

# An ACT-R Model of the Choose-Short Effect in Time and Length

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## Abstract

Duration of an event tends to be underestimated as it becomes temporally distant (Spetch & Wilkie, 1983). The current study investigated this so-called choose-short effect in time and length in order to reevaluate the claim that the choose-short effect is special to temporal memory (Wearden, Parry, & Stamp, 2002). Participants made discrimination judgments in time or length on a pair of line stimuli separated by a delay. The stimulus presented during delay was varied in time or length. A length manipulation intended to be an analogue of temporal delay induced the choose-short effect in length discrimination. We developed a computational model based on ACT-R memory mechanisms (Anderson et al., 2004) to account for the main results in both time and length. The current results indicate that domain-general memory principles could account for the seemingly unique temporal phenomenon.

**Keywords:** temporal memory; ACT-R cognitive architecture

## Introduction

One of the unresolved questions in time estimation research is whether temporal memory involves special mechanisms that fundamentally differ from non-temporal memory. Evidence for the uniqueness of temporal memory comes from studies in which temporal memory performance differs from non-temporal memory performance. For instance, increasing interstimulus interval decreases performance in non-temporal discrimination (Kinchla & Smyzer, 1967; Moss, Myers, & Filmore, 1970), whereas it has little effect on temporal discrimination (Allan, Kristofferson, & Rice, 1974). On the other hand, others have found similar patterns of performance shared between temporal and non-temporal memory. One of those examples is the end effect, which refers to better identification performance on stimuli located at either end of stimulus set. The end effect has been robustly found in non-temporal stimuli (Lacouture, 1997; Petrov & Anderson, 2005; Weber, Green, & Luce, 1977) as well as temporal stimuli (Brown, McCormack, Smith, & Stewart, 2005; Lacouture, Grondin, & Mori, 2001) suggesting some common underlying principles. To address the question whether temporal memory involves special mechanisms, the current study investigated the choose-short effect (Spetch & Wilkie, 1983) that has been claimed to be unique to temporal dimension.

## The Choose-Short Effect

Wearden and colleagues (Wearden & Ferrara, 1993; Wearden, Parry, & Stamp, 2002) investigated the choose-short effect in a temporal discrimination paradigm. Participants attended to a pair of sub-second durations presented successively with an intervening delay randomly varied across trials, and indicated whether the second duration (test) was shorter than, equal to, or longer than the first (study) duration. The paradigm had three types of trials:  $T < S$  (test shorter than study),  $T = S$  (test equal to study), and  $T > S$  (test longer than study). Predictions were made based on the subjective shortening hypothesis (Spetch & Wilkie, 1983) according to which the choose-short effect arises because analogical representation of study duration undergoes gradual foreshortening over delay. The subjective shortening hypothesis predicts worse performance after a longer delay in the first two trial types. In the  $T < S$  trials, the shortened study representation would decrease the perceived differences between study and test, making it increasingly difficult to discriminate between the two. In the  $T = S$  trials, the shortened study representation would make it more difficult to judge that the two are equal. On the other hand, it predicts better performance in the  $T > S$  trials after a longer delay, termed as the “signature of subjective shortening”. The shortened study representation would increase the perceived difference between study and test, making it easier for participants to judge that test is longer than study. Their results supported those predictions.

Wearden, Parry, & Stamp (2002) further investigated whether the choose-short effect is unique to time dimension. The authors manipulated both presentation duration and length of line stimuli and asked participants to make discrimination judgments based on an instructed dimension. Time discrimination performance exhibited the signature of subjective shortening. However, length discrimination performance was relatively unaffected by the delay manipulation. Based on these results, the authors argued that temporal memory exhibits a unique form of forgetting which is different from non-temporal memory.

Although these results seem to support uniqueness of temporal memory mechanism, a closer look at their experimental paradigm suggests a possible alternative interpretation. In this paradigm, participants were presented with a blank screen with no visual stimulus during the

delay. While waiting for the forthcoming test stimulus, participants presumably attended to time which was the only changing dimension. The delay duration was randomly varied across trials, which imposes temporal uncertainty regarding when exactly the test stimulus would appear. This temporal uncertainty makes it likely that participants attended to time during the delay in both time and length discrimination. In time discrimination, the dimension to judge (time) matches the dimension attended during the delay (time), and the choose-short effect might be explained as an interaction between the two temporal representations. In length discrimination, the dimension to judge (length) does not match the dimension attended during the delay (time), and this mismatch could explain the absence of the choose-short effect.

