the short or the long stimulus; (b) assessing differences in conditions where the short and long durations were disparate or similar. Both of these aspects of Experiment 2 are new features that have not been examined previously. As in Experiment 1, Experiment 2 also examined measures of both the strength of conditioning and the timing of responding to determine whether blocking affected only response rate or also interfered with timing accuracy.

The TD model makes the following predictions for the pattern of mean response rates: (a) blocking will occur when CS1 is long, but not when CS1 is short; (b) blocking will be similar in magnitude when the long CS is 15 s compared to 90 s because only the units that fire shortly before CS2 onset will contribute to the blocking effect; (c) a long CS2 will steal strength from a shorter CS1 during compound conditioning. This last prediction of the model is a well documented finding in the serial compound conditioning literature (e.g., Egger and Miller, 1962; Kehoe, 1979, 1983; Kehoe et al., 1987). For example, Kehoe et al. (1987)

gave initial training with a CS1 that was 500-ms in duration and then added a 2000-ms duration CS2 in an overlapping serial compound with CS2. The response to CS1 declined due to the presence of a longer CS2 in compound, a result that has been dubbed the temporal primacy effect.

The comparison of blocking by the 90 s versus 15 s long CS1 will provide a strong test of the model. While the TD model predicts no difference in blocking between these two long CSs, alternative models do expect a difference. For example, the time-of-arrival hypothesis (Goddard and Jenkins, 1988) proposes that the efficacy in blocking will be a function of the temporal predictability of the pretrained CS1 compared to the temporal predictability of the added CS2. Therefore, a 90-s CS1 should produce little or no blocking in comparison with a 15-s CS1, because it is a weak predictor of the US.

#### 3.2. Methods and materials

##### 3.2.1. Animals

Each of the two experiments employed 24 experimentally naïve male Sprague–Dawley rats (Harlan UK). Housing and husbandry procedures were the same as in Experiment 1.

##### 3.2.2. Apparatus

The apparatus was the same as in Experiment 1.

##### 3.2.3. Experiment 2a procedure

Rats were randomly assigned to four groups ( $n = 6$ ): P90-10, P10-90, and C90-10 and C10-90.

**3.2.3.1. Pretraining (Sessions 1–6).** Groups P90-10 and P10-90 received pretraining with either a houselight or 70-dB white noise. Termination of the CS was immediately followed by food. Each session comprised 48 CS-US trials separated by a variable 120-s ITI that was a minimum of 60 s in duration. During pretraining, the overshadowing control groups (C90-10 and C10-90) were placed in the experimental chambers but received no stimuli or reinforcers. During the second session of pretraining, a software crash occurred at the end of the session; there was no discernible impact on the delivery of the procedure, but some data were lost for a subset of rats.

**3.2.3.2. Compound training (Sessions 7–14).** Following pretraining, eight sessions with light and noise compounds were delivered to all four groups. Group P90-10 received compound training with a second CS that was 10 s in duration and group P10-90 received a CS2 that was 90 s in duration. Groups C90-10 and C10-90 were exposed to compound trials consisting of a 90 and a 10-s CS. The two stimuli were presented so that the long CS onset occurred 80 s before the short CS onset and both stimuli terminated at the time of food delivery. In the control groups, CS2 was defined as 10 s in Group C90-10 and 90 s in group C10-90. There were three different trial types delivered during compound training: 40 CS1/CS2, 4 CS1 alone, and 4 CS2 alone, with all trials ending in reinforcement. All other aspects of the procedure were the same as in Experiment 1. During compound training, software crashes during two different sessions

