An Exploration of Target Event Encoding in a Predictive Learning Task with Humans: Integrated or Separable Processing?

Natasha B. Nadler

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AN EXPLORATION OF TARGET EVENT ENCODING IN A PREDICTIVE LEARNING TASK WITH HUMANS: INTEGRATED OR SEPARABLE PROCESSING?

by

NATASHA B. NADLER

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The Graduate Center of the City University of New York

2016
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NATASHA B. NADLER

This manuscript has been read and accepted for the Graduate Faculty in Psychology to satisfy the Dissertation requirement for the degree of Doctor of Philosophy

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Abstract

An Exploration of Target Event Encoding in a Predictive Learning Task with Humans: Integrated or Separable Processing?

by

Natasha B. Nadler

Adviser: Andrew R. Delamater

A major theme in the study of Pavlovian learning explores how attributes of a predicted event are represented and encoded. In Pavlovian conditioning, the conditioned stimulus (CS) is frequently assumed to associate with one or more of the various attributes of a motivationally significant unconditioned stimulus (US, e.g. its hedonic, motivational, and/or sensory features). The present research asks whether humans learn to predict and encode different aspects of motivationally neutral target events, namely, their specific sensory and temporal features in a separable or integrated manner. This question of how target events are encoded has implications for associative and timing models of Pavlovian learning, and associative learning more generally. The associative approach assumes that a CS could enter into separate associations with distinctive aspects of the US, while other timing-focused models suggest that these aspects would be encoded in an integrated manner. To investigate this question, four predictive learning tasks with human participants were designed with the goal of seeking evidence to support one or
the other of these encoding possibilities. In an initial experiment, subjects were trained with a single ISI and tested with multiple ISIs in a two alternative forced choice and a go/no go version of the task. In Experiment 2 subjects were presented with four cues and two targets, where two cue-target pairs were trained at a short ISI and two at a long ISI. Then valid and invalid cue-target pairs were tested at both ISIs. Experiment 3 presented four unique cue-target pairs trained in a four-alternative forced choice task. Two pairs were trained at a short ISI and two at a long ISI. During test, valid and invalid cue-target pairs were tested at both short and long ISIs. Experiment 4 employed a conditional discrimination training procedure, where one of two cues predicted target 1 after a short ISI and target 2 after a long ISI, and the other cue signaled target 2 after a short ISI and target 1 after a long ISI. In test, subjects received probe trials in which the cue-target relations were tested at their untrained ISIs. Results from all experiments reveal a consistent pattern – subjects’ reaction times were faster to validly than invalidly cued targets when these relations were tested at the training ISI, and the magnitude of this validity effect was not reduced when testing occurred with alternative ISIs. The outcome of this investigation, of how sensory and temporal attributes of the US are encoded, has resulted in support of the separable encoding account. These findings are at odds with the limited work on this problem. However, there is support in the associative literature for independent associations forming between a CS and the sensory and motivational attributes of the US, and recent evidence that the neural mechanisms mediating these two forms of learning are dissociable. The main implication of the present studies is that a similar dissociation may exist regarding learning about specific sensory and temporal features of the US.
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Chapter 1: INTRODUCTION

Associative learning theory has provided one theoretical framework for understanding basic learning processes in both human and non-humans alike. In this approach, learning is conceptualized as the formation of new connections between the central representations of events when some sort of predictive relationship exists between those events in the world. This simple idea has been used to help explain the underlying processes at work in a wide range of learning phenomena. Classical conditioning is one of the most explored forms of associative learning, and is exemplified in Pavlov’s original experiments. He demonstrated that when a neutral stimulus (the conditioned stimulus or CS) is paired repeatedly with a biologically significant event (the unconditioned stimulus or US) this neutral stimulus became capable of eliciting a conditioned response (CR) that it had not previously elicited (Pavlov, 1927).

An important issue in the study of Pavlovian learning asks what is the nature of the representations of the events that become associated. For instance, a great deal of research has been directed towards analyzing what features of the unconditioned stimulus become encoded and, thus, enter into an association with the CS. It has been suggested that there are multiple components of the US that could be learned about. Following Konorski (1967) the US is commonly regarded as a complex event consisting of many different attributes, such as it’s specific sensory properties, motivational properties, temporal aspects, hedonic properties, and response eliciting characteristics. Any one or more of these components of the US may enter into an association with the CS (eg., see Delamater and Oakeshott, 2007; Delamater, 2012), and one experimental
challenge is devising tasks that enable a clear separation between those different forms of learning.

The dissociation of learning about the specific sensory and more general motivational attributes of the US, for example, has been clearly demonstrated in Pavlovian to instrumental transfer of control (PIT) studies conducted with both rats (e.g. Corbit & Balleine, 2005; Delamater & Holland, 2008; Dickinson & Dawson, 1987; Kruse, Overmier, Konz, & Rokke, 1983) and with humans (Bray, Rangel, Shimojo, Balleine, O'Doherty, 2008; Nadler, Delgado, & Delamater, 2011; Talmi, Seymour, Dayan, Dolan, 2008). In addition, some authors have commented on the possibility that the CS may enter into an association with some abstract temporal code of the CS-US relationship (e.g., Delamater, Desouza, Rivkin, & Derman, 2014; Delamater & Oakeshott, 2007; Matzel, Held, & Miller, 1988). While the idea that the CS can form separate associations with multiple features of the US is becoming more popular (see also Balleine & Killcross, 2006), it is not obvious just how the interval in time between CS and US might itself figure into this learning process. This issue will be a central topic of this dissertation.

There are two main findings that clearly illustrate the importance of CS-US temporal contiguity in Pavlovian learning and performance. For instance, it has been found that the amount of conditioned responding that develops to a CS is affected by the length of the CS-US interval (or the interstimulus interval). Generally, there is an optimal interstimulus interval (ISI) duration depending on the response system studied (eg. Smith et al. 1969). This results in an inverted U shaped function in that intermediate ISI durations promote better conditioned responding than very short or
very long ISIs. This finding is well documented in various animal studies (eg. Gibbon, Baldock, Locurto, Gold, & Terrace, 1977; Hawkins, Carew, & Kandel, 1986; Smith, Coleman, & Gormezano, 1969; & Yeo, 1974) and in studies with humans as well (McAllister, 1953). Another fact about conditioning suggesting that the time of US occurrence is important is the finding that when conditioning occurs with a particular CS-US interval, the CR often maximally occurs late in the CS-US interval close in time to the onset of the US. This temporal specificity has been observed in many different Pavlovian preparations (eg. Brown, Hemmes, Cabeza de Vaca, 1997; Buhusi, & Schmajuk, 1999; Drew, Zupan, Cooke, Couvillon & Balsam, 2005; Kehoe, Ludvig, & Sutton, 2009; Pavlov, 1927; Smith, 1968). While these two facts clearly illustrate the importance of temporal factors in Pavlovian learning and performance, the results do not clearly indicate how, or even whether, a temporal representation of the CS-US interval becomes incorporated into the learning process itself.

In order to more fully appreciate the issues involved in approaching an answer to this question, in the following sections I will first briefly review some of the major associative and timing-based theories of Pavlovian learning. Then I will review a small literature with humans that suggest a way in which studies may be performed to provide new information on how temporal encoding occurs in predictive associative learning tasks with humans.

**Major Theories of Pavlovian Learning**

One of the most influential theories of Pavlovian learning is that proposed by Rescorla and Wagner (1972). This model conceived of learning as a change in the
associative strength between the CS and US. On a single trial, the change in associative strength is determined by the salience of the stimuli and by the surprisingness of the US. These ideas were captured by the model in the following equation:

$$\Delta V = \alpha \beta (\lambda - \Sigma V)$$  \hspace{1cm} (1)

The change in associative strength ($\Delta V$) is equal to the salience of the CS ($\alpha$) and the salience of the US ($\beta$) multiplied by the maximum amount of conditioning supported by the US, or lambda ($\lambda$), minus the sum of the current associative strength of the all the stimuli present on a given conditioning trial ($\Sigma V$). The ($\lambda - \Sigma V$) term represents the difference between the actual US presented and the expected US, and is commonly thought to reflect the surprisingness of the US.

It is important to note that this model was intended as a trial-by-trial description of associative changes that take place over the course of a conditioning sequence and, thus, was not originally designed to address specific within-trial timing dynamics. However, in order to explain some temporal phenomena, e.g. accurate CR timing, (i.e., the finding that the peak CR occurs later in the CS-US interval), some authors have suggested a way in which the approach could be embellished to accommodate such time-dependent effects (eg. Grossberg & Schmajuk, 1989; Killeen & Fetterman, 1988). For instance, one currently popular idea that traces back to Pavlov (1927) is the notion that presentation of the CS evokes a temporal cascade of discriminably distinct internal cues with different temporal distributions (eg. Todd, Winterbauer, & Bouton, 2010).
Each of these internal temporal cues, in turn, is assumed to mark time within the CS. The final internal temporal cue within the CS that co-occurs with presentation of the US would, then, gain the most associative strength and come to maximally evoke the conditioned response at the appropriate point in time. Although this modification of the basic model may explain accurate CR timing, without making further assumptions it has difficulty explaining other temporal effects on conditioning. For instance, at first blush it is difficult to see how this approach could explain why conditioning is an inverted U shaped function of ISI.

There are other more explicit real-time models related to the Rescorla-Wagner model (e.g., Brandon, Vogel, & Wagner, 2003; Sutton & Barto, 1981; Barto and Sutton, 1982; Wagner, 1981) that were designed to account for some time-sensitive effects, but these models similarly either have difficulty with explaining accurate CR timing or with the inverted U-shaped ISI function. Moreover, more recent evidence also suggests that the CS-US interval, itself, rather than just affecting learning and/or performance of the CR, is directly encoded as part of the underlying associative content. Some of this evidence will be reviewed below, but if this were true then it clearly presents a challenge to the sort of associative theories we have been considering so far.

**Timing-based Theories of Pavlovian Conditioning**

Another class of theory has been applied to Pavlovian learning phenomena and these do more explicitly assume that temporal information is represented and importantly determines conditioned responding. Miller and colleagues have put forth the Temporal Coding Hypothesis (TCH) that assumes that the CS-US interval is
encoded as part of the underlying CS-US association (Matzel, Held, & Miller, 1988). This approach assumes that time is another dimension, in addition to associative strength, by which the CS-US relationship is encoded. While it is difficult to know precisely how time could be encoded in this way, the approach does make some testable assumptions.

One of the tenets of the TCH is that temporal maps of the stimuli presented are created in memory and that these temporal maps can be used to deduce new interval relationships between stimuli if they share a common element. This idea was nicely illustrated in sensory preconditioning experiments (Matzel, et al, 1988; Taylor, Joseph, Zhao, & Balsam, 2014). Matzel et al. (1988) initially gave two groups of rats CS1-CS2 pairings - a 5 s click CS (CS1) followed immediately by a 5 s tone CS (CS2). In phase 2 of their experiment, the tone CS (CS2) was paired with a 5 s foot shock US. In one group of rats (forward-paired group) the tone CS was immediately followed by a foot shock US, and in another group (simultaneous-paired group) the tone CS and the foot shock US were presented simultaneously. CS1 (click) and CS2 (tone) were then separately tested. The results of the two groups in the presence of CS2 were in accord with the traditional finding that conditioned responding is weaker in a simultaneous conditioned group than a forward conditioned group. However, responding in the presence of CS1 was equally strong in both groups, and greater than in appropriate control groups. This finding provides evidence that learning can occur in simultaneous conditioning. But, more importantly, these authors suggested that a predictive temporal relationship could be inferred between CS1 and the anticipated US. More specifically, CS1 signaled the arrival of CS2 in 5 s, and, in Group Simultaneous, CS2 signaled the
co-occurrence of the shock US. By combining these two temporal representations the animal could infer that CS1 precedes the shock US by 5 s, and, thus, display fear to CS1 even though they do not fear CS2. This analysis requires that the CS-US intervals are, themselves, somehow encoded.

The temporal coding hypothesis has been supported in both human and non-human animal studies (see Arcediano, Escobar & Miller, 2003; Barnet, Cole & Miller, 1997; Taylor, et al, 2014). However, as alluded to above, while this hypothesis proposes that time between CS and US is part of the underlying association, it does not answer the question of how time may itself become part of that associative content.

In a radically different approach, Balsam and Gallistel (2009; Balsam, Drew, & Gallistel, 2010; Gallistel & Balsam, 2014; see also Gallistel & Gibbon, 2000; Gibbon & Balsam, 1981) similarly proposed that the CS-US interval is an integral part of what is learned. However, unlike earlier approaches Balsam and Gallistel suggested that instead of acquiring associations in a Pavlovian task the organism directly encodes events within a temporal memory structure and makes decisions whether to respond to a given stimulus on the basis of various computations performed on the raw data stored within that temporal memory system. For example, in a situation where the CS and US are paired occasionally (but not always) and where the US can occur without the CS, the animal is assumed to encode the times of occurrence of all presentations of these events. In order to determine if the animal should respond when the CS occurs, the animal would need to compute whether the CS reduces the uncertainty about when the next US is likely to occur, relative to when the CS is not present. If the CS does reduce the temporal uncertainty of the US, then the animal will decide to respond. Furthermore,
if the temporal interval is directly encoded somehow, then they should respond at the appropriate point in time within the CS.