We questioned whether the choose-short effect could be introduced in length discrimination by presenting visual stimulus during delay and manipulating its length. We modeled our results in the ACT-R cognitive architecture (Anderson et al., 2004). Memory mechanisms of ACT-R have been established in non-temporal memory and are considered to be domain-general theories of human memory. By modeling the choose-short effect in ACT-R, we aim to test whether common principles could account for both temporal and non-temporal memory.

## Experiment

We modified the discrimination paradigm in Wearden, Parry, & Stamp (2002) and introduced a visual stimulus during the delay. We predicted that manipulating length of this stimulus would influence length discrimination in the similar way that manipulation of delay duration influences time discrimination. A longer stimulus length would result in worse length discrimination performance in the  $T < S$  and  $T = S$  trials and better performance in the  $T > S$  trials.

## Method

**Participants** Twenty-five adults (19 female, 6 male, mean age 20.3) were recruited from local community. Participants earned either course credit or cash (\$5 per 30 min).

**Stimuli and Design** We used yellow horizontal line stimuli presented in the black background. The stimuli varied in both duration of presentation and visual length. In each trial, the study stimulus was randomly selected from a predefined range in Table 1 depending on the trial type. In the time task, the test duration was equal to the study duration, or 200 milliseconds (ms) longer or shorter. In the length task, the test length was equal to the study length, or 15 pixels (px) longer or shorter. The relationship between the study and test in time was independent of the relationship in length. The major difference from the Wearden, Parry, & Stamp (2002) paradigm was the presence of a grey horizontal line stimulus. The grey line appeared at the study onset and disappeared at the test offset. During the study and test phases, the yellow line was superimposed on the grey line, both centered on the screen.

The experiment had a 2-task x 3-type x 2-delay-time x 2-line-length within-subject design. Task is either time or length discrimination. Type refers to the relationship between the study and test which could be  $T < S$ ,  $T = S$ , or  $T > S$ . Delay-time refers to the duration of the delay and was either short (DT1: 2 s) or long (DT2: 10 s). Line-length refers to the length of the grey line and was either short (LL1: 447 px) or long (LL2: 1000 px).

Table 1: Study (S) and test (T) stimulus range.

Trial Type	Duration (ms)		Length (px)	
	S	T	S	T
$T < S$	400-550	S - 200	160-250	S - 15
$T = S$	250-550	S	150-250	S
$T > S$	250-400	S + 200	150-240	S + 15

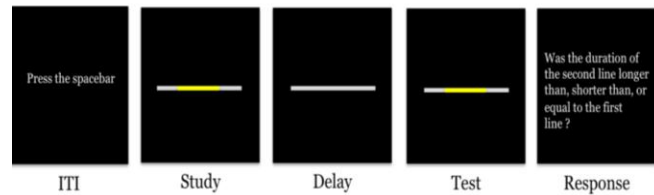


Figure 1: Experimental paradigm.

**Procedure** Participants performed six time and six length discrimination blocks in a randomized order. Each block started with a screen that informed the participant of the target stimulus dimension (duration or length) for that block. Participants performed 18 discrimination trials based on the instructed dimension in the rest of the block. Each trial (Figure 1) began with a screen that prompted participants to press the spacebar. This self-paced intertrial interval (ITI) was followed by a study-test pair of yellow lines separated by a delay during which a grey line was presented. After the test offset, participants were presented with the following question: “Was the duration (or length in the length task) of the second line longer than, shorter than, or equal to the first line?” Participants were instructed to respond within two seconds after this prompt by pressing one of the three keys: J key for Short ( $T < S$ ), K key for Equal ( $T = S$ ), and L key for Long ( $T > S$ ) responses. There was no trial-by-trial feedback. At the end of each block, a screen showed the numbers of correct and timeout trials.

## Results and Discussion

A 3-type x 2-delay-time x 2-line-length repeated measures ANOVA was performed for each task. In the time task, the only significant effect was type x delay-time interaction ( $F(2,48) = 11.24, p < .001$ , partial eta-squared = .319). In the  $T < S$  trials, performance was worse with the longer delay-time (DT1: .67, DT2: .54,  $t(24) = 3.49, p = .002$ ). In the  $T = S$  trials, performance was slightly worse with the

longer delay-time without statistical significance (DT1: .54, DT2: .49,  $t(24) = 1.12$ ,  $p = .272$ ). In contrast, performance in the  $T > S$  trials was better with the longer delay-time (DT1: .48, DT2: .63,  $t(24) = 3.38$ ,  $p = .002$ ).