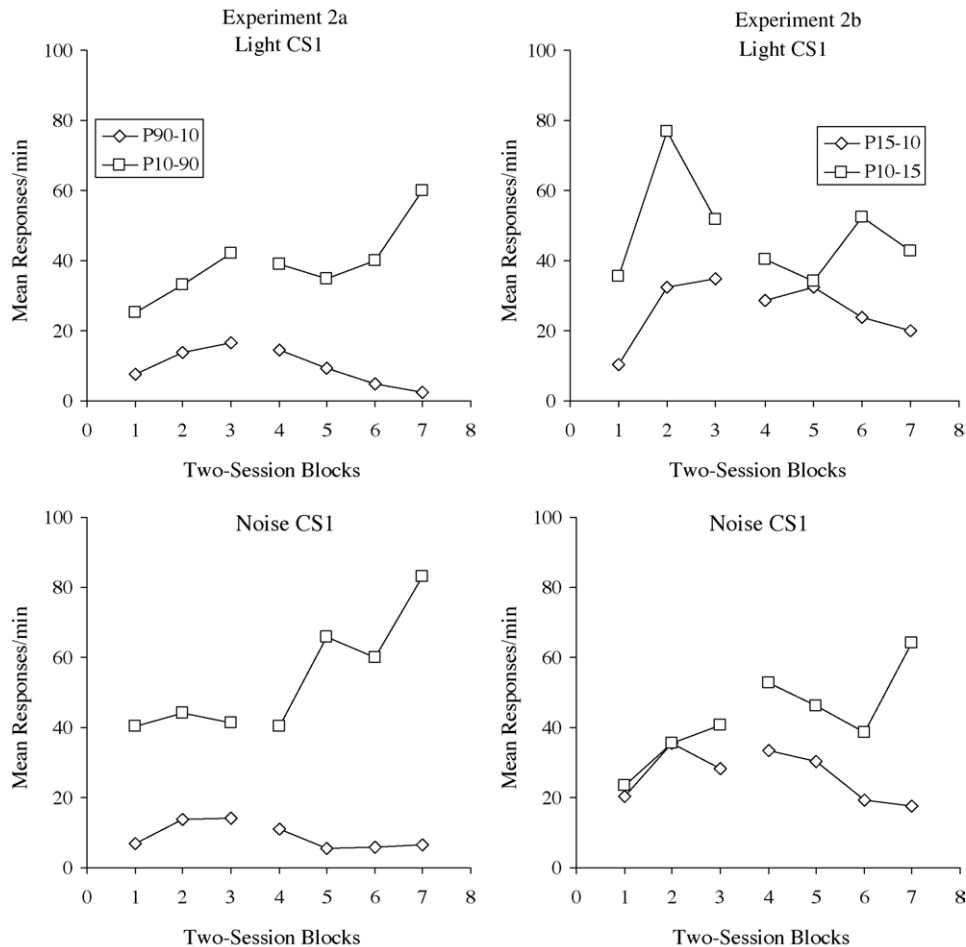


Fig. 3. The mean rate of responding (in responses/min) to the light (top panels) or noise (bottom panels) CS1 as a function of two-session blocks of pretraining (Blocks 1–3) and compound training (Blocks 4–7) in Experiment 2a (left column) and Experiment 2b (right column). The rate of responding during pretraining was obtained from reinforced CS1 conditioning trials, whereas the rate of responding during compound training was obtained from reinforced CS1-only probe trials.

(Sessions 10 and 13) resulted in the loss of data for a subset of rats in each group.

### 3.2.4. Experiment 2b procedure

The rats were randomly assigned to four groups: P10-15 ( $n = 8$ ), P15-10 ( $n = 8$ ), C10-15 ( $n = 4$ ) and C15-10 ( $n = 4$ ).

**3.2.4.1. Pretraining (Sessions 1–6).** Groups P10-15 and P15-10 received pretraining with 48 trials of either a houselight or 70-dB white noise that lasted for 10 or 15 s. The control rats were placed in the experimental chambers but did not receive any stimuli or reinforcers. All aspects of the procedure were the same as in the previous experiments.