Importantly, this purely computational approach has no place for an association between CS and US governing learning and responding. Instead, responding is the direct product of a temporal uncertainty reduction computational process. If the CS reduces the temporal uncertainty concerning the US’s occurrence, then responding will emerge to the CS.

This approach has not directly addressed the question of how other aspects of reward might enter into the learning process. Based on other research, we know that the specific sensory characteristics of the reward, as noted above, play a strong role in governing both learning (e.g., Delamater, 1995) and performance (e.g., Delamater & Holland, 2008) processes. One reasonable extension of the Gallistel and Balsam (2014) temporal information theory approach would be to assume that different reinforcing events with distinctive sensory features should be encoded in terms of their time of occurrence. This follows from the basic assumption that events are fundamentally stored within a temporal memory structure, and important response decisions are based on computations performed on that memory structure. Another way of stating this assumption is that the temporal and sensory features of an event should be encoded in an integrated fashion because that sensory event is assumed to be “time-stamped” upon its presentation. The organism should “know” when a particular event will occur because they encode that event in terms of its time of occurrence.

It is noteworthy that this model completely departs from other formal models of associative learning in supposing (a) that associations do not contribute in any
significant way to learning or performance processes, and (b) that the encoding of non-temporal aspects of an event are secondary to their temporal aspects. Indeed, more traditional associative approaches assume that organisms can learn about sensory features of reward as well as their time of occurrence relative to the CS quite independently of one another (e.g., Brown, et al, 1997; Delamater & Oakeshott, 2007; Delamater, et al, 2014; Savastano & Miller, 1998), and that different neural substrates may mediate these forms of learning.

Given these two very different approaches, one rather basic question is whether evidence can be produced that would address whether learning about sensory and temporal aspects of an event involve separable or integrated processes. The associative approach discussed above assumes that a CS, in principle, could enter into separate associations with distinctive aspects of the US, while a view that gives primacy to temporal encoding (e.g., Balsam and Gallistel, 2009; 2014) suggests that these two aspects would be encoded in an integrated manner. Figure 1 depicts these two ideas. The main purpose of this dissertation is to address this basic issue by examining this question in various human predictive learning tasks.

Panel A

<table>
<thead>
<tr>
<th>Separable</th>
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<tbody>
<tr>
<td>CUE → Target (S)</td>
</tr>
<tr>
<td>CUE ← Target (T)</td>
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</tbody>
</table>

Panel B

<table>
<thead>
<tr>
<th>Integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUE → Target (S&amp;T)</td>
</tr>
</tbody>
</table>

Figure 1: Two approaches to target encoding. In the separable account (panel A), the cue comes to predict the sensory (S) and temporal (T) attributes of the target independently, while in the integrated account (panel B), the cue predicts the integration of the target attributes in a unified target event.
**Time-event Encoding in Human Predictive Learning**

There has not been an extensive amount of research exploring the distinction between separable or integrated time-event encoding with either human or non-human animals. However, there are several relevant studies in the human literature and the general issue of the role of “temporal expectancies” has been gaining more attention in recent years (e.g., Coull & Nobre, 2008; Nobre, Correa, & Coull, 2007). Studies of this sort usually involve presenting subjects with some sort of cue (e.g., a fixation point or some other specific stimulus) followed after a specific foreperiod by some target event (usually another visual stimulus) to which the subject is asked to respond. One might draw an analogy between this procedure and normal Pavlovian conditioning procedures in that they both entail presenting a specific stimulus followed by another after a specific time delay. If predictive cues can be regarded as “CSs” and target events as “USs,” as in classical conditioning studies, then there is a formal parallel between the two sets of paradigms. It would not be surprising, then, if similar types of learning processes might be revealed in both situations.

One human study relevant to the issue of time-event encoding is a temporal cuing study by Wagener and Hoffmann (2010). In this study, subjects were trained to respond with distinct button presses to each of two target stimuli (circle or square) that appeared after different foreperiods (the time from onset of the fixation cue to the onset of the target) of either 600 or 1400 ms. Furthermore, each target was associated more frequently with one foreperiod and less commonly with the other foreperiod (a 4/1 ratio). In 100 trials per block, there were 80 “valid” trials where the target occurred after its
frequent foreperiod and 20 "invalid" trials where the target was presented after its less common foreperiod (FP).

It was found that target RT was faster on valid than on invalid trials. The subject's faster response on valid (frequent) trials indicates that the subject had generated a temporal expectation of a particular target event occurring after a particular FP. This result is consistent with the view that the subject had encoded the target event in terms of when it occurred, i.e., they associated the fixation stimulus with an integrated representation of the target event with its time of occurrence. This is why target RTs were faster when the target stimuli were presented at their frequent FP compared to their infrequent FP. Thus, these findings are in line with the Balsam and Gallistel (2014) approach that assumes that a sensory event is time-stamped when presented. Alternatively, these findings could also be explained from the perspective, discussed earlier, of a more traditional associative theory that further assumed time to be encoded in terms of a temporal cascade of temporally discriminable processes. If the FP, itself, plays the role of a predictive cue, different unique FP cues would be associated with the different target stimuli, and RT should be fastest when the targets are presented at their anticipated time of occurrence. It is noteworthy, that in this study there were no cues other than FP cues that could play these predictive roles since the fixation point was equally often followed by one target or the other. From a Pavlovian learning perspective, this is potentially important because in normal Pavlovian learning tasks different discrete cues often are trained to signal different target events. Thus, it is not clear from this study what to expect when different cues, apart from their FPs, differentially signal the occurrence of distinct target events at different FPs.
In another study, Thomaschke and colleagues (2011) explored these issues in a related human reaction time task and found results that they interpreted in terms of integrated processing of sensory and temporal features of a target event (Thomaschke, Wagener, Kiesel, & Hoffman, 2011). In this study, two different target stimuli were presented on different trials at each of 15 different foreperiods (FP). One target stimulus was presented at each FP equally often (‘uniform target’), and the other was presented very frequently at one FP (‘peak target’) and very infrequently at the others. In addition, the relative frequency of these two targets differed in that the peak target stimulus occurred 4 times as often as the uniform target. The subjects’ task was to press one response key if the uniform target appeared on a trial or to press the other response key if the peak target appeared. Once again, each of these events occurred following a common fixation stimulus (and there were no discrete cues other than that could inform the subject as to which type of trial would occur).

The results showed an interaction between target type and FP with the fastest reaction time seen for the frequently occurring target when presented at its most frequent foreperiod. Furthermore, the largest RT difference between the peak and uniform targets was observed at the peak foreperiod. The authors suggested that this finding provides evidence for integrated encoding of the temporal and sensory features of events. In essence, the subjects had formed an expectation of the “peak” target stimulus occurring at the frequently occurring foreperiod. Had subjects encoded the identities and times of the target events separately, they may have learned, in essence, that one target event was more likely than the other and that one FP was more likely to occur than all others. According to this view, Thomaschke et al. (2011) suggested that
responding at all foreperiods should have been faster to the frequently occurring target stimulus and responding to both targets should have been faster at the more frequently occurring foreperiod but these two factors should not have interacted. The implication of these results for processes involved in predictive learning tasks, more generally, are unclear because in this task, like in the Wagener and Hoffman study (2010), there were no distinct cues present on each trial that could be used to signal which type of target stimulus would appear on that trial. Thus, FP cues, themselves, may have played an especially strong role in this study, and this would complicate the analysis in terms of integrated or separable time-event processing.

Unlike the previous two experiments, a study reported by Kingstone (1992) did present discrete predictive cues for different sensory and temporal target attributes. In this study, human subjects were trained with two cues presented for 1500 ms on a computer screen following a fixation stimulus. One of these cues, the “form cue”, (either the number 1 or 2) indicated that a particular target form would follow (either the letter A or V). The other cue, the “time cue”, (either the letter S or L) signaled that the target event would occur after either 400 or 1600 ms. Each cue predicted its associated target (form or time) with a probability of 0.8. For example, presenting the cue “1S” would indicate (with a probability of 0.8) that target “A” would occur in 400 ms. Additionally, neutral cues (“+” for form and “N” for time) were presented on different trials and these signified that either letter or either time could occur with 50% likelihood. The cues were removed and the screen was blank for a period of time (either the 400 or 1600 ms time period) followed by the presentation of a target letter (either A or V). The subjects were
instructed to make different button press responses to the two target stimuli, and their speed and accuracy were recorded.

Only the results from the 400 ms test trials were analyzed in this study, and the results revealed that RT for the expected (cued) form was faster than for the unexpected (uncued) form. However, this difference was larger when the target stimuli were presented at the expected time. In other words, the magnitude of this validity effect was reduced when the target stimuli were presented at earlier times than were indicated by the “long” time cues. These data suggest that the different target + form cues may have evoked specific expectations for their associated target forms, but that these expectations were strongest at the cued time. In other words, the events are consistent with the view that cues may have associated with an integrated time-event encoding of the target stimuli. In contrast, if the cues had evoked separable representations of the target’s identity and time, then we would expect the magnitude of the validity effect to be unchanged when the target stimuli were tested at cued and uncued times and for the two types of cues to affect RT in an additive, not interactive, way. It is interesting that the present study revealed an interactive effect of time and form cues in a situation involving both time and form cues present on each training trial. Perhaps such a procedure would especially encourage the formation of an integrated encoding of the target event’s identity and time of occurrence. Most conditioning studies, however, do not involve multiple cues presented in such a way on each individual training trial. Therefore, it remains an open question as to the generality of these findings. When learning to anticipate different target events on the basis of a single cue, for instance, would such learning result in the formation of associations between the cues and an
integrated or separable representation of the target event’s identity and time of occurrence?

One possible design to address this question would be to present a set of cues indicating different target forms trained at a single time interval. Then, in a test phase the cue-target interval could be varied to be shorter than, the same as, or longer than the training cue-target interval. This situation is much simpler than in the Kingstone (1992) design, and may reveal processes that are more typically engaged in a predictive learning task. At issue is whether under such circumstances (i.e., with single predictive cues) the identities of distinct target events are encoded in terms of their times of occurrence, or whether these two target aspects are encoded separately. This experimental design would better assess whether temporal content is part of what is learned and would relate more to the types of predictive learning tasks commonly employed in the study of associative learning. The present set of studies is directed towards answering this basic question.

CHAPTER 2: METHODOLOGY

Experiment 1

The first study presented here addressed the question of whether people learn to associate distinct cues with both the specific sensory and temporal aspects of different target events (i.e., what they are and when they occur), and whether such learning is best described in terms of separable or integrated representations of the sensory and
temporal aspects of the target stimulus (see figure 1 above). Figure 2 presents the basic experimental design used in this study. Briefly, two distinct cue-target pairs were trained with a single interstimulus interval (ISI) (eg. A-T1, B-T2) in a task where subjects had to respond when a target stimulus appeared. It is hypothesized that this would encourage subjects to associate each cue with its own distinct target event, and this would enable the cue to “prime” the subject for the target stimulus to follow. To determine if this was the case, these same “valid” cue-target pairs were presented during a test phase in which the reverse “invalid” cue-target pairings could also appear (eg. A-T2, B-T1). If each cue had associated with its own distinct target stimulus, then target RT should be faster on valid than invalid test trials. In addition, each of the valid and invalid test trials occurred at multiple ISIs – one shorter, one equal to, and one longer than the training ISI. This was done to assess whether the cues had additionally associated with some temporal component of the training cue-target relation.

Forced-Choice Task: Procedure

<table>
<thead>
<tr>
<th>Training:</th>
<th>Test:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A → T1 → R1</td>
<td>A → T1 → R1</td>
</tr>
<tr>
<td>B → T2 → R2</td>
<td>B → T2 → R2</td>
</tr>
<tr>
<td>500 ms</td>
<td>Valid trials</td>
</tr>
<tr>
<td>300 ms</td>
<td>Invalid trials</td>
</tr>
</tbody>
</table>

- ISI = 800 ms
- No-Go Trials: A → T3; B → T3

FIGURE 2: EXPERIMENT 1A DESIGN
If sensory and temporal attributes of the target stimulus are encoded as an integrated representation (see figure 1B), then we would expect, much like the findings of Tomaschke et al. (2011), that the validity effect would be largest at the training ISI and diminish at the other test ISIs. On the other hand, if subjects acquire specific cue-target associations and encode the sensory and temporal aspects in a separable fashion, we expect the magnitude of the validity effect to remain the same at the various test ISIs. This would imply that each cue had associated with the sensory and temporal aspects of the target stimulus independently. Figure 3 contrasts these two predictions. The separable encoding approach could be thought of as an abstract temporal coding account, where the cue is assumed to associate with an abstract temporal code of the cue-target interval. An alternative separable encoding account can be developed in which the cue is assumed to activate a cascade of temporal elements (see general introduction). This view would predict an interaction between validity and ISI with a greater validity effect occurring at the training ISI. This interaction is predicted on the basis that there is a summation of two expectations – one generated by the physical cue and the other by the specific cascaded temporal element that coincided with the target during training trials. The summation of these two expectations would result in the greatest validity effect at the training ISI, because the target expectation at that interval should be the greatest.
Figure 3: Predictions of two approaches to target encoding. In the separable account (panel A), and for the integrated account (panel B).

Experiment 1A used a choice RT task to study these predictions, and Experiment 1b used a Go/No-Go task. The two versions of this task were conducted with the purpose of exploring whether the response method has an effect on the resulting validity effect. The main difference between these 2 versions was how subjects are asked to respond to the target events. In the forced choice task, subjects responded with distinct button presses for each target and in the Go/No-Go version; a single button press was the response to both presented targets. The rationale for exploring this is to determine if the anticipated increase in RT on invalid test trials is caused by subjects’ incorrectly anticipating the specific target event, or by subjects’ preparing to make an incorrect motor response.