In the length task, there was a significant type  $\times$  delay-time interaction ( $F(2,48) = 6.35$ ,  $p = .004$ , partial eta-squared = .209). Performance did not significantly differ between the delay-time conditions in the  $T < S$  (DT1: .42, DT2: .45) and the  $T > S$  trials (DT1: .53, DT2: .53). In the  $T = S$  trials, performance was worse with the longer delay-time (DT1: .57, DT2: .41,  $t(24) = 4.04$ ,  $p < .001$ ). Importantly, the type  $\times$  line-length interaction ( $F(2,48) = 4.59$ ,  $p = .015$ , partial eta-squared = .161) was significant. In the  $T < S$  trials, performance was slightly worse with the longer line-length (LL1: .48, LL2: .40,  $t(24) = 1.96$ ,  $p = .061$ ). In the  $T = S$  trial, performance did not differ between the line-length conditions (LL1: .50, LL2: .49,  $t(24) = .27$ ,  $p = .785$ ). In the  $T > S$  trials, performance was significantly better with the longer line-length (LL1: .49, LL2: .57,  $t(24) = 2.65$ ,  $p = .014$ ).

Short response decreased with the longer line-length in the  $T < S$  trials. In the  $T = S$  trials, the Equal response changed little, but the changes in the error responses were consistent with the choose-short effect (decreased Short and increased Long). In the  $T > S$  trials, the Long response increased, exhibiting the signature of the choose-short.

The results indicated that we replicated the choose-short effect in time discrimination (Wearden, Parry, & Stamp, 2002). More importantly, the line-length effects in length discrimination were qualitatively similar to the delay-time effects in time discrimination. In both tasks, performance was better with the longer delay stimulus in the  $T > S$  trials. In both tasks, participants increased their Long responses and decreased their Short responses with the longer delay stimulus in the  $T = S$  trials. The results support the assumption that stimulus information presented during the delay can bias discrimination performance, and this bias occurs when the stimulus dimension attended during the delay matches the dimension attended for discrimination.

These results can be accounted for by either contrast or assimilation account. If the study representation is contrasted with delay representation, the longer delay would make the study look shorter. Alternatively, if the test representation is assimilated with the delay representation, the longer delay would make the test look longer. Both accounts predict better performance in the  $T > S$  trials. In a follow-up study in which ITI duration was manipulated (Moon & Anderson, 2015), the longer ITI resulted in better time discrimination performance in the  $T < S$  trials and worse performance in the  $T > S$  trials, which can be explained by the assimilation account. The longer ITI makes the study look longer, which results in easier discrimination in the  $T < S$  trials and harder discrimination in the  $T > S$  trials. Overall, our results suggested that the choose-short effect arises out of a tendency to assimilate the current stimulus with the most recent stimulus.

## ACT-R Modeling

We implemented a model of the choose-short effect in the ACT-R cognitive architecture (Anderson et al., 2004), an integrated theory of human cognition. Declarative memory in ACT-R consists of chunks that can represent associations learned between stimuli and labels (e.g., “short” is  $n$  units). Each chunk is associated with an activation value that reflects the likelihood that information will be useful in the future. The assimilative effects will be produced by the variations in activation and its effects on performance.

The declarative memory interacts with multiple other modules as coordinated by a central production system. Each module is dedicated to a specific operation (e.g., vision module processes visual features of a stimulus). The outcome of processing within each module is communicated with the production system through an interface called buffer. The production system selects a production that satisfies the current status of buffers. Execution of a production can modify the buffers and thus change the current status of the model. Time estimation in ACT-R is