**3.2.4.2. Compound training (Sessions 7–14).** Following pretraining, eight sessions using a compound of light and white noise were delivered to all three groups. In the present experiment, group P10-15 received compound training with a second CS that was 15 s in duration and group P15-10 received a CS2 that was 10 s in duration. Groups C10-15 and C15-10 were exposed to compound trials of a 10 and a 15 s CS. The com-

ound was presented so that the 15-s CS onset occurred 5 s prior to the 10-s CS onset and both stimuli terminated at the time of food delivery. In the control groups, CS2 was either 10 or 15 s in both groups. In other words, both groups were tested on both 10 and 15 s stimuli and the data from both of these contributed to the assessment of the conditioning to CS2. There were three different trial types: 40 CS1/CS2, 4 CS1 alone, and 4 CS2 alone, and all trials ended in reinforcement. All other aspects of the procedure were the same as in the previous experiments.

### 3.3. Results

#### 3.3.1. Pretraining

The mean rate of responding to the 90 and 10-s CS1 durations (left panels) and the 15 and 10-s CS1 durations (right panels) is shown as a function of two-session blocks of pretraining (Blocks 1–3) and compound training (Blocks 4–7) in Fig. 3. In the pretraining phase of Experiment 2a, responding to the 10-s CS1 was higher than responding to the 90-s CS1,  $F(1,8) = 26.9$ ,  $p < 0.01$ . There was no main effect of CS modality,  $F(1,8) < 1$ , nor was there an interaction between CS duration and modal-