**Method: Experiment 1A**

**Participants:**

Eighteen (18) Brooklyn College undergraduate students (2 male, 16 females) aged 19 to 32 were recruited from introductory psychology and advanced psychology
classes. All students received course credit for their participation and had normal or corrected vision.

**Stimuli & materials:**

A computer-based task was designed using E-prime software (Psychology Software Tools) and was conducted on a Dell PC computer. Participants responded by pressing buttons on a multi-button response pad (Cedrus, model RB-730) using the index and middle fingers of their dominant hand (all but one participant was right handed). Figure 4 shows the various stimuli used as cues and targets in the experiment. The target stimuli were rectangular images (35 mm x 20 mm) of different colors (red – r225, g0, b0; blue – r0, g0, b225; & green – r0, g225, b0) created in Microsoft Paint and each was individually presented at the center of the screen until the participant’s response. After the participant responded to the target stimulus, feedback was presented centrally on the computer screen for 1500 ms. When the participant responded correctly, the word “Correct” was presented, and simultaneously below the word, their reaction time on that trial was presented (in ms). When the participant’s response was incorrect, just the word “Incorrect” was presented without any accompanying reaction time information. The stimuli designated as cues were images of an hourglass shape (63.5 mm x 45 mm) and a star (76.2 mm x 76.2 mm), and each was presented centrally on the screen for 300 ms. A black fixation cross (35 mm x 35 mm) was presented on the center of an otherwise white screen for 1500 ms during the intertrial interval (ITI). All participants performed the experiment individually seated at a viewing distance of approximately 45 cm from the screen.
**Procedure:**

Upon entering the laboratory participants were seated at a computer station and were presented with an on-screen consent form. All procedures used throughout this dissertation were in compliance with the City University of New York’s Institutional Review Board procedures. Upon giving consent to participate in the experiment, the task instructions were presented on the computer screen for the subjects to read (see appendix A). The experimenter reviewed the instructions with the participant and answered any questions before proceeding. The task involved the presentation of different cue-target pairs and subjects were asked to respond as quickly and accurately as they could with one of two button press responses when the appropriate target stimulus appeared. In addition, they were asked to attempt to learn about the relationships between the different cues and target stimuli that would appear on the screen. The specific button press requirement for each target stimulus was counterbalanced across subjects. Two cues (A and B) were each paired with different target stimuli (T1 and T2) and this formed A-T1 and B-T2 pairs. The specific identities

![Experimental Stimuli: Cues:

- Star
- Cross Targets:

- Red
- Blue
- Green](Figure 4: EXPERIMENT 1a STIMULI (not to scale))
of these cue-targets pairs were also counterbalanced across subjects. Additional “No-Go” trials were included on 20% of the trials in which both cues A and B were paired with a third target stimulus to which subjects were asked not to respond (A-T3, B-T3). The purpose of these trials was to discourage indiscriminant button pressing and to encourage participants to focus on the specific cue-target pairings. In addition, these trials were included because a companion study (Experiment 1B) also included these trials types in a Go/No-Go version of the task (to be described below).

The events that took place on a given training trial were as follows: the intertrial interval was 1500 ms during which time the fixation cross was presented on the screen. This was followed by the presentation of a cue for 300 ms, and then after a 500 ms gap (or trace interval), during which time there were no stimuli present (just a blank white screen), the target stimulus was presented until the subject responded. In the case of a “No-Go” target, the target stimulus was presented on the screen for 1000 ms and then disappeared before the next inter-trial interval began. The cue-target interstimulus interval (ISI) was, thus, 800 ms on all trials. Following each response to a target stimulus, feedback was presented for 1500 ms in the form of the subject’s reaction time and the accuracy of the response (as noted above). If the subject responded during the presentation of the cue or during the trace interval an error message was presented on the screen for 1000 ms - “Do not respond to this stimulus”. If the subject responded to the “No-Go” target, an error message was presented on the screen for 1500 ms – “Incorrect. Do not respond to this stimulus.”

The experimental design is depicted in figure 2. The experiment consisted of a set of training trials followed by a set of test trials, and this training-test sequence was
then repeated. Each training phase included 120 conditioning trials in which there were 48 A-T1 and 48 B-T2 trials, as well as 12 A-T3 and 12 B-T3 “No-Go” trials. These training trials were presented in 12 blocks of 10 trials (4 A-T1, 4 B-T2, 1 A-T3, 1 B-T3). Within each block the order of trials was randomized. Following this initial training phase, a test phase was presented and consisted of 60 test trials that were randomly presented (30 with A and 30 with B). During this test phase, the two cues were paired with all three target stimuli. On “valid” test trials the cues were paired with the targets with which they had been trained during the learning phase (A-T1, B-T2). On “invalid” trials the cue-target relations were switched (A-T2, B-T1). In addition, occasionally both cues were paired with the “No-Go” target as in the training phase. Valid, invalid, and No-Go trials occurred, respectively, on 24, 24, and 12 of the total number of test trials. The trial organization during this phase was such that each cue was followed equally often by its valid and invalid targets. Thus, any difference in RT on these trial types reflects an effect of the learning phase on test performance. In other words, if participants learned the task, this learning should be revealed by faster RTs to the valid than invalid targets.

Additionally, the ISI was manipulated during the test block. The training ISI was 800 ms on all trials, but during the test phase equal numbers of trials with ISIs of 400, 800, and 1600 ms were randomly intermixed across the trials. Following the initial training and test phases, a “break” screen was presented with the words “Please take a moment for a break. When you are ready to continue, press the SPACE bar.” When the participant pressed the spacebar, the second training-test sequence began.
After subjects completed the task, they were given a questionnaire (Appendix B) designed to provide an independent assessment of whether learning about the cue-target contingencies had taken place during the various phases of the experiment. This questionnaire probed their general knowledge of the cue-target relations by asking subjects to indicate which target was most likely to follow each cue. In addition, subjects were asked to provide a more specific quantitative assessment of the likelihood of the different target events occurring after each cue. More specifically, subjects were asked to estimate the percentage of trials in which each cue was followed by each type of target stimulus, and they were asked to provide these estimates for both the training and test phases of the experiment.

**Statistical Analyses:**

Standard analysis of variance procedures were used to analyze the data for the experiments reported in this thesis. Rodger’s post-hoc methods and critical F tables (Rodger, 1974; 1975) were used to assess the significance of all tests because this method is among the most powerful methods available at detecting true effects (e.g., Rodger & Roberts, 2013). Use of this approach ensures that the expected rate of rejecting true null contrasts in error, $E\alpha$, does not exceed a value set by the experimenter. An $E\alpha = 0.05$ criterion was adopted throughout.

**RESULTS**

The RT and accuracy data from the acquisition phases of Experiment 1a are presented in figure 5 (panels A and B). The training phase proceeded uneventfully, and
there was no difference between the mean RT of the two target stimuli. Figure 5 (panel A) shows the acquisition data in 6-trial blocks collapsed across the two stimuli. The greatest effect on RT was seen in the initial training blocks, with the highest average RT of 625 seen in the first training block of the first training phase, after which a decrease in RT was seen and remained stable between an average of 400 – 450 ms for the remainder of the first training phase and throughout the second training phase. A two-way repeated measures ANOVA with Training Phase (first, second) and Blocks as factors found a significant main effect of Blocks, $F(7,119) = 4.543, \text{MSE} = 11042.57, p < 0.001$, and a Training Phase x Blocks interaction was found as well, $F(7,119) = 4.461, \text{MSE} = 7730.11, p < 0.001$.

Error data were also collected for the acquisition phases. There were several types of errors that could have occurred. For instance, subjects could have made button press responses to the cue, during the gap (time between cue offset and target onset), or they could have made an incorrect button press response to the target stimuli. In total, there were very few errors during the two acquisition phases. Overall, cue errors were found on 0.02% of trials, gap errors on 0.42% of trials, and incorrect target responses were found on 2.8% of trials. Additionally, of these errors, no differences were seen between the two target stimuli in training. The most errors occurred during the presence of the target (or target errors), and the proportion of target errors decreased over the first training phase and remained low thereafter (figure 5B). A two-way repeated measures ANOVA with Training Phase and Blocks as factors found a main effect of Blocks, $F(7,119) = 3.5, \text{MSE} = 0.002, p < 0.01$, and a marginal main effect of Training Phase, $F(1,17) = 4.391, \text{MSE} = 0.003, p = 0.051$. Additionally, a marginally
significant Training Phase x Blocks interaction was found $F(7,119) = 2.050$, MSE = 0.003, $p = 0.054$.

Panel A

Panel B

**Figure 5: Experiment 1A Acquisition Data.** Acquisition RT data in 6-trial blocks collapsed across the two stimuli for each training phase (panel A) and acquisition error data collapsed across the two stimuli for each training phase (panel B).

The test phase RT data for Experiment 1A are presented in figure 6a. The figure shows mean RT in the presence of valid and invalid target presentations at each of the three test ISIs. A preliminary analysis revealed that the data did not differ across test phases and so they have been collapsed across this factor. The data reveal that subjects responded faster to valid targets than invalid targets and that this result was similar across the three ISI times, although RTs were overall faster at the training ISI. A two-way repeated measures ANOVA with Validity (Valid, Invalid) and ISI (400, 800, 1600) as factors found a main effect of Validity, $F(1,17) = 6.187$, MSE = 5992.23, $p < 0.05$. However, no main effect was seen for ISI, or for the interaction between these factors. An additional analysis was performed by examining each subject’s median RT scores across the different test conditions (figure 6b). This tended to reduce the effects of aberrantly large or small RTs on individual trials that could have arisen from the fact that the task did not explicitly force subjects to respond quickly during training. A two-
way repeated measures ANOVA with Validity and ISI as factors performed on these data also resulted in a main effect of Validity, \( F(1, 17) = 20.477, \text{MSE} = 5740.88, p < 0.001 \), and no interaction. However, in this case the ISI main effect was also reliable, \( F(2, 34) = 2.869, \text{MSE} = 9972.79, p < 0.05 \).

Overall, there were very few errors during the test phases. Cue errors were found on 0.05% of trials, gap errors were found on 0.14% of trials, and target errors were found on 3.7% of trials. The target error data for the test phases combined are presented in figure 6c. The figure shows the mean target errors (as percentage of trials) on valid and invalid trials at each of the three ISI times. The data showed a consistent trend indicating that subjects responded more accurately to valid targets than invalid targets and that this result was similar across the three ISI times. A two-way repeated measures ANOVA with ISI and Validity as factors performed on this data, however, only found a marginal main effect of Validity, \( F(1,17) = 3.432, \text{MSE} = 0.006, p = 0.081 \). No main effect was seen for ISI, or for the interaction between these factors.
Figure 6: Experiment 1A Test Data. Mean RT data for valid and invalid trials at 400 ms, 800 ms, and 1600 ms ISIs (panel A), median RT data for valid and invalid trials at each of the three ISIs (panel B), and mean percent target error data for valid and invalid trials at the three ISIs (panel C).

Finally, the post-experimental questionnaire data are shown in figure 7. This questionnaire was administered after subjects had completed the task and it asked them to reflect on the experiment and estimate the percentage of trials in which each target stimulus followed each cue (where the total should equal 100) during the acquisition and test phases. Based on these data we see that subjects roughly estimated the valid and no go target presentations in both training and test, though in
In the training phase the subjects overestimated the invalid target presentations and in test they underestimated the invalid target presentations. A two-way repeated measures ANOVA with Phase (training/test), and Target type (valid/invalid/no go) as factors was run on these data and resulted in a main effect of Target type, $F(2,32) = 12.196$, $MSE = 489.58$, $p< 0.001$, indicating that subjects estimates for valid cue-target pairings were higher in both training and test phases than for the other types of cue-target pairings.

![Figure 7: Experiment 1A Post-Experiment Questions](image)

**Figure 7: Experiment 1A Post-Experiment Questions.** Mean percent estimates of the three target types (valid/invalid/NoGo) in training and test phases.

**Method Experiment 1B**

**Participants:**

Thirty (30) Brooklyn College undergraduate students (6 male; 24 female) aged 19 to 40 were recruited from introductory psychology and advanced psychology classes. All students received course credit for their participation, and had normal or corrected vision.
Stimuli & materials:

Identical stimuli and materials were used for Experiment 1b as were used in Experiment 1a. The only difference was that instead of two button press response options on the response pad as in Experiment 1a, subjects in Experiment 1b only responded with a single button press.

Procedure:

Experiment 1b used a Go/No-Go design and, except for how the subject responded to the cue-target pairs, was very similar to Experiment 1a. This difference in the response requirement is reflected in the experimental task instructions (see Appendix A). Like in Experiment 1a, a speed and accuracy stress was presented in the instructions. However, a second speed stress was presented in training in the form of a feedback message - “Too Slow!” – if the subject had not responded within 1000 ms from target onset. Note that in this task, the No Go trials are especially important because, otherwise, subjects would need to respond on every trial.