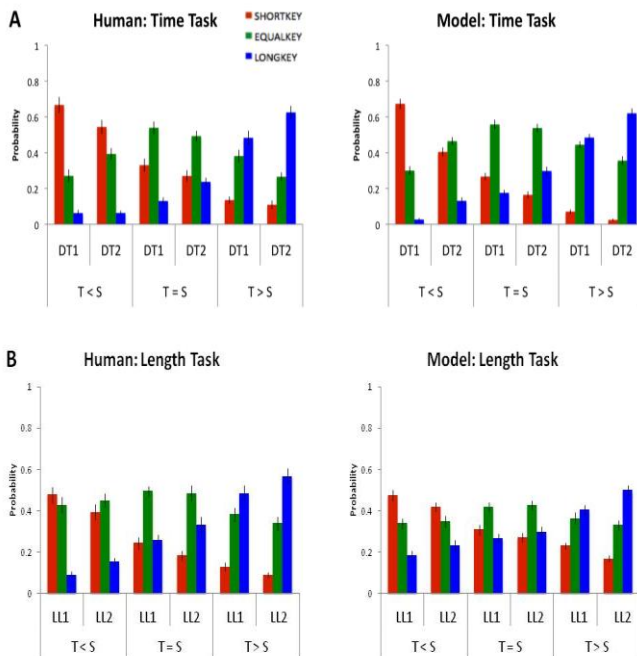


Figure 2: Probabilities of response choice in time (A) and length (B) discrimination. Left: Participants. Right: Model.

The left panel of Figure 2 plots the probabilities of response choice (Short in red, Equal in green, and Long in blue bars) as a function of the delay-time (DT) in the time task and the line-length (LL) in the length task. In the time task (Figure 2A), the longer delay-time decreased correct responses in both  $T < S$  (red bars) and  $T = S$  trials (green bars). In addition, performance in the  $T = S$  trials indicated an increased tendency to judge that test is longer than study (decreased Short and increased Long) with the longer delay-time. In the  $T > S$  trials, the Long response increased with the longer delay-time. In the length task (Figure 2B), the

achieved through the processing in the temporal module (Taatgen, Van Rijn, & Anderson, 2007) and its interaction with the rest of the system. Based on the internal clock model (Matell & Meck, 2000), a pacemaker in the temporal module starts accumulating pulses in the temporal buffer once a start signal is given. The number of the accumulated pulses corresponds to the estimated time duration<sup>1</sup>.

### Blending Mechanism

Critical to our model is the blending mechanism (Lebiere, Gonzalez, & Martin, 2007) in declarative memory. The blending process has been used to model various kinds of magnitude judgments in both temporal (Moon & Anderson, 2013; Taatgen & Van Rijn, 2011) and non-temporal (Peebles & Jones, 2014) dimensions. Instead of retrieving a specific chunk, blending produces a weighted aggregation of all candidate chunks available in memory. Each candidate chunk is given a different weight based on how recently the chunk has been created and how closely it matches the current retrieval request.

Several models of magnitude estimation assume that a stimulus is represented with a category label selected on the basis of its similarity to the category prototype (Petrov & Anderson, 2005; Ward, 1979). Building on this notion, we assume that participants assign a label to each stimulus based on the similarities between the stimulus information and the prototypes of multiple rank-ordered categories. In our model, those prototypes are represented in reference chunks. The model has three reference chunks for duration (T1 through T3) and six for length (L1 through L6)<sup>2</sup>. Each of those reference chunks stores task information, label, and the associated stimulus information that increases with the label (e.g., T1: time task, label 1, & 12 pulses. T2: time task, label 2, & 15 pulses). For the delay stimulus, the model makes a binary judgment (“short” or “long”) and assigns one of the two extreme labels based on the estimated stimulus information (e.g., label 1 for the short delay-time and label 3 for the long delay-time). For the target stimulus, the model makes a more fine-grained judgment by retrieving a label.

Figure 3 illustrates the blending process for labeling the test duration. The model makes a blending request (A) specifying the task condition and the pulse value that

represents the estimated test duration. Upon the request, candidate chunks in the declarative memory (B) that meet the conditions are selected for blending. The task condition is strictly applied and only the “time” chunks can participate in the blending<sup>3</sup>. Those chunks include three reference chunks (T1 through T3) as well as chunks that store delay durations experienced over the trials: Delay-1 (not shown in Figure 3) through Delay-9. The partial matching process in ACT-R allows chunks with pulse value other than 15 to participate in the blending but with a penalty based on the match.