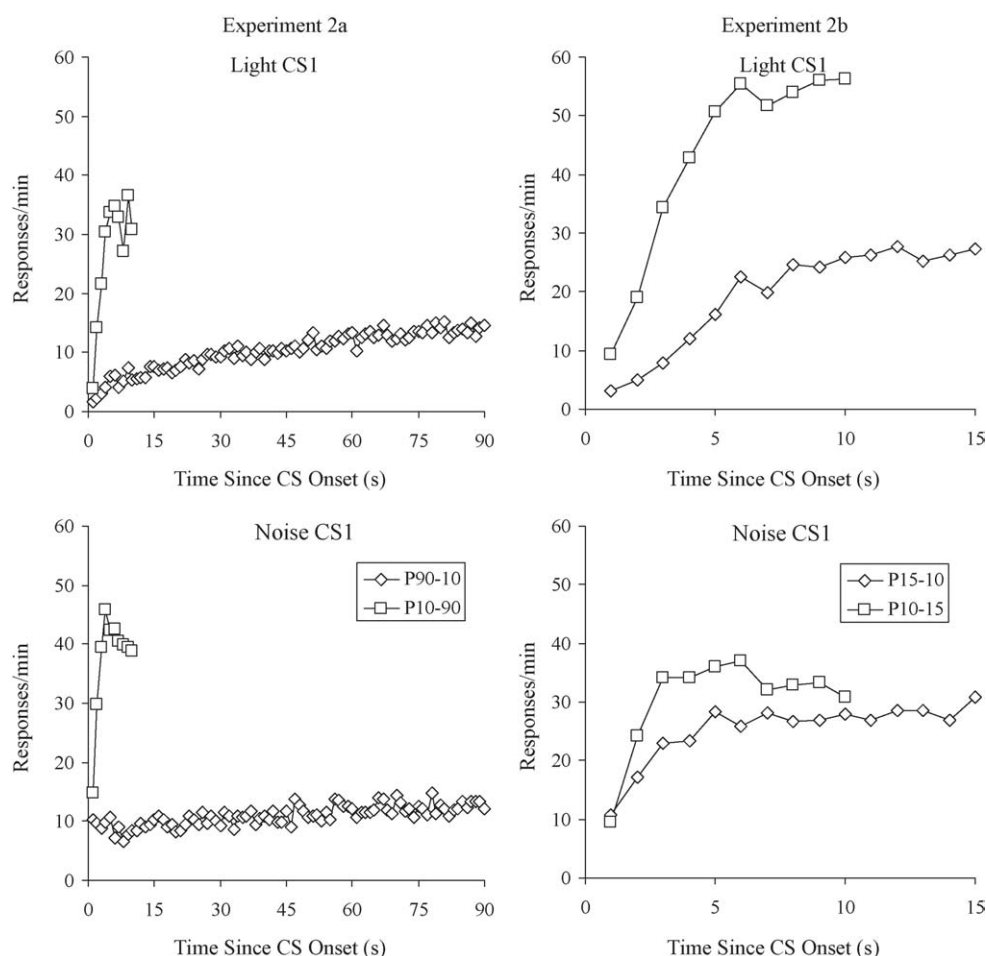


Fig. 4. The local rate of responding during the light (top panels) or noise (bottom panels) CS1 as a function of time since CS onset over the six sessions of pretraining in Experiment 2a (left column) and Experiment 2b (right column). The timing functions were obtained during reinforced CS1 conditioning trials.

ity,  $F(1,8) < 1$ . In Experiment 2b, the two stimuli were similar in duration (10 s versus 15 s), and there was no effect of CS duration on the mean rate of responding during CS1, although it approached significance,  $F(1,12) = 4.5$ ,  $p = 0.06$ . There was no main effect of CS modality,  $F(1,12) = 1.5$ , ns, nor was there any interaction between CS duration and modality,  $F(1,12) = 2.2$ , ns.

The timing functions during pretraining in Experiments 2a (left column) and 2b (right column) are displayed in Fig. 4 for the noise and light CS1 stimuli. In Experiment 2a, the response to the noise and light appeared similar, with all functions displaying a general increase and with steeper functions for the 10-s CS1 compared to the 90-s CS1. An ANOVA on the slopes, conducted separately for the two different CS durations revealed no effect of modality on the response to the 10-s CS1,  $F(1,4) < 1$ , but a significant effect of modality on responding to the 90-s CS1,  $F(1,4) = 9.7$ ,  $p < 0.05$ , which arose from the steeper slopes during the light.

In Experiment 2b (right column), the noise CS1 resulted in flatter response rate functions, as evidenced by a significant effect of modality on the slope of responding during the 10-s CS1,  $F(1,6) = 18.5$ ,  $p < 0.01$ . There was also a trend towards steeper slopes during the 15-s light CS1, but this did not reach significance,  $F(1,6) = 3.6$ , ns.

### 3.3.2. Compound training

The mean rate of responding during CS1-only probe trials was examined over the course of compound training, to assess whether there was any effect of compound presentations on responding to the pretrained CS1; these data are shown in Fig. 3 (Blocks 4–7). In contrast to Experiment 1, where there were no noticeable changes in responding to CS1, there were changes over the course of compound conditioning in both Experiments 2a and 2b [block  $\times$  duration interaction: Experiment 2a,  $F(3,24) = 3.0$ ,  $p = 0.05$ ; Experiment 2b,  $F(3,36) = 3.6$ ,  $p < 0.05$ ]. Follow-up analyses examining the effect of block separately for the short and long durations revealed that there was a significant decline in responding to the long CS1 duration in both experiments [Experiment 2a:  $F(3,15) = 4.8$ ,  $p < 0.05$ ; Experiment 2b:  $F(3,21) = 7.0$ ,  $p < 0.01$ ]. There were no significant changes over the course of compound training to the short CS1 duration [Experiment 2a:  $F(3,15) = 2.3$ , ns; Experiment 2b:  $F(3,21) < 1$ ].