<table>
<thead>
<tr>
<th>Go/No Go Task:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training:</td>
</tr>
<tr>
<td>A → T1 → R1</td>
</tr>
<tr>
<td>B → T2 → R1</td>
</tr>
<tr>
<td>500 ms</td>
</tr>
<tr>
<td>300 ms</td>
</tr>
<tr>
<td>Test:</td>
</tr>
<tr>
<td>A → T1 → R1</td>
</tr>
<tr>
<td>B → T2 → R1</td>
</tr>
<tr>
<td>A → T2 → R1</td>
</tr>
<tr>
<td>B → T1 → R1</td>
</tr>
<tr>
<td>Valid trials:</td>
</tr>
<tr>
<td>Invalid trials:</td>
</tr>
<tr>
<td>ISI = 800 ms</td>
</tr>
<tr>
<td>ISI = 400 ms, 800 ms, 1600 ms</td>
</tr>
<tr>
<td>No-Go Trials:</td>
</tr>
<tr>
<td>A → T3; B → T3</td>
</tr>
</tbody>
</table>

FIGURE 8: EXPERIMENT 1B DESIGN
The experimental design is depicted in figure 8. Experiment 1b consisted of 60 training trials presented in 6 blocks of 10 trials (4 A-T1, 4 B-T2, 1 A-T3, 1 B-T3). Within each block the order of trials was randomized. Following this initial training phase, a test phase was presented and consisted of 120 trials, 2 blocks of 60 trials that were randomly presented within each block. In Experiment 1b there was only one training-test sequence. Additionally, as in Experiment 1a, the target remained on the screen until the subject responded during the test phase since we anticipated that RTs might be especially long on invalid test trials. Other than this and the total number of trials there were no other differences between Experiments 1B and 1A. After subjects completed the task, they were given a questionnaire, the same one as in Experiment 1a (see Appendix B), designed to assess their awareness of the cue-target contingencies during the training and test phases of the experiment.

RESULTS

The RT data from the acquisition phase of Experiment 1B are presented in figure 9. The training phase proceeded uneventfully, and there was no difference between the mean RT of the two target stimuli. Figure 9 shows the acquisition data in 4-trial blocks collapsed across the two stimuli. The greatest effect on RT was seen in the initial training trials, with the highest average RT of 382.85 ms seen in the first training block, after which a decrease in RT was seen and remained stable with an average of 328.14 ms for the remainder of the training phase. A repeated measures ANOVA examining learning across the acquisition phase found an effect of Block (4-trials each), $F(5,145) = 8.602, \text{MSE} = 1876.62, p < 0.001$. 
Error data were also collected for the acquisition phase. As in Experiment 1a, there were several types of errors that could have occurred. Subjects could have made cue errors, gap errors, or, although they were asked to use a single response button, participants could have pressed some other response button on the response box in response to the target stimuli. In total, there were very few errors during the acquisition phase. Overall, there were no cue errors, gap errors were found on only 0.49% of trials, and incorrect target responses were found on 1.04% of trials.

The test phase RT data for Experiment 1b are presented in figure 10. The figure shows mean RT in the presence of valid and invalid target presentations at each of the three test ISIs. The data reveal that subjects responded faster to valid targets than invalid targets and that this result was similar across the three ISI times. A two-way repeated measures ANOVA with Validity (Valid, Invalid) and ISI (400, 800, 1600) as factors found significant main effects of Validity $F(1, 29) = 5.242$, $MSE = 690.68$, $p < 0.05$, and of ISI $F(2, 58) = 2.518$, $MSE = 1326.6$, $p < 0.05$, but no interaction between these factors was found.
Overall, there were very few errors during the test phase. Cue errors were found on 0.14% of trials, gap errors were found on 0.24% of trials, and there were no reliable differences on valid or invalid test trials at any of the test ISIs. No target errors were found.

Finally, the post-experimental questionnaire data are shown in figure 11. This questionnaire was administered after subjects had completed the task and it asked them to estimate the percentage of trials in which each target stimulus followed each cue (where the total should equal 100) during the acquisition and test phases. Based on these data we see that subjects estimated the valid target to occur more frequently than both the invalid and no go targets in both training and test, however in the test phase the invalid target was estimated to occur more frequently than the no go target though still less frequently than the valid target. A two-way repeated measures ANOVA with Phase (training/test), and Target type (valid/invalid/no go) as factors was run on these data and resulted in a main effect of Target type, $F(2, 58) = 21.291$, $MSE = 498.99$, $p < 0.001$, and a Phase x Target type interaction, $F(2, 58) = 12.690$, $MSE =$
187.53, p < 0.001. Further post-hoc tests were run to examine the basis of this interaction and found that in training the mean percent estimate of the valid condition differed from the invalid and no go conditions which did not differ from each other. In the test phase, the post-hoc tests indicated that subjects’ estimates for the valid target differed from the invalid target and that this later condition differed from the no go target.

![Post-Experiment Questions](image)

**Figure 11: Experiment 1B Post-Experiment Questions.** Mean percent estimates of the three target types (valid/invalid/NoGo) in training and test phases.

**Discussion of Experiment 1**

The results of Experiment 1 suggest that participants' learned the 'valid' cue-target associations as indicated by slower RT on 'invalid' trials. This finding was obtained when both choice RT and Go/No-Go tasks were employed. Furthermore, the magnitude of this validity effect was unchanged across different test ISIs that were shorter than or longer than the training ISI. These outcomes indicate that anticipating the sensory and temporal features of the target event each had independent effects on subject’s reaction time, and supports the idea that these features are encoded separately and not in an integrated fashion.
One of the purposes of this initial study was to employ a design that is more similar to Pavlovian conditioning procedures with the use of distinct cues to signal different target events. This Pavlovian design would be better able than the Thomaschke et al. (2011) design to assess the question of how multiple features of the target is encoded in a predictive learning task. The use of distinct cues to predict target events allowed for subjects to predict target events based on the cue presented. With this design, it becomes possible to determine whether the identities of distinct target events are encoded in terms of their times of occurrence or whether these two target aspects might be encoded separately. Based on the results of Experiment 1, it seems reasonable to say that the experimental design is useful in addressing this issue.

The critical distinction between Experiment 1A and 1B, was that a single button press response was used in the presence of both presented targets in Experiment 1B (as opposed to two button presses used in Experiment 1A). The rationale for exploring this distinction was to determine if the choice RT results in Experiment 1a were based on subjects developing a specific sensory expectation of the target event in the presence of each cue, or, alternatively, whether the cue merely readied the subjects for which response to make. The validity effect found in Experiment 1a (i.e. faster RTs to valid than invalid targets) could have resulted from a cue priming the target representation prior to its occurrence, and this would lead to faster responding on valid than invalid trials. However, if the cue merely primed the motor response required by the target stimuli, then this would also lead to faster RTs on valid than invalid trials. In Experiment 1B, however, the same response was required to both target stimuli. If the validity effect in Experiment 1A was caused by a cue-induced readiness to respond on
one of the two buttons, then the validity effect should have disappeared when using the go/no-go task in Experiment 1B since in that study both targets were responded to in exactly the same way. However, the validity effect was also found in Experiment 1B and this suggests that it at least partly reflects the cue’s ability to activate a rather specific sensory representation of the target just prior to its actual occurrence. The effect appears numerically smaller in Experiment 1B than in 1A, so we cannot completely rule out the possibility that motor preparation effects may also contribute to the basic validity effect we have observed in Experiment 1A. Nonetheless, the basic conclusion that our paradigm reflects control by sensory-based expectations seems a secure one.

At the center of this investigation into cue-target encoding was to determine if target sensory and temporal features are encoded separately or in an integrated fashion. If sensory and temporal target attributes are encoded as an integrated representation, then we expected to find the largest validity effect at the training ISI (Figure 3, Panel B; and see Thomaschke et al, 2011). However, this outcome was not observed. In contrast, if sensory and temporal attributes are encoded in a separable way, then the validity effect would not be expected to vary across test ISIs and responding should be faster, overall, at the training ISI (Figure 3, Panel A). This is more in line with our findings. According to the view of the abstract temporal coding idea, the separable account would predict two parallel lines for valid and invalid target associations across the three ISIs, as opposed to an interaction which the cascading temporal coding idea would predict (see earlier discussion). Our results support the abstract temporal coding idea.
It is noteworthy that the experimental design of Experiment 1 involved training with distinct cue-target relations at a single ISI. In the Thomaschke et al. (2011) study, on the other hand, different target stimuli could appear at different times from trial onset. Learning in the present circumstance involves discriminating between different cue-target pairs in terms of their sensory and motor aspects, but not in terms of their temporal relations. As a result, cue-target learning may be dominated by the target’s sensory over its temporal features. If so, then training different cue-target pairs with multiple ISIs may affect how the outcome is encoded, and, in particular, may especially emphasize learning about the temporal features of the target stimuli. The next two experiments explored this issue.

**Experiment 2**

This second study follows up on the ideas explored in the initial study - that human subjects learn to associate neutral cues with both the sensory and temporal features of a target event. Experiment 1 explored target encoding by training with distinct cue-target relations at a single ISI, and found support for the separable encoding account. With that experimental design subjects appeared to learn distinct associations between the cues and the sensory and temporal features of the presented target stimuli. However, training with a single ISI may have affected encoding by highlighting the distinction in the target’s sensory features over its temporal features. Experiment 2 addressed this issue by using an experimental design in which different cues were trained as discrete signals for a unique target event and also a unique ISI (see figure 12).
As in Experiment 1, two target stimuli were used. However, in Experiment 2, two cues were trained with different target stimuli after a short ISI (800 ms; “short cue”), and two other cues were trained with the different targets after a long ISI (1600 ms; “long cue”). This addition to the experimental design, allows subjects to learn that 2 cues predict a target after a short ISI and two after a long ISI. Perhaps under these circumstances, the temporal features of the targets will become more salient. If so, then on test trials with valid and invalid cue-target arrangements, we might expect the size of the validity effect to be greatest at the training ISI. On the other hand, if the results from Experiment 1 would apply to this training situation we would not expect the validity effect to be diminished when the cue-target relations are tested at a non-training ISI.

### Multiple ISIs

<table>
<thead>
<tr>
<th>Training</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A → T1 - R1</td>
<td>Valid: A → T1; B → T2; A ----→ T1; B ----→ T2;</td>
</tr>
<tr>
<td>B → T2 - R2</td>
<td>C ----→ T1; D ----→ T2; C → T1; D → T2</td>
</tr>
<tr>
<td>C ----→ T1 - R1</td>
<td>Invalid: A → T2; B → T1; A ----→ T2; B ----→ T1;</td>
</tr>
<tr>
<td>D ----→ T2 - R2</td>
<td>C ----→ T2; D ----→ T1; C → T2; D → T1</td>
</tr>
</tbody>
</table>

**FIGURE 12: EXPERIMENT 2 DESIGN**
Method

Participants:

Twenty-four (24) Brooklyn College undergraduate students (5 male, 19 female) aged 17 to 46 were recruited from introductory psychology and advanced psychology classes. All students received course credit for their participation, and had normal or corrected vision.

Stimuli & materials

The same stimuli as used in Experiment 1 were used in Experiment 2, except for the addition of two cues – a circle geometric shape (38.1 mm in diameter) and a diamond shape (60 mm x 43 mm). These cues can be seen in figure 13. In Experiment 2, only two of the three target stimuli used in Experiment 1 (the red and blue rectangular images) were paired with the cue stimuli. The third No-Go target was not used in this experiment or throughout the rest of this dissertation. Like Experiment 1a, a choice RT task was employed in which participants were to respond by pressing different buttons on the response pad in response to the two target stimuli. As in Experiment 1b, the feedback message appeared during training - “Too Slow!” – if the subject had not responded within 1000 ms since the target presentation, while in test the target was presented until the subject responded without this feedback.
The general procedures used in Experiment 2 were very similar to those used in the choice RT task of Experiment 1a, except as noted below. The experimental design can be seen in Figure 12. In the present experiment four cues (distinct geometric shapes) were initially trained to predict two different target stimuli (T1 and T2). Additionally, two ISIs were used in the training phase. Two cue-target pairs (A-T1, B-T2) were trained with a short ISI (800 ms; “short cues”) and two (C---T1, D---T2) with a long ISI (1600 ms; “long cues”). However, the duration of all cues was the same (300 ms). Thus, the duration of the trace interval (i.e., the time from cue offset to target onset) was different for the different trial types (either 500 or 1300 ms). During the test phase, valid and invalid cue-target combinations were tested at the two ISIs used in the training phase in order to assess whether the validity effect would vary across ISI.

In the present study, the training phase included 120 conditioning trials in which there were 30 of each of the cue-target pairings presented, A-T1, B-T2, C---T1, and D---T2. These training trials were presented in 10 blocks of 12 trials (3 A-T1, 3 B-T2, 3 C---T1, & 3 D---T2). Within each block the order of trials was randomized. In addition, as in
Experiment 1b, the target stimuli were presented during training until the subject responded or until 1000 ms elapsed at which point a “Too Slow” message appeared.

The test phase consisted of 128 test trials that were presented in four blocks of 32 trials (with random trial order within a block). In every block of test trials each of the four cues was paired twice with both of the target stimuli at each of the two ISIs used during training. In all, there were 64 valid and 64 invalid test trials and half of each occurred with the same ISI as in training and half at the alternate ISI.

After subjects completed the task, they were given a questionnaire (Appendix B) designed to assess their awareness of the cue-target contingencies during the various phases of the experiment as in the previous experiment.