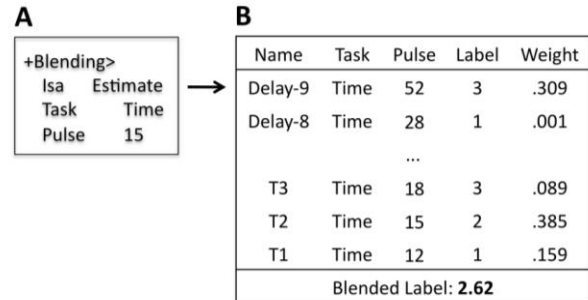


Figure 3: An example of blending in time discrimination.

The activation associated with each chunk reflects a combination of its recency, match with the request, and activation noise. The activation in turn determines the weight (Figure 3B) of the chunk and determines the degree to which the chunk contributes to the blending. For instance,

- Delay-9 chunk holds the estimation of the long delay in the current trial. It mismatches the pulse value but is most recent: Weight .309.
- Delay-8 chunk holds the estimation of the short delay in the last trial. It mismatches pulse value and is the second-most recent: Weight .001.
- T3 chunk holds the reference duration for label 3 and is close but not the perfect match: Weight .089.
- T2 chunk holds the reference duration for label 2 and is the perfect match: Weight .385.
- T1 chunk holds the reference duration for label 1 and is close but not the perfect match: Weight .159<sup>4</sup>.

Product of weight and label is computed for each chunk, and then aggregated over the chunks to give the label of 2.62. This label is greater than the best-matching label 2 due to the assimilative bias from the most recent long delay.

### Model of Discrimination Task

Figure 4 illustrates how the model performs time discrimination in a T = S trial. The model starts accumulating pulses in the temporal buffer whenever a stimulus appears and stops accumulation when it disappears.

<sup>3</sup> Assuming that participants attended to the instructed stimulus dimension, we restricted the candidate chunks to only those that match the task condition.

<sup>4</sup> Both T1 and T3 are 3 pulses away from the requested pulse value, but T1 gets a higher weight due to activation noise.

<sup>1</sup> The temporal module produces a logarithmic representation of time. The pulse length keeps increasing as time progresses. The following equations describe how the initial ( $t_0$ ) and the  $n$ th ( $t_n$ ) pulse lengths are computed:  $t_0 = \text{start} + \epsilon_1$ ,  $t_n = a * t_{n-1} + \epsilon_2$  (start: value of the time-master-start-increment parameter, a: value of the time-mult parameter, b: value of the time-noise parameter.  $\epsilon_1$ : noise generated with the act-r-noise command with an s (scale parameter of logistic distribution) of  $b * 5 * \text{start}$ ,  $\epsilon_2$ : noise generated with the act-r-noise command with an s of  $b * a * t_{n-1}$ ). We used the default parameter values (:time-master-start-increment .011 s, :time-mult 1.1, and :time-noise .015).

<sup>2</sup> The numbers of reference chunks were determined based on the stimulus range and the resolution sufficient for discrimination in each task.

After estimating the study duration, the model makes a blending request with 15 pulses (blue box). The blended study label 1.95 (green box) is close to 2 (white box) which is the best match with the requested pulse value. After estimating the long delay (52 pulses), the model assigns label 3 (red box). After estimating the test duration, the model makes another blending request with 15 pulses. Due to the assimilative (red arrow) bias from the most recent delay (label 3), the blended test label 2.62 (green box) is greater than the best-matching label of 2 (white box). The model rounds the study and test labels to the closest integers and makes a response based on the comparison ( $2 < 3$ : “Long”). The example shows that the longer delay can exert an assimilative bias and make the test look longer than the study (i.e., increased Long response in the  $T = S$  trials in Figure 2A). The model performs length discrimination in a similar manner using the estimated length information (in pixels) available in the vision module. Based on the same blending mechanism, the label for the grey line presented during the delay exerts an assimilative bias on the test label.

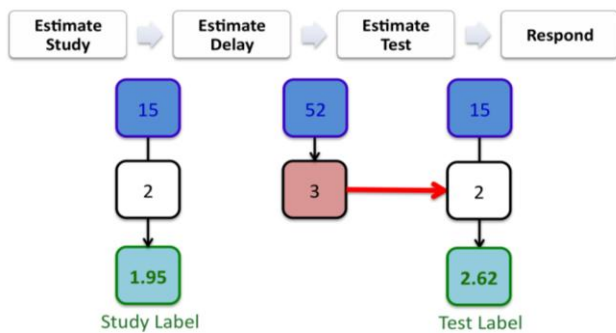


Figure 4: ACT-R model of time discrimination.

## Model Results

The right panel in Figure 2 plots the model results. In the time task (Figure 2A), the model performed worse with the longer delay-time in the  $T < S$  trials. The model somewhat overproduced the effect showing a greater reduction of the Short response than participants. In the  $T = S$  trials, the model decreased the Short response and increased the Long response with the longer delay-time. In the  $T > S$  trials, the model increased the Long response with the longer delay-time. In the length task (Figure 2B), the model captured performance decrease in the  $T < S$  trials and increase in the  $T > S$  trials with the longer line-length. In the  $T = S$  trials, the model also decreased the Short response and increased the Long response albeit to a weaker extent. Overall, the model captured the major effects of delay-time and line-length and exhibited the choose-short effect in both tasks. The correlations between the participants and the model were .94 in the time task and .95 in length task<sup>5</sup>.

<sup>5</sup> Adjusted model parameters: Retrieval threshold (:rt -10), latency factor (:lf .1 s), activation noise (:ans .35), imaginal-delay

## Discussion

The current study investigated whether temporal and non-temporal memory could be accounted for by the common principles. An experiment was designed based on the assumption that stimulus information attended during the delay could bias processing target stimulus information. We found that the length manipulation introduced during the delay could influence length discrimination performance in a manner parallel to the choose-short in time discrimination.

A computational model was developed based on the ACT-R blending mechanism. The model encoded and labeled stimulus information presented during the delay, which exerted an assimilative influence on the subsequent memory retrieval. Due to the push and pull factors of recency and match, the judgments based on the retrieved representations were overall close to the correct responses but biased towards the most recent stimulus information. The common blending mechanism accounted for the major behavioral patterns in time and length discrimination.

Our account for the choose-short effect is in accord with some accounts proposed for priming effects. In social psychology, priming a cognitive category (e.g., hostility) by unobtrusive exposure to exemplars of category increases the likelihood that a subsequent ambiguous stimulus (e.g., person who shows ambiguous behaviors) is judged as a member of the category (e.g., Higgins, Rholes, & Jones, 1977). According to category accessibility account (Herr, Sherman, & Fazio, 1983), a frequent or recent presentation of exemplars of a category increases the availability of the category and influences judgment on a new stimulus to assimilate to the category. In psychophysical judgments, response in the current trial tends to be positively correlated with the response in the previous trial. Petrov and Anderson (2005) accounted for this sequential assimilation effect based on the activation-mediated priming mechanism. Presentation of stimulus in the previous trial strengthens the activation of the associated category. Due to the residual activation, the current stimulus tends to be judged as a member of the previously strengthened category. Our model categorizes each stimulus by assigning a label, which is influenced by the relative availabilities of the categories (i.e., weights). Exposure to the long delay stimulus activates the long category and increases the likelihood that the target stimulus is judged as the long category.

The current study provides a new perspective on the choose-short effect, which has been traditionally framed as forgetting of temporal memory over time. Models in time estimation domain (e.g., Spetch & Wilkie, 1983) have

(0 s), :visual-onset-span (.01 s), and mismatch penalty (:mp 2.0). The :ans parameter was set at a level that matches overall performance level of participants. The :mp parameter was estimated to match the magnitude of the delay stimulus effect. Increasing :mp tends to weaken the delay stimulus effect because the chunks with delay stimulus information get weighed less (i.e., more heavily penalized) due to their worse match with blending request. The rest of the parameters were set to ensure that the model performs the task within the response deadline.

treated the choose-short effect as a case unique in the time dimension rather than seeking domain-general explanations. The current study redefined the choose-short effect as an interaction between two memory representations in the matching dimension. Based on this definition, the choose-short effect is not “a unique form of forgetting”, but is an instance of domain general memory effects. Our results argue against the uniqueness of temporal memory mechanisms and prompt further investigations of the choose-short effect outside the temporal domain.

By modeling the results in the domain-general ACT-R memory mechanism, we showed that the common principles could account for both temporal and non-temporal memory. The current approach is in the same vein as previous efforts (Brown et al., 2005; Taatgen & Van Rijn, 2011) on modeling temporal phenomena based on principles developed outside the temporal domain. We showed that principles that have accounted for non-temporal memory could successfully apply to accounting for temporal memory. In comparison with time estimation models developed within temporal domain, the current approach allows a rigorous comparison between temporal and non-temporal memory.

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