As in Experiment 1, there were different patterns of responding to CS2 as a function of modality (see Fig. 5). Analyses conducted on the mean rate of responding during noise CS2 trials in Experiment 2a revealed an effect of duration,  $F(1,14) = 26.3$ ,  $p < 0.001$ , but no effect of condition,  $F(1,14) < 1$ , and no interac-



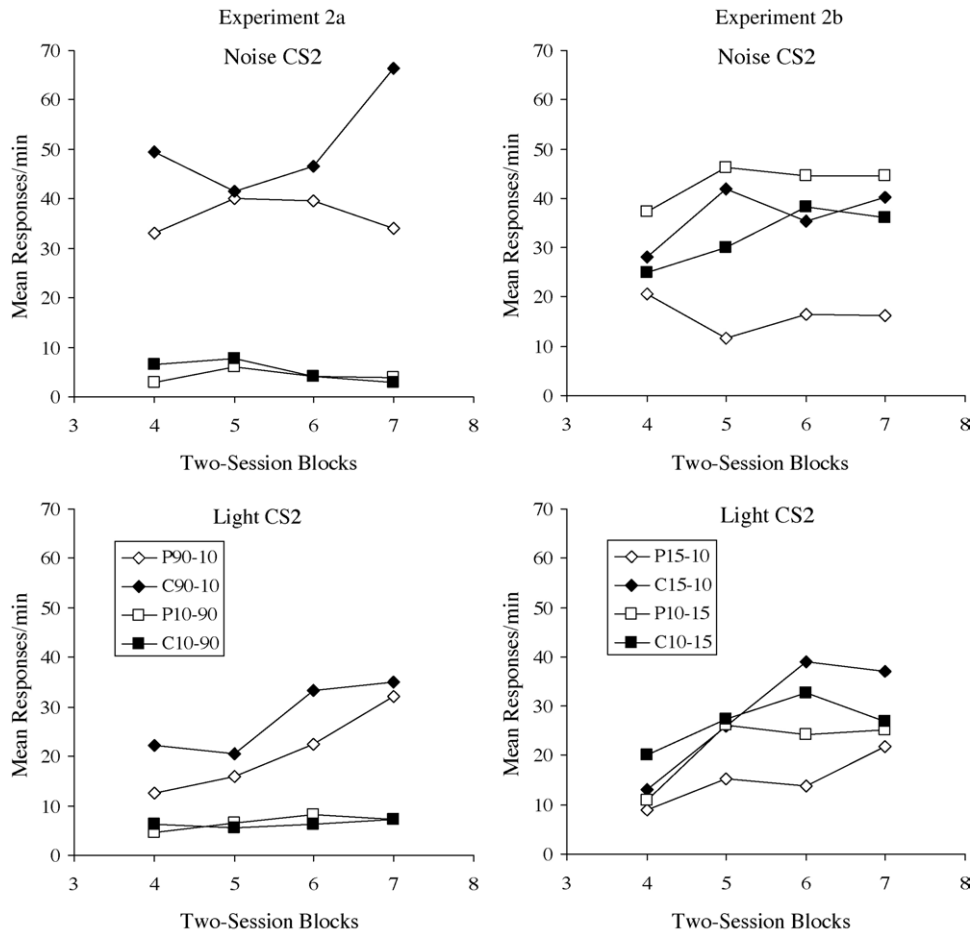


Fig. 5. The mean rate of responding (in responses/min) to the noise (top panels) or light (bottom panels) CS2 as a function of two-session blocks of compound training in Experiment 2a (left column) and Experiment 2b (right column). The mean rate of responding was obtained during reinforced CS2-only probe trials.

tion,  $F(1,14) < 1$ . Additional analyses conducted separately for the short and long CS2 trials did not reveal any evidence of a blocking effect when CS1 was light and CS2 was noise (top-left panel of Fig. 5, both  $F$ s  $< 1$ ). An ANOVA conducted on the mean rate of responding during the light CS2 trials in Experiment 2a (bottom-left panel of Fig. 5) revealed a significant effect of duration,  $F(1,14) = 46.9$ ,  $p < 0.001$ , but there was no effect of condition,  $F(1,14) = 2.5$ , ns, or any condition  $\times$  duration interaction,  $F(1,14) = 2.7$ ,  $p = 0.1$ . Additional analyses were conducted to assess any effect of blocking condition separately for the short and long light CS2 durations. Here, a significant blocking effect was observed when analyzing the short CS,  $F(1,7) = 6.2$ ,  $p < 0.05$ , but not the long CS,  $F(1,7) < 1$ . Thus, a 90-s CS1 blocked a 10-s CS2, but not vice versa.