RESULTS

The RT and accuracy data from the acquisition phases of Experiment 2 are presented in figure 14 (panels A and B). The training phase proceeded uneventfully, and there was no difference between the mean RT of the two target stimuli as a function of their physical identity. Figure 14 (panel A) shows the acquisition data in 6 trial blocks collapsed across the two trial types with ‘short’ ISIs and the two with ‘long’ ISIs. Generally, RTs got faster over the course of training, but RTs were consistently faster on trials with long than with short ISIs. A two-way repeated measures ANOVA with Training ISI (short, long) and Blocks as factors found a significant main effect of ISI, $F(1,23) = 52.468$, MSE = 1453.45, $p < 0.001$, and a main effect of Blocks, $F(4,92) = 8.936$, MSE = 3849.41, $p < 0.001$. However, no interaction was found between these factors.
Error data were also collected for the acquisition phase. Overall, cue errors were found on only 0.14% of trials, gap errors on 1.5% of trials, and incorrect target responses on 3.2% of trials. Over training the percentage of target errors decreased but somewhat more errors were made on long ISI trials (figure 14B). A two-way repeated measures ANOVA with Training ISI and Blocks as factors found a main effect of ISI, $F(1,23) = 4.378$, $MSE = 0.005$, $p < 0.05$, and a main effect of Blocks, $F(4,92) = 5.442$, $MSE = 0.005$, $p = 0.001$, but no interaction.

Panel A

**Acquisition Reaction Time Data**

![Graph showing mean RT (ms) for short and long ISIs across blocks.]

Panel B

**Acquisition Accuracy Data**

![Graph showing mean % target errors for short and long ISIs across blocks.]

**Figure 14: Experiment 2 Acquisition Data.** Mean RT data in 6-trial blocks for short and long ISI trials (panel A) and mean percent target error data for short and long ISI trials (panel B).

The test phase RT data for Experiment 2 are presented in figure 15. The figure shows mean RT in the presence of valid and invalid target presentations at each of the test ISIs. The data at each test ISI are shown separately for cues trained with a short or long ISI (Panel A). Generally, subjects responded faster to valid targets than invalid targets and they responded faster at the long test ISI, but these effects were comparable between cues trained with short and long ISIs. A three-way repeated measures ANOVA with Training ISI (800, 1600), Test ISI (800, 1600), and Validity
(Valid, Invalid) as factors found a main effect of Test ISI $F(1,23) = 37.772$, MSE = 1255.68, $p < 0.001$, and a main effect of Validity, $F(1,23) = 5.791$, MSE = 1307.5, $p < 0.05$. However, no main effect was seen for Training ISI, or for any of the interactions between these factors.

Overall, there were very few errors during the test phase. Cue errors were found on 0.0% of trials, gap errors on 0.13% of trials, and target errors on 2.5% of trials. The target error data for the separate test trial types are presented in figure 15b. The figure shows the mean percentage target errors on valid and invalid trials at each test ISI, and is further subdivided by training ISI. The data showed a consistent trend indicating that subjects responded more accurately to valid targets than invalid targets, however, the reverse appears true when trained at 800 ms and tested at 1600 ms. A three-way repeated measures ANOVA with Trained ISI (800, 1600), Test ISI (800, 1600), and Validity (Valid, Invalid) as factors, however, detected no significant effects or interactions.

Panel A

![Test Phase Data](image1)

Panel B

![Test Accuracy Data](image2)

**Figure 15: Experiment 2 Test Data.** Mean RT data for valid and invalid trials at 800 ms and 1600 ms test ISIs for each training ISI (panel A), and mean target error data for valid and invalid trials at 800 ms and 1600 ms test ISIs for each training ISI (panel B).
Finally, the post-experimental questionnaire data are shown in figure 16. Subjects’ estimates of the valid and invalid cue-target contingencies in both training and test phases were fairly accurate. A three-way repeated measures ANOVA with Phase (training/test), Cue (short/long), and Validity (valid/invalid) revealed a main effect of Validity, $F(1,23) = 54.158, \text{MSE} = 2875.71, p < 0.001$, and a Validity x Phase interaction, $F(1,23) = 28.086, \text{MSE} = 4047.03, p < 0.001$, indicating that subjects estimates for the valid and invalid cue-target contingencies fairly closely matched the actual contingencies in both the training and test phases.

![Figure 16: Experiment 2 Post-Experiment Questions](image)

**Figure 16: Experiment 2 Post-Experiment Questions.** Mean percent estimates of valid and invalid trials for the short and long cues in training and test phases.

**Discussion of Experiment 2**

The results from the training phase of Experiment 2 found that subjects responded more quickly to the targets after a long ISI than a short ISI. However, subjects also made more errors in responding to targets after a long ISI than a short ISI. These results reveal that performance during training was governed by a speed-
accuracy tradeoff (Heitz, 2014; Standage, Wang, Heitz, & Simen, 2015), and suggest that subjects may have adopted different response criteria in the two cases.

The primary data came from the test phase, and, as in Experiment 1, subjects responded faster to validly cued than invalidly cued targets. But, importantly, the magnitude of this effect at each ISI was no different for cue-target relations trained at one or the other ISI. These findings are consistent with Experiment 1, and support the notion that the cues form separate associations with both the sensory and temporal features of the target event.

It may be argued that with the design of Experiment 2, the identity of the target stimuli was not linked to any particular ISI since each target stimulus could follow a cue after both a short and long ISI. This may have interfered with the formation of an integrated time-event representation of the target stimulus. It is possible that if the different targets are trained with their own unique ISI this may encourage the development of a more integrated time-event representation of the target. Experiment 3 investigated this possibility.

**Experiment 3**

Experiments 1 and 2 found evidence consistent with the view that cues associate with separate encodings of the sensory and temporal attributes of a target event in different predictive learning tasks. This next study continues to explore whether more integrated sensory and temporal target processing might occur under other training circumstances. The design employed in Experiment 2 paired four cues with two different target events after different ISIs. It is plausible that in this situation poor learning about the target’s temporal aspects would occur because each target could
appear after each ISI. In Experiment 3 (see figure 17), four distinct cue-target pairs were trained in a four-alternative forced choice task, but two of these unique pairs were trained at a short ISI and two at a long ISI. This permits for each cue to signal a unique target event at a specific temporal interval, and may better encourage integrated processing of the sensory and temporal target attributes.

As in Experiment 2, here this idea was assessed by testing both valid and invalid cue-target relations at both the training ISI and the other, non-training, ISI. If training in this manner supports integrated time-event target encoding, then the validity effect should be stronger at the training ISI.

<table>
<thead>
<tr>
<th>Multiple Cue-Target Pairings at Multiple ISIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training</td>
</tr>
<tr>
<td>A → T1 - R1</td>
</tr>
<tr>
<td>B → T2 - R2</td>
</tr>
<tr>
<td>C ----&gt; T3 - R3</td>
</tr>
<tr>
<td>D ----&gt; T4 - R4</td>
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<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>ISI-s (→) = 800 ms; ISI-L (-----) = 1600</td>
</tr>
</tbody>
</table>

**FIGURE 17: EXPERIMENT 3 DESIGN**
Method

Participants:

Sixteen (16) Brooklyn College undergraduate students (4 male, 12 female) aged 18 to 48 were recruited from introductory psychology and advanced psychology classes. All students received course credit for their participation, and had normal or corrected vision.

Stimuli & materials

In Experiment 3, the same stimuli as in Experiment 2 were presented, except for the return of the green target stimulus (as used in Experiment 1a and Experiment 1b) and the addition of a fourth target, a yellow colored rectangular box (35 mm x 20 mm; r39, g245, b0). Additionally, in this experiment four different buttons were used in a 4-alternative forced choice procedure (see figure 18).

FIGURE 18: EXPERIMENT 3 STIMULI (not to scale)
Procedure:

The design of Experiment 3 can be seen in Figure 17. All of the general procedures were the same as in Experiment 2, except as noted below. The task used a 4-alternative forced choice procedure in which 4 distinct cue-target pairs were trained with each target stimulus being responded to with one of four button press options on the response pad. The specific button press requirement for each target stimulus was counterbalanced across subjects. Specifically, the physical identity of cues A and B (on “short” trials) were balanced with C and D cues (on “long” trials). Similar to Experiment 2, two cue-target pairs were trained with a short ISI (800 ms; “short cues”) and two with a long ISI (1600 ms; “long cues”), and during test trials valid and invalid cue-target test trials occurred at both ISIs.

The training phase included 160 conditioning trials in which there were 40 presentations of each of the cue-target combinations. Each cue was paired with a distinct target, where cues A and B predicted targets T1 and T2 after a short ISI (800 ms) and cues C and D predicted targets T3 and T4 after a long ISI (1600 ms). These training trials were presented in 10 blocks of 16 trials (4 of each cue-target pair per block). Following this training phase, a test phase was presented and consisted of 160 test trials (five 32-trial blocks). During this test phase, cues A and B were only paired with targets T1 and T2 and cues C and D only with targets T3 and T4 in test. On “valid” test trials the cues were paired with the targets with which they had been trained (A-T1, B-T2, C-T3, D-T4). On “invalid” trials the cue-target relations were switched (A-T2, B-T1, C-T4, D-T3). Thus, in test there were 80 valid trials and 80 invalid trials. Additionally, the ISI was manipulated during the test phase. For half of the test trials
each cue was presented with the ISI with which it was trained, and for the remaining trials the alternate ISI was tested.

After subjects completed the task, they were given a questionnaire (Appendix B), as in the other experiments, designed to assess their awareness of the cue-target contingencies during the various phases of the experiment.

RESULTS

The RT and accuracy data from the acquisition phase of Experiment 3 are presented in figure 19 (panels A and B). As was seen in the previous experiments, RTs generally decreased over training. Also, as was seen in Experiment 2, by the end of training RTs on long ISI trials were faster than on short ISI trials. A two-way repeated measures ANOVA with ISI (short, long) and Blocks (8-trials) as factors found a significant main effect of ISI, $F(1,16) = 6.538$, $MSE = 4321.12$, $p < 0.05$, a main effect of Block $F(4, 64) = 14.476$, $MSE = 10842.66$, $p < 0.001$, and an ISI x Block interaction, $F(4, 64) = 4.152$, $MSE = 1742.77$, $p < 0.01$ indicating that RTs were faster on Long ISI trials later in training.

Error data (cue, gap, target) were also collected for the acquisition phases. Overall, cue errors were found on 0.0% of trials, gap errors on 3% of trials, and incorrect target responses were found on 11.6% of trials. When exploring the gap errors further, subjects made more errors in the presence of the long ISI than the short ISI. A two-way repeated measures ANOVA with ISI and Blocks (8-trial) as factors revealed main effects of ISI, $F(1, 16) = 11.512$, $MSE = 0.004$, $p < 0.01$, and Blocks $F(4, 64) = 2.910$, $MSE = 0.002$, $p < 0.05$, as well as an interaction between these factors $F(4, 64) = 3.031$, $MSE = 0.002$, $p < 0.05$. Initially in training there were many target errors, but the percentage of
target errors steadily decreased to approximately 5% by the end of training (figure 19C). A two-way repeated measures ANOVA with ISI and Blocks (8-trial) as factors only found a main effect of Blocks, $F(4, 64) = 14.368$, $\text{MSE} = 0.012$, $p < 0.001$, and no interaction between these factors was found.

Panel A

Panel B

Panel C

**Figure 19: Experiment 3 Acquisition Data.** Mean RT data in 8-trial blocks for short and long ISI trials (panel A), mean gap error data for short and long ISI trials (panel B), and mean target error data for short and long ISI trials (panel C).

The test phase RT data for Experiment 3 are presented in figure 20a. The figure shows mean RT in the presence of valid and invalid target presentations at each test ISI and is further subdivided by the training ISI. The data were very similar to that seen in
Experiment 2. In particular, subjects responded faster to valid targets than invalid targets and they responded somewhat faster at long than short test ISIs, but this was true for cue-target pairings at both training ISIs. A three-way repeated measures ANOVA with Training ISI (Short, Long), Test ISI (Short, Long) and Validity (Valid, Invalid) as factors found main effects of Test ISI, $F(1,16) = 9.055$, $MSE = 4004.97$, $p < 0.01$, and Validity, $F(1,16) = 7.032$, $MSE = 5339.48$, $p < 0.05$. However, no main effect was seen for Training ISI, or for any interaction between these factors.

Overall, there were very few errors during the test phases. Cue errors were found on 0.0 % of trials, gap errors were found on 0.25% of trials, and target errors were found on 6.9% of trials. The target error data for the test phase are presented in figure 20b. Overall, it appears as though more errors were displayed on invalid than valid trials on test trials with a long ISI, however, a three-way repeated measures ANOVA with Test ISI, Training ISI, and Validity as factors revealed no significant differences.