The right panels of Fig. 5 display the mean rate of responding as a function of two-session blocks in Experiment 2b, when the long CS1 was 15 s. Analyses of responding to the noise CS2 (top-right panel of Fig. 5) revealed that there was no main effect of condition,  $F(1,12) < 1$  or any effect of duration,  $F(1,12) = 4.1$ , ns, but there was a condition  $\times$  duration interaction,  $F(1,12) = 7.6$ ,  $p < 0.05$ . Additional analyses of the blocking effect for each duration revealed a significant blocking effect when CS2 was 10 s,  $F(1,6) = 8.7$ ,  $p < 0.05$ , but not when CS2 was 15 s,  $F(1,6) = 1.5$ , ns.

Analyses on the response rate during the light CS2 (bottom right panel of Fig. 5) revealed a significant main effect of condition,  $F(1,12) = 7.7$ ,  $p < 0.05$  that was indicative of a blocking effect. There was no effect of duration,  $F(1,12) < 1$  or any condition  $\times$  duration interaction,  $F(1,12) = 1.6$ , ns. Although there was no interaction, further analyses were conducted by analyzing the blocking effect when the light CS2 was short or long. This revealed a significant blocking effect when CS2 was 10 s,  $F(1,6) = 6.5$ ,  $p < 0.05$ , but there was no effect of condition when CS2 was 15 s,  $F(1,6) = 1.5$ , ns.

The response rate as a function of time since CS2 onset is displayed in Fig. 6 for Experiments 2a (left panels) and 2b (right panels). In Experiment 2a, the analysis of the slopes of responding during the noise CS2 revealed no effect of condition for either of the CS durations, both  $F$ s(1,7)  $< 1$ . When testing the 10-s light CS2, there was an effect of condition,  $F(1,7) = 8.4$ ,  $p < 0.05$ , that was due to steeper slopes in the control group. There was no effect of condition on responding during the 90-s light CS2,  $F(1,7) = 1.5$ , ns.

A different pattern was apparent in Experiment 2b, where the two CS durations were similar (10 and 15 s), and there was no effect of condition on responding to any of the stimuli, all  $F$ s(1,6)  $< 1$ .