![Panel A and Panel B](image)

**Figure 20: Experiment 3 Test Data.** Mean RT data for valid and invalid trials at 800 ms and 1600 ms test ISIs for each training ISI (panel A), and mean target error data for valid and invalid trials at 800 ms and 1600 ms test ISIs for each training ISI (panel B).
Finally, the post-experimental questionnaire data are shown in figure 21. This questionnaire was administered after subjects had completed the task and it asked them to reflect on the experiment and estimate the percentage of trials in which each target stimulus followed each cue (where the total should equal 100) during the acquisition and test phases. Additionally, subjects were asked to estimate which of the cue-target pairings were presented with a short ISI and which were presented with a long ISI (an analysis on the subjects' estimates for this question failed to find any differences). Subjects' estimates of the valid and invalid cue-target contingencies in both training and test phases were reasonably accurate. The invalid cue-target contingency was subdivided into 2 categories, ISI consistent or “same” and ISI inconsistent or “different” (see figure 21). Where for example in training, cue A was paired with T1 after a short ISI, in test, “valid” refers to a valid cue-target pairing at the training ISI (for example like A-T1 at a short ISI or C—T3 with a long ISI). “Invalid-Same ISI” refers to an invalid cue-target pairing like A-T2 when this pairing was presented at the same ISI as in training (in this case with a short ISI). “Invalid-Different ISI” refers to estimates a subject made of an invalid cue-target pairing like A-T3 or A-T4 at a different ISI (in this case with a long ISI). A three-way repeated measures ANOVA with Phase (training/test), Cue ISI (short/long), and Validity (valid / invalid-sameISI / invalid-differentISI) revealed a main effect of Validity, $F(2,30) = 45.619$, $MSE = 1163.91$, $p < 0.001$, and a Phase x Validity interaction, $F(2,30) = 9.110$, $MSE = 1017.77$, $p < 0.01$. This analysis was followed up with a one-way analysis of the data across the six validity conditions (collapsed across short and long cues), and this analysis revealed a significant main effect $F(5,75) = 28.332$, $MSE = 440.27$, $p < 0.001$. Post-hoc tests were
performed on this analysis, (training validity means: Valid = 74.77, Invalid-Same ISI = 9.45, Invalid-Different ISI = 7.89; test validity means: Valid = 51.33, Invalid-Same ISI = 34.14, Invalid-Different ISI = 7.30), and revealed that in training the mean percent estimate of the valid condition differed from the two invalid conditions which did not differ from each other. In the test phase, the post-hoc tests indicated that subjects’ estimates for the valid target differed from the invalid-same ISI target and that this later condition differed from the invalid-different ISI.

![Post-Experiment Questions](image)

**Figure 21: Experiment 3 Post-Experiment Questions.** Mean percent estimates of valid and invalid (same ISI and different ISI) trials for the short and long cues in training and test phases.

**Discussion of Experiment 3**

The results of Experiment 3, similarly to Experiment 2, found that subjects responded more quickly in training to targets after a long ISI than short ISI. However, an analysis of the error data for Experiment 3 revealed that subjects made significantly more errors in responding to the long ISI than the short ISI during the gap, but not in the presence of the target as found in Experiment 2. That the difference in error rate was
found during the gap, it seems likely that subjects were anticipating the target during the long ISI window (figure 19B).

Again as in the earlier experiments, the primary results of Experiment 3 found that the sensory and temporal features of the target event each had independent effects on subject's reaction time. These results indicate that the participants learned the 'valid' cue-target associations as indicated by slower RT on 'invalid' trials and further the magnitude of this effect was the same across the two ISIs. These findings are consistent with Experiment 1 and 2, and again support the separable encoding hypothesis, the notion that the cues form separable associations with the sensory and temporal features of the target event.

The design of Experiment 3, trained four distinct cue-target pairs – four different cues, two short and two long, were paired with four different targets. As such, the identity of the target was linked to a particular ISI and could be predicted by a particular cue. This should have especially encouraged integrated processing of the targets sensory and temporal features. Nevertheless, the results were very similar to those seen in the previous experiments. It is possible that an experimental design in which specific ISI-target combinations are trained will force an integrated time-event encoding strategy. Experiment 4 explored this possibility.

**Experiment 4**

The previous three experiments explored whether humans encode the specific sensory and temporal aspects of target stimuli in a separable or integrated manner in different predictive learning situations. Our findings have consistently supported the
view that predictive cues associate with separate encodings of a target event’s sensory and temporal features. The different experiments varied aspects of the training procedure that might have encouraged integrative time-event processing of the target stimuli. In Experiment 4, a conditional discrimination training procedure was used in which the only way for subjects to learn the task would be to develop integrative time-event representations of the target stimuli. Specifically, a two cue - two target forced choice procedure was used, but four distinct cue-target ISI relations were trained (see figure 22). For example, cue A was paired with T1 at a short ISI and T2 at a long ISI, and cue B was paired with T1 at a long ISI and T2 at a short ISI. It is possible, that this design, where the predictive value of the cue depends on learning the distinct cue-target ISI relation, will promote integrated time-event target encoding. This was assessed by switching the specific cue-target time relations during the test phase.

<table>
<thead>
<tr>
<th>Training</th>
<th>Procedure</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>A → T1 - R1</td>
<td>Same: A → T1; B ----→ T1;</td>
<td>A ----→ T2; B → T2</td>
</tr>
<tr>
<td>B ----→ T1 - R1</td>
<td>Opposite: A → T2; B ----→ T2;</td>
<td>A ----→ T1; B → T1</td>
</tr>
<tr>
<td>A ----→ T2 - R2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B → T2 - R2</td>
<td>ISI-s (→) = 800 ms; ISI-L (----→) = 1600</td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 22: EXPERIMENT 4 DESIGN
Method

Participants:

Thirty-one (31) Brooklyn College undergraduate students (9 male; 22 female) aged 18 to 37 were recruited from introductory psychology and advanced psychology classes. All students received course credit for their participation, and had normal or corrected vision.

Stimuli & materials:

In Experiment 4, the stimuli used were the same as those used in Experiment 1, two cues (star and an hourglass geometric shapes) and two targets (red and blue colored rectangular boxes).

Procedure:

The present study used a 2-alternative forced choice RT conditional discrimination task (see Figure 22). The same general choice RT procedures were used as in Experiment 2, unless noted below. Two cues were initially trained to predict two different target stimuli at two different ISIs. Specifically, cue A predicted T1 at 800 ms and T2 at 1600 ms, whereas cue B predicted T1 at 1600 ms and T2 at 800 ms. In this design, unlike in the previous experiments, a single cue was trained with both ISIs and both targets. However, each cue could be used to predict at which time a specific target stimulus would occur. This learning was then assessed by comparing target RTs on trials in which the same cue-target-ISI combinations occurred as in training or in which the opposite combinations occurred.

The training phase included 200 conditioning trials in which there were 50 of each of the aforementioned cue-target pairings presented. These training trials were
presented in 25 blocks of 8 trials (2 of each trial type per block). Within each block the order of trials was randomized. Following this training phase, a test phase was presented and consisted of 64 test trials that were presented in four blocks of 16 trials and within each block the trials were randomly presented. On “same” test trials the cues were paired with the targets and ISIs with which they had been trained during the learning phase (e.g. A-T1 after a short ISI and B---T1 after a long ISI). On “opposite” trials the cue-target identity and ISI pairings were switched (e.g. A---T1 after a long ISI and B-T1 after a short ISI). In test there were 32 same trials and 32 opposite trials. Thus, any difference in RT on these trial types will reflect an effect of the learning phase on test performance. In other words, if participants learned the task, this learning should be revealed by faster RTs on same than opposite test trials.

After subjects completed the task, they were given a questionnaire (Appendix B) designed to assess their awareness of the cue-target contingencies during the various phases of the experiment. As before, subjects were asked about the cue-target identity relationships; however, in Experiment 4, subjects were also asked about the cue-target temporal relationships by indicating the likelihood of different target events occurring after a short or long period since the cue onset in both the training and test phases of the experiment.

RESULTS

Figure 23 (panel A) shows the RT data for short and long ISI trials (collapsed across the two stimuli) across 10-trial blocks during the training phase. RTs were faster on long ISI than on short ISI trials. A two-way repeated measures ANOVA with ISI
(short, long) and Blocks as factors found a significant main effect of ISI, F(1,30) = 25.642, MSE = 3975.16, p < 0.001, as well as a significant ISI x Block interaction, F(4,120) = 2.864, MSE = 646.04, p < 0.05, indicating that this difference increased over training.

Error data were also collected for the acquisition phase. Overall, cue errors were found on only 0.02% of trials, gap errors on 0.34% of trials, and incorrect target responses were found on 2.4% of trials. Additionally, of these errors, no differences were seen between the two target stimuli in training. Overall errors were low and inconsistent and there were no significant effects of ISI or Block (figure 23B).

Panel A
Panel B

Figure 23: Experiment 4 Acquisition Data. Mean RT data in 10-trial blocks for short and long ISI trials (panel A) and mean percent target error data for short and long ISI trials (panel B).

The test phase RT and accuracy data for Experiment 4 are presented in figure 24 (Panels A and B). Panel A shows mean RT in the presence of valid and invalid target presentations at each of the two test ISIs. The data reveal no difference in subjects’ responses to valid (same) and invalid (opposite) targets, although RTs were overall faster on test trials with a long ISI. A two-way repeated measures ANOVA with Validity
(Valid, Invalid) and ISI (800, 1600) as factors found a main effect of Test ISI, \( F(1,30) = 23.813, \text{MSE} = 1139.21, p < 0.001 \). However, no main effect was seen for Validity, or for the interaction between these factors.

Overall, there were very few errors during the test phase. Cue errors were found on 0.0% of trials, gap errors were found on 0.5% of trials, and target errors were found on 2.5% of trials. The target error data for the test phases combined are presented in figure 24 (Panel B). The figure shows the mean target errors (as percentage of trials) on valid and invalid trials at each of the short and long test ISIs. Overall errors were low and inconsistent and there were no significant effects of Validity or ISI, and the interaction was also not significant.

**Figure 24: Experiment 4 Test Data.** Mean RT data for valid and invalid trials at 800 ms and 1600 ms test ISIs (panel A), and mean target error data for valid and invalid trials at 800 ms and 1600 ms test ISIs (panel B).

Post-experimental questionnaire data for this conditional discrimination task were administered after subjects had completed the task and it asked them to estimate the percentage of trials in which each target stimulus followed each cue (where the total
should equal 100) during the acquisition and test phases. The result indicated that subjects estimated each target roughly 50% of the time in the presence of each cue, and there was no difference between targets, ISIs, or the experimental phase (training/test). Subjects were also asked to identify the targets appearing after a short or long ISI in the presence of the cues. Each cue-target combination was presented and subjects were asked to indicate which of the cue-target combinations occurred with a short versus long ISI. Overall, the accuracy for identifying a target occurring after a short ISI was 53.03% and after a long ISI was 43.94%. This difference was only marginally significant $F(1,32) = 3.918$, $MSE = 0.070$, $p = 0.056$.

**Discussion of Experiment 4**

Analysis of the acquisition data in Experiment 4 once again found that subjects responded more quickly to targets after a long ISI than short ISI. However, unlike the previous 2 experiments the error data revealed no differences in the accuracy rate between the 2 ISIs. As the error rates between the two ISIs did not differ, the faster reaction time to the longer ISI in training may be reflective of an increased readiness to respond to the target at the longer ISI. These training results may appear encouraging for an integrated account explanation, as subjects seemed to learn the distinctive cue-target pairing at the particular ISI, however this was not the case. The test results found that subjects had not learned the cue-target pairings, as evidenced by no difference in responding to the valid and invalid targets. Subjects simply responded faster in the presence of the long ISI regardless of the target presented, perhaps due to a greater overall preparation time with a longer ISI.
The design of Experiment 4, trained four distinct cue-target pairs – each a distinct combination of two cues, two targets, and two ISIs (see figure 22). As such, the identity of the target could be predicted by the particular cue-ISI combination. In this way we thought we would encourage, or even force, integrated time-event encoding. However, this outcome was not found.

In the previous three experiments, the separable encoding account was inferred from the fact that the sensory and temporal features of the target event had independent effects on RT. Evidence of this result was reflected in slower RT on invalid than valid trials coupled with the magnitude of this effect being unchanged when testing occurred with a different ISI than used in training. For Experiment 4, however, the separable account would have predicted no learning at all. This follows from the fact that each cue was paired with each target stimulus, and each cue was paired with target stimuli occurring at each of two ISIs. Thus, if separate associations had formed between the cues and different time-independent representations of the two targets and subjects had also learned that targets generally could occur at either of two ISIs, there would be no basis for expecting a specific target stimulus at a particular ISI following either cue. While the results of Experiment 4 can be taken to support the separable encoding account of target processing, it should be stressed that this is a null result and there could be other reasons why learning failed to occur. One obvious potential problem is that there was too little training given for subjects to acquire the task. Furthermore, if the problem was too difficult, then subjects may have learned to pay little attention to the cues and focused more on the reaction time aspect of the task. This
could have prevented them learning the various cue-target relations. Future work will be required to investigate these possibilities.

Chapter 3: GENERAL DISCUSSION

The objective of this dissertation was to explore a basic question of predictive learning, namely, whether a predictive cue enters into separate associations with distinctive sensory and temporal attributes of a target event or if such a cue enters into a single association with an integrated representation of the sensory and temporal attributes of the target event. The question of whether multiple attributes of the US are encoded separately or in an integrated manner is a basic question that has implications for associative and timing models of Pavlovian learning, and associative learning more generally. To investigate this question, four predictive learning tasks with human participants were designed with the goal of seeking evidence to support one or the other of these encoding possibilities.

The outcome of this investigation, of whether the sensory and temporal attributes of the US are encoded separately or as an integrated whole, has resulted in support of the separable encoding account. Results from all experiments revealed a consistent pattern – subjects’ reaction times were faster to validly than invalidly cued targets when these relations were tested at the training ISI, and the magnitude of this “validity” effect was not reduced when testing occurred with ISIs that differed from the training ISI. This effect was seen in both a two alternative forced choice and a go/no go version of the task. The ubiquity of this outcome was tested under a variety of conditions and still this result remained supported. In my initial experiment, subjects were trained with a single
ISI, and were tested at multiple ISIs. The results of this experiment revealed faster responding to valid targets than invalid targets and this result was similar across the three test ISI times, although RTs were overall faster at the training ISI. It was considered that perhaps training with a single ISI might have resulted in cue-target learning that was dominated by the target’s sensory over its temporal features, and encouraged the separable encoding of these features. Thus for the remaining experiments, different cue-target pairs were trained at different ISIs to determine if this would have an effect on how the outcome is encoded.

In Experiment 2 subjects were presented with four cues and two targets, where two cue-target pairs were trained at a short ISI and two trained at a long ISI. Then valid and invalid cue-target pairs were tested at both ISIs. As in Experiment 1, subjects responded faster to validly than invalidly cued targets, and the magnitude of this effect was not diminished when testing occurred at an ISI different from training. These results agreed with those from Experiment 1. However, in this study since there were only 2 target stimuli, each target stimulus could follow a cue after both a short and long ISI in training. As such, this circumstance may have impeded the development of an integrated time-event representation. In Experiment 3 four unique cue-target pairs were trained in a four-alternative forced choice task. Two pairs were trained at a short ISI and two at a long ISI. During test, valid and invalid cue-target pairs were tested at both short and long ISIs. The results of Experiment 3 again found that subjects responded faster to validly than invalidly cued targets, but, critically, the magnitude of this effect was not reduced when testing occurred at an ISI other than that used in training. In this study there was no support for the idea that training with only two targets (where each could
follow a short and long ISI) impeded the formation of an integrated time-event representation.

In these first three experiments, we interpret the findings to support separate learning of the sensory and temporal attributes of the US. It is clear from our results that subjects learned about the sensory identity of the targets, but whether the subjects learned about temporal control within the CS-US association is less clear. The best evidence of temporal control can be seen in Experiment 1 in that the magnitude of the validity effect was similar across the three ISIs, and particularly that subject's reaction time was overall fastest at the training ISI. Experiment 2 and 3 also found that the magnitude of the validity effect was similar across test ISIs, however responding was not faster at the training ISI than the alternative ISI. It is possible that training with two training ISIs and testing at the same two ISI resulted in this observation. To explore whether subjects learned about temporal control, a design similar to Experiment 1, but where different groups were trained at different ISIs and then all groups were be tested at all intervals, would be needed.

In Experiment 4 I attempted to force the development of an integrated time-event representation by using a conditional discrimination training procedure. In this task one of two cues predicted target 1 after a short ISI and target 2 after a long ISI, whereas the other cue signaled target 2 after a short ISI and target 1 after a long ISI. Then subjects were tested with occasional probe trials in which the various cue-target relations were tested at their untrained ISIs. In order for subjects to learn this task, specific time-event encodings would need to be acquired and associated with the different cues. In contrast, if the cues had formed separate associations with the temporal and sensory
qualities of the targets, then this task would be unsolvable because each cue was paired with each target and also with some target occurring at both ISIs. The results of this experiment (Experiment 4) revealed no difference in responding to the targets when tested at the trained and untrained ISI values. This result is what would be expected if subjects had encoded the sensory and temporal target attributes separately; however, it is difficult to take a null result as definitive evidence against an integrated time-event learning mechanism because there could be other reasons why subjects failed to learn the experimental contingencies in this experiment.

An interesting finding in the post-experiment questionnaire data for Experiments 1 and 3, showed that subjects estimated the valid cue-target contingencies fairly accurately in training. In test, however, the valid targets were estimated to occur more frequently than the invalid targets (for Experiments 1 & 3) even though these contingencies were presented with equal frequency. We understand this result to mean that subjects learned the valid cue-target associations in training and that this explicit learning affected subjects’ frequency estimates and RTs during the test phase. In other words, the frequency estimates for valid and invalid cue-target pairs were negatively correlated with test RTs reflecting the validity effects we observed (for Experiments 1 & 3). Looking at the post-experiment questionnaire data for Experiment 2, however, we see near accurate estimations of the cue-target contingencies in both the training and the test phases. The cue-target frequency estimates in this study, therefore, were uncorrelated with the test RT results which showed faster RTs in the presence of validly cued targets over invalidly cued targets despite equal frequency estimates for valid and invalid cue-target pairs. This result shows a dissociation between RT and explicit
knowledge of the cue-target contingencies. Further research would be needed to explore the effect of explicit knowledge of the cue-target contingencies and the affect it may have on learning.

*Relations to Earlier Work*

As we found consistent support for the separable encoding account of target attributes, our findings are at odds with the limited work on this problem conducted with humans exploring the distinction between separable or integrated time-event encoding (eg. Kingstone, 1992; Thomaschke et al., 2011; Wagener & Hoffman, 2010). All of these studies either found support for or the authors interpreted their results as supporting an integrated encoding strategy, whereas the findings of the studies presented in this paper support separable time-event encoding. It is possible that the different outcomes found are due to differences in experimental design. One particularly important difference was the use of the foreperiod as the cuing stimulus in the Thomaschke et al. (2011) and Wagener and Hoffmann (2010) studies. In both these cases, the foreperiod (FP) itself was the only available “stimulus” that could have served as a predictive cue. Recall that in these studies subjects were presented with a fixation cross and then one or another target stimulus occurred after different foreperiods. A procedure such as this differs substantively from conventional associative learning tasks in which there are discrete cues that signal different target events. The present studies asked whether in predictive learning tasks a discrete cue could enter into an association with an integrated time-event representation of the target, or whether separate associations are formed with the time and event components of the target stimulus. It is
difficult to generalize, therefore, from the results in procedures where there are no
discrete cues (other than the FP itself) to ones in which there are. Apparently, when the
only available cue to predict an outcome is the FP, then subjects can learn to anticipate
the target stimulus on the basis of these temporal cues. But, this may not be the norm
when discrete cues are available.

However, the Kingstone (1992) study used discrete predictive cues, and would appear to be most similar to the procedures used in the present set of studies. It is
noteworthy, though, that in the Kingstone (1992) study one time and one form cue were
presented simultaneously on every trial. In contrast, in the present studies only a single
cue was present on every trial. Concurrently presenting one time with one event cue
may, indeed, encourage integrated time-event target encoding. In other words, when
subjects are explicitly given information about what form to expect and when to expect
it, they are likely to anticipate that a specific target form will occur at a specific time and
not at other times. It is of some interest that in Experiments 2 and 3 presented here, the
different cues could have been used to signal that a particular target stimulus would
occur only at one particular ISI. However, when the cues were probed at the different
ISIs the magnitude of the validity effect was not diminished as it was in the Kingstone
(1992) study. Kingstone’s (1992) findings, therefore, do not appear to be generalizable
to situations that do not involve multiple time and event cues.

Implications for Associative Theories

The present findings support the notion that a predictive cue enters into separate
associations with the sensory and temporal attributes of a target stimulus. Similarly, in
studies of Pavlovian learning, Konorski (1967) earlier suggested that the CS can enter into separate associations with sensory and motivational attributes of the US and, more recently, Corbit and Balleine (2005; 2011) provided evidence that the neural mechanisms mediating these two forms of learning are dissociable. However, while there is support in the associative literature for independent associations forming between a CS and the sensory and motivational attributes of the US, the main implication of the present studies is that a similar dissociation may also exist regarding learning about specific sensory features of the US and the specific time at which the US occurs. However, one challenge for associative theories concerns specifying how temporal attributes of the US, the focus of this paper, could be explained in associative terms.

The classic Pavlovian learning theory that is at the heart of the associative approach is the Rescorla and Wagner model (1972). Described in more detail earlier in this paper, this model asserts that on a single trial, the change in associative strength is determined by the salience of the stimuli and by the surprisingness of the US. Though this model is one of the most significant approaches to understanding Pavlovian learning, it was not originally intended to capture within-trial timing features. One idea has proposed that the presentation of a CS induces a set of distinct internal temporal cues each successively marking time until the US appears (McClelland, 1979). This idea, this temporal cascade of discriminable cues between the CS and the US, suggests that the final internal temporal cue that co-occurs with the US presentation would gain the most associative strength and would thus maximally evoke the CR at that point in time.
Another model, Wagner’s componential – sometimes opponent processes (C-SOP) model is a real-time conditioning model supports a similar idea as the temporal cascade hypothesis (Brandon, Vogel, & Wagner, 2003; Wagner & Brandon, 2001). The C-SOP model was designed to account for some of the timing aspects of the CS-US association, and considers the formation of associations to be a function of stimulus activation in memory. According to this theory, the CS has a multi-component representation with both time-dependent and time-independent elements. The occurrence of the CR at a particular point in the CS trace is a function of the associative strength acquired by the temporal elements that are active at the moment of US delivery (Brandon et al. 2003). In this way, C-SOP can provide an explanation for when a CR will occur in time. C-SOPs way of representing the CS-US interval is similar to the temporal cascade notion since different elements have different time courses.

These ideas would seem to have difficulties with the findings presented here in that subjects were able to encode the timing of the target separately from its identity. As the temporal interval was changed during test trials, subjects still responded more quickly to valid then invalid targets. If the maximal expectancy of the target is linked to its time of occurrence, through maximal activation of particular time-dependent elements, then larger validity effects would be expected to occur at the training ISI. It seems possible that time-independent elements may contribute to learning as well, but, nonetheless, target expectancy should still be greatest at the relevant time of occurrence. Thus, without additional assumptions, it is not clear that appealing to a temporal cascade of internal cues will help this type of model explain the results reported here (see also Smith et al, 1969).
Classic Theories of Interval Timing

One influential model in the timing literature, the pacemaker-clock model, was originally developed by Treisman (1963). This model introduced the idea of a pacemaker device that functions as an internal time-keeper capable of registering time by sending pulses to an accumulator which collects these pulses. The pacemaker-clock model (PCM) as developed by Gibbon, Church, & Meck (1984; also Meck & Church, 1983) is comprised of three components - a clock-accumulator mechanism, working and reference memory stores, and a comparator. This model asserts that at stimulus onset a switch is closed and a pacemaker sends out pulses that are collected in an accumulator and processed in working memory (e.g., see Grommet, Droit-Volet, Gil, Hemmes, Baker & Brown, 2011). When the stimulus is terminated, the number of pulses accumulated represents the length of the stimulus interval. The number of pulses accumulated is then stored (at the time of reinforcement delivery) in reference memory, which contains a distribution of these remembered durations. Finally, the third component, the comparator, is the decision unit. The comparator computes a ratio of the difference between the number of pulses currently in working memory and in reference memory relative to the number of pulses in reference memory. Accordingly, a decision to respond at any moment in time is made by comparing this ratio to a response threshold value.

Church and Broadbent (1990) developed a connectionist model that incorporated some of the same basic elements of the pacemaker-clock approach of Gibbon, Meck, and Church (1984). However, a key difference in this approach is that time is encoded through a multiple-oscillator timing system. In this model, there are multiple timing
elements, or oscillators, each with its own timing period. Each of these oscillators has a status indicator which records phase information of the oscillator. This input is then represented in reference memory by a matrix of connection weights that can produce a value of the input received at any given point in time. The decision to respond occurs when the current time (based on the periodicity of the multiple oscillators) is similar to the stored time of reinforcement in the reference memory matrix. This memory matrix of the MO model represents time as an intricate network of weights and is thus capable of representing multiple time values.

The PCM and the MO models have similar components: both have mechanisms for a 'clock', memory, and decision-making; however, they differ in how time itself is represented. Notably, the pacemaker of PCM is represented by multiple oscillators in the MO model and, according to Gallistel (1980), this is a more plausible mechanism for timing in a biological system rather than a pulse stream. Additionally, time in PCM is represented as an accumulation of pulses and stored in memory as a single value, while in MO, time is stored in a memory matrix involving an intricate network of weights and capable of representing multiple time values. However, these timing models were not explicitly designed to explain simple Pavlovian learning phenomena (e.g., CR timing, outcome expectancy effects), and so it is not clear how one might integrate these two classes of models.

Towards an Integration of Associative and Timing Theories

Two theories of Pavlovian conditioning that are timing-based - the temporal information theory (Balsam & Gallistel, 2009; Gallistel & Balsam 2014) and the temporal
coding hypothesis (Matzel et al., 1988) - have elements to them from both the associative and timing models and may offer insight on how associative and timing theories might be integrated. (See also Kirkpatrick & Church, 1998 for a more comprehensive overview of the strengths and limitations of various models from the traditional conditioning approach and the timing literature as well a review of some hybrid theories which have difficulty in being able to integrate both the associative principles and the perceptual representation of time.)

The Temporal Coding hypothesis suggests that the CS-US interval itself is directly encoded as part of the underlying associative content. Some evidence in support of these ideas can be found in both human and non-human animals (Arcediano, et al., 2003; Barnet, et al., 1997; Matzel, et al, 1988; Taylor, et al., 2014). One of the tenets of this approach claims that temporal maps of the stimuli are created in memory and that if these maps share an element they can be combined and affect responding. It is difficult to know precisely what is meant by a “temporal map,” but one idea is that time is another dimension within which associations are formed (Miller & Barnet, 1993). If the temporal aspect of learning is separate from its specific sensory content, then this framework may be applied to the results presented here. I have argued that in the tasks explored here the cues associate with separable encodings of the sensory and temporal aspects of the target events. The validity effect could be explained by assuming that the cue activates a memory of its associated target event and that this enhances processing of that event when it is actually presented. If the association is formed along separate time and sensory specific dimensions, then those two aspects of learning may affect performance in additive ways in the experiments reported here. However, it
should be clear that if these presumed dimensions are engaged more interactively, then the present findings would be difficult to handle because, then, the appropriate target expectation would be maximal at the specific training ISI. That would lead to smaller validity effects when testing occurs with ISIs other than the training ISI.