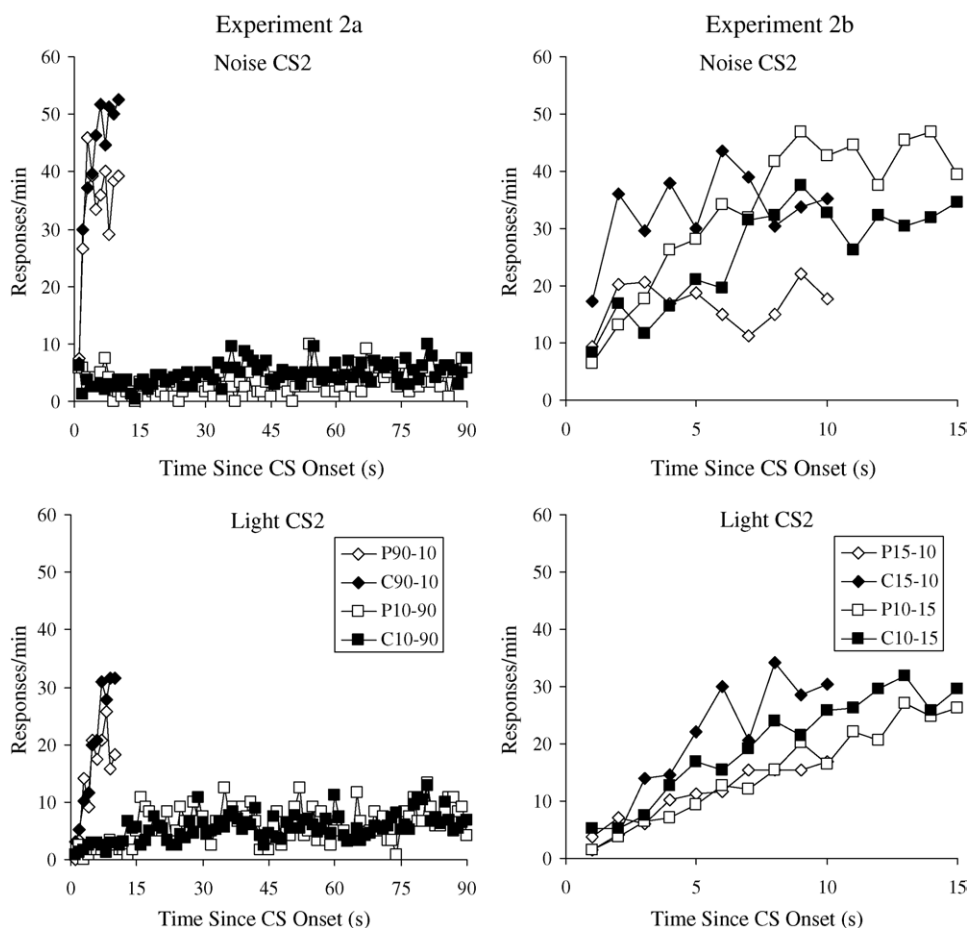


Fig. 6. The local rate of responding during the noise (top panels) or light (bottom panels) CS2 as a function of time since CS onset over the eight sessions of compound training in Experiment 2a (left column) and Experiment 2b (right column). The timing functions were obtained during reinforced CS2-only probe trials.

### 3.4. Discussion

Experiments 2a and 2b both revealed evidence of a long CS1 blocking a short CS2, but not vice versa, even though the long CS1 was much longer in Experiment 2a than in Experiment 2b. In addition, the 90-s CS1 blocked the 10-s CS2 despite producing only modest acquisition in the pretraining phase (Fig. 3). Although the long CS1 was successful in blocking the short CS2, there was evidence of a loss of control over responding by the long CS1 that did not appear to be a simple product of the presentation of the compound stimulus because this effect was not apparent in the response to the short CS1. The loss in responding to the long CS1 is potentially of theoretical interest, and will be considered in Section 4.

The failure to observe blocking by the 10-s CS1 may have been due to a floor effect in Experiment 2a, because of the low rates of response to the 90-s CS in general. However, a floor effect cannot easily explain the failure to observe blocking by this CS in Experiment 2b, where response rates to the 15-s CS were robust.

As in Experiment 1, there was no clear effect of blocking on the accuracy of timing, with one exception. There was evidence of shallower slopes of responding to the short light CS2 in Experiment 2a that was indicative of possible interference in

timing due to the long CS1 blocking the short CS2. This pattern was not observed in Experiment 2b. This raises the possibility that interference in timing is only apparent when the two CSs are very different in duration.

## 4. General discussion

Experiment 1 examined the effect of absolute duration in simultaneous compounds, an issue that has been overlooked in the blocking literature. This experiment revealed that the magnitude of the blocking effect was similar, regardless of whether the compound was composed of two short or two longer durations. The results indicate that short and long stimuli are equally capable of blocking in simultaneous compounds, and thus any differential effects in non-simultaneous compounds is unlikely to be due to differences in the efficacy of blocking as a function of duration.

Experiments 2a and 2b, in which blocking was examined in partially overlapping long–short compounds indicated that a long CS blocked a short CS, whether the long CS was marginally longer or much longer than the short CS. Conversely, the short CS did not block the long CS in either case. These results are unlikely to be due to a floor effect with the long CS2 because the 15-s long CS resulted in as robust of levels of responding as

the 10-s short CS. In addition, the failure of the 10-s short CS1 to block the longer CS2 was not due to a failure of this stimulus to produce blocking because robust blocking was observed with this CS in a short–short simultaneous compound in Experiment 1.

The results of Experiments 2a and 2b are consistent with earlier findings by Kehoe et al. (1981) and Gaioni (1982). The present experiments expanded on these results by indicating the generality of blocking of a short CS by a long CS in long–short compounds across procedures and across different stimulus durations. The present experiment also expanded on the earlier research by indicating that this form of blocking occurs when the long CS is similar in duration to the short CS, as well as when the long CS is much longer than the short CS. In addition, the present experiment contrasted blocking by short and long CS1 stimuli in short–long compounds and indicated that short CSs are not able to block long CSs, even though the short CS is more contiguous with the US.

One purpose of the present set of experiments was to determine whether the TD model (Moore and Choi, 1997; Sutton and Barto, 1990) would accurately predict the results. There were a number of findings that were consistent with the model, including: (a) the robust blocking in short–short and long–long simultaneous compounds in Experiment 1; (b) the asymmetry in blocking in short–long compounds whereby a long CS blocked a short CS but not vice versa; (c) the similar degree of blocking exhibited by the 15- and 90-s long CSs.

However, this model does not predict the loss of responding to the long CS1 in a serial compound with a shorter CS2. The model actually predicts the reverse pattern with a loss in responding to a short CS1 when it is compounded with a longer CS2. Thus, the mechanism by which the TD model predicts the pattern of blocking results may not be correct.

Other models within the domain of timing and conditioning are even less able to explain the present results. The temporal coding hypothesis predicts that blocking should only occur in simultaneous compounds, as was found by Barnett et al. (1993). This model presumes that blocking would be best when the two CSs share the same temporal space. Alternatively, the time-of-arrival hypothesis (Goddard and Jenkins, 1988) predicts that blocking would be best with a short stimulus, regardless of compound type because the short stimulus would be a better predictor of US occurrence. Thus, this model would expect blocking of the long stimulus by the short stimulus in Experiments 2a and 2b, and would also predict a difference in blocking depending on whether the long CS was 15 or 90 s.

While the TD model provides a good fit to the pattern of CS2 conditioning in compound training, it does not provide an explanation of the effect of blocking on timing in group P90-10. Pretraining with the 90-s long CS1 resulted in a decrease in the accuracy of timing of the 10-s CS2, as measured by the slope of the response function (Fig. 6). Previous examinations of interval duration effects on blocking have not examined measures of timing of responding, so the generality of these effects is unknown, and further study would be beneficial. One can only speculate that these effects may have been due to a within-compound interaction between the 90- and 10-s CSs that was

magnified by previous experience with the 90-s CS1. Comparisons of responding in the 90-10 compound versus a 10-s CS trained on its own would be worthwhile to determine whether or not the presence of the long CS in compound might have produced a detriment in timing of the 10-s CS.

In all other cases examined in all three of the present experiments, timing of CS2 appeared to be unaffected by pretraining of CS1. This suggests that the interval duration effects on blocking were separate from the effects of interval duration on timing processes. CS duration did produce effects on timing, with shorter CSs resulting in steeper response rate functions. However, timing accuracy did not predict the pattern of blocking. For example, the short CS (which was timed more accurately) was able to block another short CS, but unable to block a long CS. This result indicates that blocking effectiveness was not determined by temporal predictability, at least with regard to interval duration effects. Thus, timing and blocking appeared separable in that: timing was unaffected by blocking treatment, except in the one instance mentioned above; and temporal predictability did not relate to the pattern of blocking results.

In summary, the present results replicate and expand on earlier research by determining that absolute duration does not affect blocking, but that there are asymmetries in blocking in non-simultaneous short–long compounds. The occurrence of blocking by a long stimulus (but not a short stimulus) in these compounds is best explained by a real-time conditioning model such as the TD model (Sutton and Barto, 1990). Although this model was originally developed to account for nictitating membrane conditioning, which occurs with stimuli in the millisecond range, it may be able to explain many results from appetitive conditioning in the seconds-to-minutes range.

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