In a related approach, Balsam and Gallistel (2009; Gallistel & Balsam, 2014) asserted that events are directly encoded within a temporal memory structure and the decision to respond is based on data stored within that temporal memory system. I have argued here that this idea suggests that the temporal and sensory features of an event should be encoded in an integrated fashion because that sensory event is assumed to be “time-stamped” upon its presentation within that temporal memory system. If this were true then this is also at odds with the results of the studies presented here because larger validity effects should occur at the point in time in which the target expectancies are greatest, i.e., at the training ISI.

While these more timing-based Pavlovian conditioning models place more emphasis on time as either a “dimension” of the association or as a fundamental component of memory encoding, exactly how timing processes might play a role in Pavlovian learning is still largely unanswered. The classic timing theories noted above suggest an interesting alternative to the idea that time is tied to the CS, e.g., as conceptualized by a cascade of temporal elements. It is not obvious, though, how one might integrate these timing models with a standard associative model of Pavlovian learning. One possibility to consider is that a trained CS might become associated with a specific temporal interval value that is stored in the temporal interval memory matrix of the MO model. If such an association were to be established, then when the CS is
subsequently presented, it should come to activate this specific interval representation. In this way, when the CS is presented, the expected US time could be retrieved from memory and result in an appropriately timed response through some comparison process not unlike that assumed by the PCM approach. If a separate, non-temporal, system encoded associations between the CS and the sensory features of the US (or cue and target), then these two systems could operate independently of one another (e.g., Brown, et al. 1997; Delamater, Desouza, Rivkin, & Derman, 2014). The evidence presented here would support such a 2-process approach. This highly speculative idea of integrating a purely timing based theory with more traditional Pavlovian conditioning models may offer one way of thinking about how one could begin to integrate timing theories with basic associative learning theories. Continuing along this line of reasoning, this assimilation of timing within the associative framework it might be possible to explain, much like the separate encoding of sensory and motivation aspects of the US (eg. Corbit & Balleine, 2005; Dickinson & Dawson, 1987), how sensory and temporal attributes can be dissociated as well. In other words, the approach predicts that learning in one system could occur quite normally when the other system is damaged.

Final Comments/Conclusions

In conclusion, this paper has provided a discussion of the role of temporal factors in predictive learning, and how various models of Pavlovian conditioning ranging from traditional associative models to time-based models handle these temporal factors. The central question of this paper asked whether learning about sensory and temporal
attributes of a target event involve separable or integrated processes. This question was pursued empirically and in contrast to other recent studies that seem to support the integrated encoding account, the results of my studies consistently provide evidence for separable encoding of these target features. An attempt was made to understand the differences between these lines of research. However, how to understand the nature of this encoding within purely associative or timing frameworks remains unclear. One potential avenue considered suggests some assimilation of a classic timing model with an associative approach, an idea that needs development.

One final area of research to consider is work on temporal expectancy in the attention literature (eg. Coull & Nobre, 1998; Jones 2015; Nobre, 2001). This idea refers to a general expectancy about when ‘something’ will happen. A few studies in this area have suggested that temporal expectancies can enhance attentional focus and, consequently, the processing of sensory information presented at an anticipated time (Coull & Nobre 1998; Nobre, Correa, & Coull, 2007). In one relevant study, Rohenkohl, Cravo, Wyart, & Nobre (2012) presented subjects with a stream of stimuli (visual gratings), where most were just Gaussian noise patches. Gabor patches (the target stimuli) were presented within the steam and these target patches were tilted 45 degrees clockwise or counter-clockwise and presented at various contrast levels above and below the threshold contrast (based on 75% accuracy for each participant). The stimulus stream was presented either with a fixed ISI of 400 ms (regular condition) or variable ISI ranging from 200 ms to 600 ms (irregular condition), however the ISI immediately preceding and following a target stimulus was always 400 ms in both conditions. The target stimuli were identified by a change in color surrounding the
presented stimulus, but no cue signaling the likely orientation was provided. The subjects’ task was to indicate the orientation of the target (as tilted left or tilted right). The results showed that temporal expectation reduced the threshold contrast needed to correctly identify the orientation of the target stimulus in the fixed ISI (regular) condition relative to the irregular condition. There was also a larger d’ for targets in the regular than the irregular condition (Rohenkohl et al., 2012). These results support the idea that temporal expectation can enhance the processing of fairly low-level sensory information. Further, it is usually assumed that this can be accomplished by the deployment or focusing of attention to information presented at times when events are anticipated (Rohenkohl et al., 2012).

In may be possible to apply this idea to the experimental approach and findings reported here. When pairing a cue with a target at a specific ISI the subject may learn to associate the cue with that target event, and one consequence of this association may be that the cue engages the subjects’ attentional focus to events that occur at the specific ISI. If this time-specific deployment of attention played a role in our results, then larger validity effects would be expected to occur when the cue deploys attention to the training ISI. However, that is not what we found in our studies; our results showed that the magnitude of validity effects consistently remained unchanged at the alternative ISIs presented in test. This result seems at odds with the idea that attention may have played a role in these experiments. Regardless, the methods used to study temporal expectancy effects are related to associative learning procedures, more generally, and, as such, further consideration of potential ties between these two literatures may lead to new insights.
In sum, the present findings, unlike previous work on predictive learning tasks with humans thus far, add critical empirical evidence in support of the idea that cues associate with separable encodings of the sensory and temporal features of target events. Results such as these could open the door to additional work that considers how timing and associative processes relate to one another.
Appendix A: Experimental Instructions

Experiment 1a Instructions: (example)

Welcome.

In this experiment, you will see geometric figures followed by colored boxes.

Your task is to respond to the colored boxes by pressing the appropriate button on the response box, but note that not all colored boxes are to be responded to. Specifically, press button #1 when you see the BLUE and button #2 when you see the RED colored box, but do not press any buttons when you see the GREEN colored box. Feedback will be provided to indicate the accuracy and speed of your response.

In addition to this task, you are to learn the relationships between the different geometric figures and the colored boxes that follow. Both the speed and accuracy of your response is recorded. So please respond quickly, but accurately.

Each trial will begin with a fixation cross (+), please focus your attention on the fixation cross.

Press the spacebar when you are ready to begin.

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Experiment 1b Instructions: (example)

Welcome.

In this experiment, you will see geometric figures followed by colored boxes.

Your task is to respond by pressing the WHITE button on the response box when you see the appropriate colored box, but note that not all colored boxes are to be responded to. Specifically, press the button when you see the BLUE or RED colored box, but not when you see the GREEN colored box. Feedback will be provided to indicate the accuracy and speed of your response.

In addition to this task, you are to learn the relationships between the different geometric figures and the colored boxes that follow. Both the speed and accuracy of your response is recorded. So please respond quickly, but accurately.

Each trial will begin with a fixation cross (+), please focus your attention on the fixation cross.

Press the spacebar when you are ready to begin.

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Welcome.

In this experiment, you will see geometric figures followed by colored boxes.

Your task is to respond to the colored boxes by pressing the appropriate button on the response box. Specifically, press button #1 when you see the BLUE and button #2 when you see the RED colored box. Feedback will be provided to indicate the accuracy and speed of your response.

In addition to this task, you are to learn the relationships between the different geometric figures and the colored boxes that follow. Both the speed and accuracy of your response is recorded. So please respond quickly, but accurately.

Each trial will begin with a fixation cross (+), please focus your attention on the fixation cross.

Press the spacebar when you are ready to begin.
E3 Instructions (example):

Welcome.

In this experiment, you will see geometric figures followed by colored boxes.

Your task is to respond to the colored boxes by pressing the appropriate button on the response box. Specifically, press:

button #1 when you see the RED colored box;
button #2 when you see the GREEN colored box;
button #3 when you see the BLUE colored box;
button #4 when you see the YELLOW colored box.

Feedback will be provided to indicate the accuracy and speed of your response.

In addition to this task, you are to learn the relationships between the different geometric figures and the colored boxes that follow. Both the speed and accuracy of your response is recorded. So please respond quickly, but accurately.

Each trial will begin with a fixation cross (+), please focus your attention on the fixation cross.

Press the spacebar when you are ready to begin.
*E4 Instructions (example):*

Welcome.

In this experiment, you will see geometric figures followed by colored boxes.

Your task is to respond to the colored boxes by pressing the appropriate button on the response box. Specifically, press button #1 when you see the RED and button #2 when you see the BLUE colored box. Feedback will be provided to indicate the accuracy and speed of your response.

In addition to this task, you are to learn the relationships between the different geometric figures and the colored boxes that follow. Both the speed and accuracy of your response is recorded. So please respond quickly, but accurately.

Each trial will begin with a fixation cross (+), please focus your attention on the fixation cross.

Press the spacebar when you are ready to begin.
Appendix B: Post-Experiment Questionnaire

Post-Experiment Questionnaire: (Experiment 1)  

Sub ID# ________________

Based on your general impression of the experiment as a whole, please circle:

The colored box that was most likely to follow the STAR figure?

BLUE  GREEN  RED

The colored box that was most likely to follow the HOURGLASS figure?

BLUE  GREEN  RED

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In this experiment there were actually two phases to this task. The first set of trials was part of the training phase and a second set of trials were part of the test phase. Please enter in the space provided the likelihood of each colored box following the geometric figure in each phase. (Please provide your answer in the form of a percentage of likelihood, the percentages for each figure should total 100%).

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<tr>
<th>Training phase:</th>
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Total = 100% | 100%  

Total = 100% | 100%
Post-Experiment Questionnaire (Experiment 2): Sub ID# _____________

Based on your general impression of the experiment as a whole, please circle:

- The colored box that was most likely to follow the DIAMOND figure?
  - BLUE
  - RED

- The colored box that was most likely to follow the HOURGLASS figure?
  - BLUE
  - RED

- The colored box that was most likely to follow the CIRCLE figure?
  - BLUE
  - RED

- The colored box that was most likely to follow the STAR figure?
  - BLUE
  - RED

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In this experiment there were actually two parts to the task. The first part was a training phase and the second a test phase. Please enter in the space provided the likelihood of each colored box following the geometric figure in each phase. (please provide your answer in the form of a percentage of likelihood, the percentages for each figure should total 100%)

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Total = 100% | 100% | 100% | 100%
Post-Experiment Questionnaire (Experiment 3):

In this experiment there were actually two parts to the task. The first part was a training phase and the second a test phase. Please enter in the space provided the likelihood of each colored box following the geometric figure in each phase. (Please provide your answer in the form of a percentage of likelihood, the percentages for each figure should total 100%).

### Training phase:

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Additionally, there was a time component to this task. Two possible time periods were presented between the figure and the colored box, one was short and the other was long. Please indicate the likelihood that each time period was presented after each figure. (Please provide your answer in the form of a percentage of likelihood, the percentages for each figure should total 100%).

### Training phase:

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<td>______</td>
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<td>______</td>
</tr>
<tr>
<td>Long</td>
<td>_______</td>
<td>______</td>
<td>_______</td>
<td>______</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Test phase:

<table>
<thead>
<tr>
<th></th>
<th>Diamond</th>
<th>HourG</th>
<th>Circle</th>
<th>Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>_______</td>
<td>______</td>
<td>_______</td>
<td>______</td>
</tr>
<tr>
<td>Long</td>
<td>_______</td>
<td>______</td>
<td>_______</td>
<td>______</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

- Thank you!
In this experiment there were actually two parts to the task. The first part was a training phase and the second a test phase. Please enter in the space provided the likelihood of each colored box following the geometric figure in each phase. (Please provide your answer in the form of a percentage of likelihood, the percentages for each figure should total 100%).

### Training phase:

<table>
<thead>
<tr>
<th>HourG</th>
<th>Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLUE</td>
<td>____</td>
</tr>
<tr>
<td>RED</td>
<td>____</td>
</tr>
</tbody>
</table>

Total = 100% | 100%

### Test phase:

<table>
<thead>
<tr>
<th>HourG</th>
<th>Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLUE</td>
<td>____</td>
</tr>
<tr>
<td>RED</td>
<td>____</td>
</tr>
</tbody>
</table>

Total = 100% | 100%

Additionally, there was a time component to this task. Two possible time periods were presented between the figure and the colored box, one was short and the other was long. Please indicate the likelihood that each time period was presented after each figure. (Please provide your answer in the form of a percentage of likelihood, the percentages for each figure should total 100%).

### Training phase:

<table>
<thead>
<tr>
<th>HourG</th>
<th>Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>____</td>
</tr>
<tr>
<td>Long</td>
<td>____</td>
</tr>
</tbody>
</table>

Total = 100% | 100%

### Test phase:

<table>
<thead>
<tr>
<th>HourG</th>
<th>Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>____</td>
</tr>
<tr>
<td>Long</td>
<td>____</td>
</tr>
</tbody>
</table>

Total = 100% | 100%

Finally, in training, each figure was paired with each colored box and with each time window. Please indicate the color & time window combination that you believe was paired with each figure. (Please write “S” for short & “L” for long in each space).

<table>
<thead>
<tr>
<th>HourG:</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>____</td>
</tr>
<tr>
<td>Star:</td>
<td>____</td>
</tr>
</tbody>
</table>

-Thank You!
References:


