Foreperiod priming in temporal preparation:

Testing current models of sequential effects

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Abstract

Sequential foreperiod effects in temporal preparation are typically asymmetric such that a previous experience of preparation has a strong impact on participants' responses to a forthcoming target stimulus presented at the current short rather than at the current long foreperiod. The trace-conditioning model explains this asymmetry by an automatic process of trace-conditioning, which is sufficient and independent from a strategic process of conditional probability monitoring considered by the dual-process model.

The present study contrasted trace-conditioning and dual-process models in three experiments that employed a non-aging distribution to keep conditional probability of target occurrence constant across foreperiod durations. In Experiment 1 (no catch trials), the typical pattern of asymmetric sequential effects was replicated, whereas in Experiments 2 and 3 (25% and 50% of catch trials, respectively) the results showed shorter RTs when previous and current foreperiods were repeated rather than alternated for both current short and long foreperiods. These results are discussed in relation to the two most influential models of sequential effects and to a novel account based on repetition priming.

Keywords: attention; time; foreperiod; trace-conditioning; dual-process; non-aging distribution; catch trials.

1. Introduction

In our dynamic world, multiple events unfold over time yielding sequences that are continuously shaping our neurocognitive system. Sequential effects are a general phenomenon in cognition and are subject of research from different fields in relation to priming, task-switching and conflict adaptation among others (Cofer, 1967; Gratton, Coles, & Donchin, 1992; Jersild, 1927). The current study focuses on sequential effects in the time domain, that is, on the influence of sequences of different foreperiod durations upon temporal preparation.

Temporal preparation can be defined as the ability to initiate cognitive processing (either at perceptual, central or motor levels) in anticipation of the moment of occurrence of a relevant stimulus, which optimises the subsequent processing of such stimulus when it actually occurs. For example, if the moment of stimulus onset can be predicted, the reaction time (RT) to respond to that stimulus will be shorter as compared to unpredictable onsets. It is then assumed that high temporal preparation is underlying this RT benefit.

A simple procedure to study temporal preparation involves presenting a warning signal (e.g., a brief tone), a foreperiod and then a stimulus to which participants have to respond ("target"). The foreperiod is the time interval from the offset of the warning signal to the onset of the target and is the period in which preparation is assumed to take place.

Experimental designs in which different foreperiod durations are equally distributed ("rectangular or aging distribution") and randomly presented within a block of trials ("variable foreperiod design") typically lead to shorter RTs for long

vs. short foreperiods, i.e. "*the foreperiod effect*" (see Coull, 2009; Niemi & Näätänen, 1981, for reviews). In addition to foreperiod duration of the current trial, foreperiod duration of the preceding trial has also a strong influence on the RT function, i.e. "*sequential effects*" (e.g., Drazin, 1961; Los & Van den Heuvel, 2001; Steinborn, Rolke, Bratzke, & Ulrich, 2008; Vallesi & Shallice, 2007; Woodrow, 1914). In a variable foreperiod design, sequential effects are indexed by the interaction between current foreperiod duration (short, long) and previous foreperiod duration (short, long).

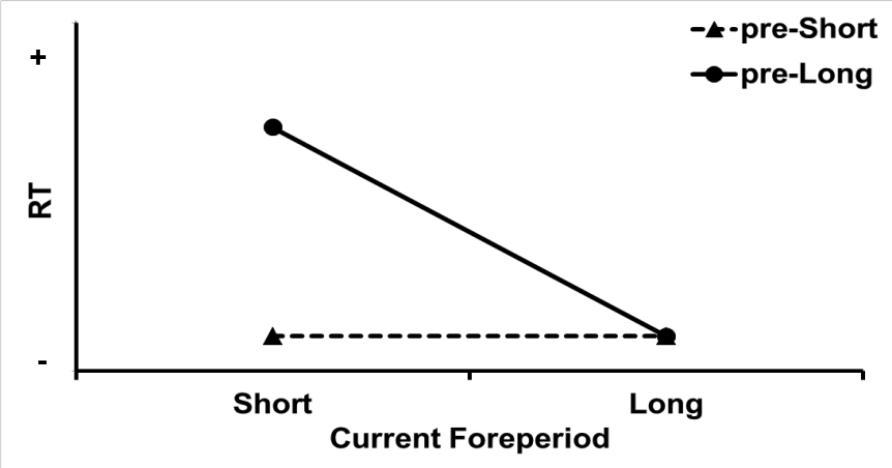
This interaction, as shown in Figure 1A, reflects that sequential effects are typically asymmetric, as the previous foreperiod duration exerts a stronger influence on RTs at the current short foreperiod as compared to the current long foreperiod. Specifically, on current short trials participants' responses are faster after repetition of a previous short as compared to alternation from a previous long foreperiod (i.e., short-short foreperiod sequences vs. long-short sequences). By contrast, on current long trials participants' responses are fast irrespective of whether the previous foreperiod duration has been short or long (i.e., short-long foreperiod sequences vs. long-long sequences).

Since their first report (Woodrow, 1914), sequential effects have been proven to be a robust finding in temporal preparation research. The two most influential models developed to explain such effects differ with regard to the mechanisms underlying them. According to Los' trace-conditioning account (Los & Van den Heuvel, 2001; see also Los, 1996; Los, Knol, & Boers, 2001), sequential effects would be the outcome of implicit learning rules operating across trials on the basis of trace-conditioning principles. On the alternative dual-process model proposed

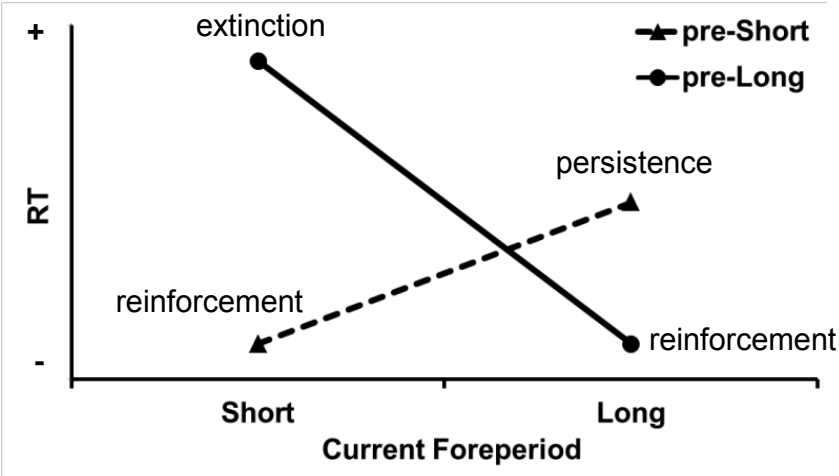
by Vallesi and colleagues (Vallesi, 2010; Vallesi & Shallice, 2007), sequential effects would be instead the product of both automatic arousal modulation from the previous trial and controlled monitoring processes at the current trial.

The main aim of the present study was to contrast these two, trace-conditioning and dual-process, models of sequential effects by means of a foreperiod distribution manipulation.

A. Asymmetric sequential effects: empirical data



B. Trace-conditioning model



C. Dual-process model

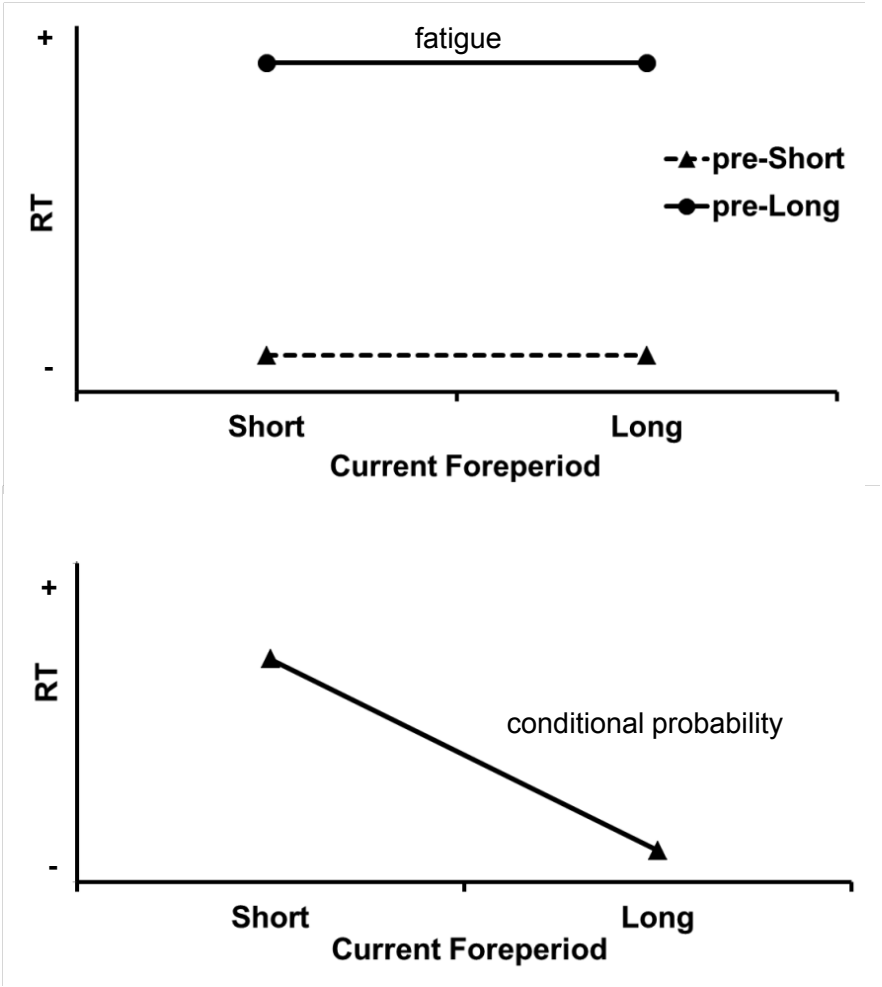


Figure 1. A: *The typical pattern of asymmetric sequential effects in a variable foreperiod paradigm following a rectangular or aging distribution of foreperiods. That is, the effect of the previous foreperiod is larger at the current short vs. long foreperiod. Panels* ***B and C*** *represent the predictions derived from the two most influential models explaining asymmetric sequential effects (please refer to the main text for further details).*

The key feature of the trace-conditioning account is the idea that the paired presentation of a warning signal and a target stimulus would elicit a state of automatic conditioning. The foreperiod would correspond to the blank interstimulus interval or memory trace that is needed to associate warning and target stimuli. The state of conditioning during the foreperiod would be regulated by three learning rules, namely, reinforcement, extinction and persistence. At the start of a given trial, each possible moment of target presentation would have an equal conditioned strength. As time goes by during the foreperiod, the conditioned strength associated with a possible moment is: 1) *reinforced* if the target actually occurs and is responded to; 2) *extinguished* if the moment is bypassed during the foreperiod; and 3) left *unchanged* if the moment occurs later than the actual target presentation (see Los & Van den Heuvel, 2001, page 372). It follows that high preparation (as revealed by shorter RTs) in the short-short foreperiod sequence would be due to reinforcement of the conditioned strength associated with the short foreperiod. As represented in Figure 1B, the current short foreperiod benefits from *reinforcement* since it was presented and responded to in the previous trial. In contrast, low preparation (as revealed by longer RTs) in the long-short foreperiod sequence would be due to *extinction* of the conditioned strength associated with the short foreperiod since it was bypassed in the previous trial by a longer foreperiod.

Unlike the trace-conditioning model, the dual-process model attributes relatively longer RTs in long-short foreperiod sequences vs. short-short sequences to reduced arousal (or readiness to respond). Assuming that maintaining a heightened preparatory state is effortful and energy consuming (Gottsdanker, 1975), the model surmises that a previous long foreperiod would decrease

participants' arousal thus lengthening RT. By contrast, a previous short foreperiod would increase the level of arousal thus speeding up RT. Accordingly, as shown in Figure 1C (top), RTs would be longer when the previous foreperiod has been long rather than short, since at the current foreperiod participants are still fatigued from having prepared for a longer period of time in the previous trial.

Given that sequential effects have been mainly observed at the current short foreperiod, it is not surprising that prior studies have focused on determining the source of this RT difference between previous long and previous short foreperiod at the current short foreperiod rather than on explaining why sequential effects would be absent or reduced at the current long foreperiod. Note, indeed, that trace-conditioning and dual-process models share similar behavioural predictions for sequential effects at the current short foreperiod, which precludes a straightforward comparison between such models on the basis of purely behavioural data. Another point of convergence between these models is that they both attribute sequential effects at the current short foreperiod to automatic processing (based on either conditioning or arousal mechanisms, respectively).

The attenuation of sequential effects at the current long foreperiod is hence an appropriate element to contrast the two models, as they clearly diverge in explaining the source of sequential effects asymmetry. Whereas the trace-conditioning model relies on a single automatic process of trace-conditioning governed by three learning rules, the dual-process model considers the influence of an additional controlled process (i.e., the conditional probability monitoring) on the automatic arousal process.

In brief, the trace-conditioning model ascribes attenuated sequential effects at the long foreperiod to the absence of extinction, as the long foreperiod is never bypassed by an even longer foreperiod. According to the third rule of the model, the conditioned strength associated with a current long foreperiod, in case a previous short foreperiod occurred, remains unchanged (*persistence, see* Figure 1B) as it was neither reinforced nor extinguished in the previous trial. Note that the long foreperiod still gets reinforcement after a previous long foreperiod, so that it would make sense to expect sequential effects also at the current long foreperiod (but see Los, Knol, & Boers, 2001, page 140, for a discussion on this issue). In any case, it is worth noting that in the trace-conditioning model the size of sequential effects at the current long foreperiod has received little attention compared to the current short foreperiod, as it is supposed to be always smaller at long rather than short foreperiods for the differential involvement of extinction in the two time intervals. That is, sequential effects would be asymmetric because preparing for the current short foreperiod leads to larger RT difference (RT-cost by extinction in the long-short foreperiod sequence vs. RT-benefit by reinforcement in the short-short sequence) than preparing for the long foreperiod (RT-baseline by persistence in the short-long foreperiod sequence vs. RT-benefit by reinforcement in the long-long sequence).

The dual-process model ascribes attenuated sequential effects at the current long foreperiod to the fact that, in a variable foreperiod design, conditional probability for target onset at the long foreperiod is always equal to 1 irrespective of the previous foreperiod duration. That is, as time goes by without target presentation, the participant's preparatory state would increase as a function of the passage of time itself (e.g., Elithorn & Lawrence, 1955). As shown in Figure 1C (bottom), this

full certainty would lead to high preparation (short RTs) for the long foreperiod, which might compensate for fatigue (long RTs) from a previous less arousing long foreperiod (i.e., long-long sequence). By combining arousal and likelihood-monitoring processes, this model accounts for the typical pattern of asymmetric sequential effects shown in Figure 1A. Neural and developmental data by Vallesi and colleagues have consistently supported the key role of the monitoring process in the asymmetry of sequential effects. For example, sequential effects become symmetric (i.e., longer RTs for long-long foreperiod sequences vs. short-long sequences) when the monitoring process is impaired either by applying transcranial magnetic stimulation (TMS) to the right dorsolateral prefrontal cortex (Vallesi, Shallice, & Walsh, 2007) or by insufficient pre-frontal maturation in young children of 4-5 years of age (Vallesi & Shallice, 2007).

Building upon these theoretical differences between the two models, we reasoned that experimental manipulations of the processes underlying conditional probability monitoring at the long foreperiod could be critical to contrast the two accounts since the dual-process, but not the trace-conditioning, model would predict a stronger influence of such controlled factor on the asymmetry of sequential effects. In this vein, a straightforward procedure is to manipulate the distribution of foreperiod durations in order to hold conditional probability constant over the course of the foreperiod ("non-aging distribution").

In the present study, we thus used a non-aging distribution to contrast the two main models of sequential effects on the basis of the following predictions:

If the dual-process model correctly accounts for sequential effects, they should be symmetric in a non-aging distribution. Namely, a non-aging distribution should

prevent the compensatory effect of increasing conditional probability, so that only the arousal/fatigue process would be available to produce sequential effects. Top Figure 1C represents the specific prediction of the model: we should find a main effect of previous foreperiod duration but not a previous foreperiod by current foreperiod interaction. This means longer RTs for both long-short and long-long foreperiod sequences (due to fatigue from a previous long interval) as compared to short-short and short-long sequences (due to arousal from a previous short interval). If the trace-conditioning model correctly accounts for sequential effects, they should be still asymmetric in a non-aging distribution since in the model the current long foreperiod would be either reinforced or left unchanged but not extinguished. Accordingly, as represented in Figure 1B, we should find a significant interaction between previous foreperiod and current foreperiod, such that the size of the RT difference between previous short and previous long foreperiod should be null (or smaller) at the current long as compared to the current short foreperiod.

2. Experiment 1

In Experiment 1, we used a non-aging distribution to contrast trace-conditioning and dual-process models of sequential effects. A non-aging foreperiod distribution was implemented by manipulating the proportion of short and long foreperiods such that, on any given trial, a short foreperiod was twice as likely to occur as a long foreperiod.

2.1. Method

2.1.1. Participants

Eleven undergraduates psychology students (6 males, all right-handed, age range: 19–37 years, mean: 22.6 years, SD: 6.1 years) from the University of Bangor took part in Experiment 1. All the participants had normal or corrected-to-normal vision, gave informed consent under a research protocol approved by the School of Psychology Ethics Committee, and all received £6 for their time and effort.

2.1.2. Stimuli and Procedure

The E-prime software was used to control the experiment (Schneider, Eschman, & Zuccolotto, 2002). All the stimuli were visual and presented at the centre of the computer screen against a black background. Participants were seated at a viewing distance of about 60 cm and performed a simple-RT detection task. They were instructed to respond as quickly as possible to the target onset by pressing the "b" key on the computer keyboard with the index finger of their preferred hand. A trial began with the fixation point (a dark gray square, 0.25º x 0.25º of visual angle) presented for a random interval ranging between 500 and 1500 ms. The warning signal (a red rectangle, 0.38º x 0.95º) was then displayed for 50 ms. Next, the screen remained blank for a variable delay of 350 or 1350 ms depending on the foreperiod condition (short or long) for that trial. The target (the letter 'O' presented in white, bold Arial font size: 18, 0.38º x 0.76º) was displayed for 100 ms and was then replaced by a blank screen until the participant made a response or for a maximum duration of 2000 ms. A final pause of 500 ms, which was used to

present feedback, preceded the next trial. Feedback was displayed in red throughout the experiment to inform participants in the following cases: if they accidentally pressed a response key different from the "b" key ("wrong key"), if a premature response was given before target onset ("wait!") and if no response was made within the deadline ("no response detected"). Feedback was displayed in green for 1000 ms on practice trials only to inform participants about RT detection performance. The experiment included one practice block of 15 trials, which could be repeated if participants wished to further familiarize themselves with the task, and 15 experimental blocks of 33 trials each. Each block of trials included 22 short foreperiods and 11 long foreperiods.

2.1.3. Design and data analysis

Practice trials, the first trial of each block, trials with premature responses (i.e., responses before target onset) and trials without responses were not analysed. RTs within each condition were normally distributed (Shapiro-Wilk test, *p*s>.1). The RT analysis included mean correct RTs between 100 and 1000 ms (5% of rejected trials in total), which were submitted to a repeated-measures analysis of variance (ANOVA) with Previous Foreperiod (short, long) and Current Foreperiod (short, long) as within-participants factors. Significant interactions were analysed by planned comparisons. Descriptive statistics are presented in Table 1.

Table 1. *Mean reaction times, with standard deviation in parentheses, for the three experiments as a function of previous foreperiod (short, long) and current foreperiod (short, long) for Experiment 1, and of previous foreperiod (catch, short, long) and current foreperiod (short, long) for Experiments 2 and 3.*

	Experiment 1		**Experiment 2**		**Experiment 3**	
Previous Foreperiod	*Current Foreperiod*					
	Short	Long	Short	Long	Short	Long
Catch	–	–	294 (28)	376 (36)	293 (34)	399 (44)
Short	260 (35)	282 (35)	276 (31)	369 (57)	284 (27)	393 (42)
Long	286 (45)	289 (45)	297 (33)	345 (34)	297 (29)	379 (38)

2.2. Results

The analysis showed a significant main effect of Current Foreperiod, $F(1,10)=5.18$, $p=.046$, partial $\eta^2=.3$, which followed the opposite direction to the typical foreperiod effect in designs under an aging distribution. That is, RTs were longer for the current long foreperiod as compared to the current short foreperiod. There was also a significant main effect of Previous Foreperiod, $F(1,10)=17.31$, $p=.002$, partial $\eta^2=.6$, with faster responses following a previous short foreperiod than a previous long foreperiod. The interaction between Previous Foreperiod and Current Foreperiod was also significant, $F(1,10)=19.63$, $p=.001$, partial $\eta^2=.6$ (see Figure 2). Planned comparisons for this interaction showed the typical asymmetry

of sequential effects, with a significant effect of the previous foreperiod at the current short foreperiod but not at the current long foreperiod [$F(1,10)=28.002$, $p<.001$, and $F(1,10)=2.89$, $p=.1$, for the current short and the current long foreperiod, respectively].

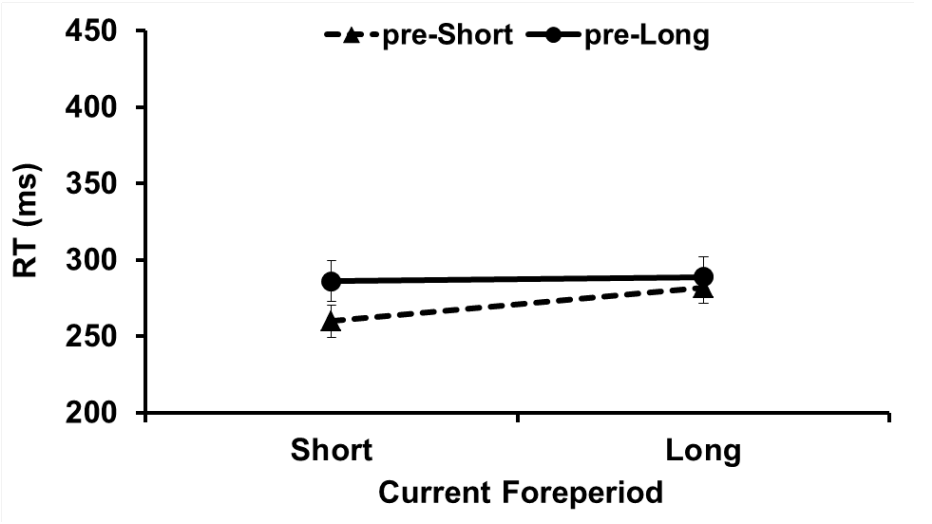


Figure 2. *Mean reaction time (RT) in Experiment 1 as a function of previous foreperiod (400-ms short, 1400-ms long) and current foreperiod (400-ms short, 1400-ms long). Vertical bars represent standard errors of the mean.*

2.3. Discussion

The results of Experiment 1 replicated the typical pattern of data under a non-aging distribution, with faster responses at the short rather than at the long foreperiod (e.g., Trillenberg, Verleger, Wascher, Wauschkuhn, & Wessel, 2000). It is likely that the high probability of target onsets at the short foreperiod would

have induced an early participants' expectancy leading to faster responses at the short foreperiod as compared to the less probable long foreperiod (e.g., Zahn & Rosenthal, 1966; Los & Agter, 2005). More important for our goal, the asymmetry of sequential effects was replicated in this experiment. That is, participants' responses at the current long foreperiod were not influenced by the foreperiod duration that was used in the previous trial. Such a pattern of data is not compatible with the predictions of the dual-process model. In contrast, our data are in agreement with Los' model stating that the long foreperiod either receives reinforcement, in case of a previous long foreperiod, or persistence, in case of a previous short foreperiod, but not extinction.

We reasoned that the introduction of a non-aging distribution should discourage the monitoring process such that symmetric sequential effects would be observed, with faster responses for short-long foreperiod sequences vs. long-long sequences. Accordingly, on the basis of the present results it would make sense to conclude that only the trace-conditioning, but not the dual-process model, could explain the pattern of asymmetric sequential effects observed in our experiment. However, one might argue that since our design did not include catch trials, participants were still able to monitor the passage of time even when conditional probability remained constant using a non-aging distribution. That is, although participants were fully able to prepare for the most frequent short foreperiod, which caused a reversed foreperiod effect, this ultimately would have not interfered with preparation to the long foreperiod. Once the target did not appear at the expected short foreperiod, it surely had to appear at the long foreperiod. This certainty might have counteracted the negative effects on RTs of a long-long foreperiod sequence.

Earlier research has shown that the introduction of a small proportion of trials in which the target is not presented, i.e., catch trials, can be a more powerful manipulation to reduce the objective probability of target occurrence over the course of the foreperiod (see Näätänen, 1972; Correa, Lupiáñez, Milliken, & Tudela, 2004; Sanabria, Capizzi, & Correa, 2011; Steinborn, Rolke, Bratzke, & Ulrich, 2008). Catch trials effectively decrease the probability of target onset so that, as time goes by without target presentation, there is no need keeping track the passage of time since it is not assured that the target is going to occur. It follows that the process of conditional probability monitoring is no longer relevant as a consequence of the loss of participants' expectancy. Evidence in support of this claim comes from the finding of a general RT increase at the current long foreperiod when catch trials are intermixed along the block (e.g., Sanabria, Capizzi, & Correa, 2011; Steinborn, Rolke, Bratzke, & Ulrich, 2008).

Building upon the above studies, in Experiment 2 we kept a non-aging distribution, like in Experiment 1, but we included 25% of catch trials. By adding temporal uncertainty through catch trials, we aimed at discouraging the conditional probability monitoring at the long foreperiod.

To our knowledge, only a previous study by Los and Agter (2005) employed a non-aging distribution with catch trials to investigate sequential effects in a variable foreperiod paradigm. However, this was done for a different purpose than that of the present study. Indeed, the authors were interested in addressing the question as to whether the effects of different foreperiod distributions (i.e., aging, non-aging and peaked) might be accounted for by automatic trace-conditioning principles alone or also by strategic temporal preparation (see below for further details). To

this end, participants were presented with three foreperiod durations (300, 600, 1200 or catch trials) that were divided into three foreperiod distributions (uniform or aging, exponential or non-aging and peaked) according to the following ratio of trials occurrence (uniform: 1:1:1:1, exponential: 4:2:1:1, peaked: 1:5:1:1). Through a mathematical procedure of reweighting, which consisted in "equating the relative contribution of specific intertrial transitions" (page 1167) for the three types of distributions, the authors concluded that trace-conditioning principles would be restricted to the uniform (or aging) foreperiod distribution. An additional strategic mechanism of attentional orienting would instead come into play, overruling trace-conditioning principles, when some particular foreperiod durations would be more often presented than others. For example, in a positive skewed foreperiod distribution, the frequent presentation of the short foreperiod would tune participants' responses to the most probable early target onset thus enhancing preparation to the shortest interval. Regarding the (less frequent) long foreperiod in a non-aging distribution, Los and Agter (2005) found RTs to be shortened when the previous foreperiod had also been long. Such a pattern of data was attributed to the effects of catch trials. According to Los' model (see also Los, 2010), a catch trial should be conceived as a trial with a longer foreperiod. Therefore, in a design with catch trials the conditioned strength associated with the long foreperiod can also be extinguished, and not only left unchanged, if bypassed by an extra-long (catch) trial during the foreperiod. This could explain the advantage observed in Los and Agter's (2005) study for the long-long foreperiod sequence, as the previous long foreperiod benefitted greatly from reinforcement when catch trials were interspersed along the block.

To sum up, as for Experiment 1, the dual-process model would predict sequential effects to be symmetric in a non-aging distribution with catch trials due to the discouragement of the monitoring process by catch trials. The trace-conditioning model would instead predict to replicate an asymmetric pattern of sequential effects. However, according to what was previously reported by Los and Agter (2005) in the context of a non-aging distribution with catch trials, RTs at the current long foreperiod should be shortened when the previous foreperiod had also been long.

3. Experiment 2

Experiment 2 was similar to Experiment 1 except for the inclusion of a proportion (i.e., 25%) of catch trials in which the target was not presented.

3.1. Method

3.1.1. Participants

Ten new undergraduate psychology students (4 males, age range: 20-31 years, mean: 22.7 years, SD: 3.6 years) from the University of Bangor participated in Experiment 2 in exchange for cash payment of £6. All but two participants were right-handed.

3.1.2. Stimuli and Procedure

The stimuli and procedure were the same as those used in Experiment 1 except for the inclusion of catch trials. Participants were instructed to respond as quickly as possible to the target and to avoid responding when no target was presented. The experiment included one practice block of 16 trials and 15 experimental blocks of 32 trials each. According to the presence of catch trials (i.e., 25%), each block of trials included 16 short foreperiods, 8 long foreperiods and 8 catch trials.

3.1.3. Design and data analysis

Like in Experiment 1, practice trials, the first trial of each block, trials with premature responses (i.e., responses before target onset), trials without responses and trials with responses to catch trials were not analysed. RTs within each condition were normally distributed (Shapiro-Wilk test, *p*s>.1). The RT analysis included mean correct RTs between 100 and 1000 ms (3.6% of rejected trials in total), which were submitted to a repeated-measures ANOVA with Previous Foreperiod (short, long) and Current Foreperiod (short, long) as within-participants factors. Since the inclusion of catch trials as a third level of the Previous Foreperiod factor provided similar results, only data from the simple ANOVA are reported here (see Table 1 and Figure 3 for detailed data on previous catch trials condition).

3.2. Results

Participants' responses were faster at the current short foreperiod than at the current long foreperiod, which led to a significant main effect of Current Foreperiod, $F(1,9)=72.81$, $p<.001$, partial $\eta^2=.8$ .The interaction between Previous Foreperiod and Current Foreperiod was also significant, $F(1,9)=18.14$, $p=.002$, partial $\eta^2=.6$ (see Figure 3).

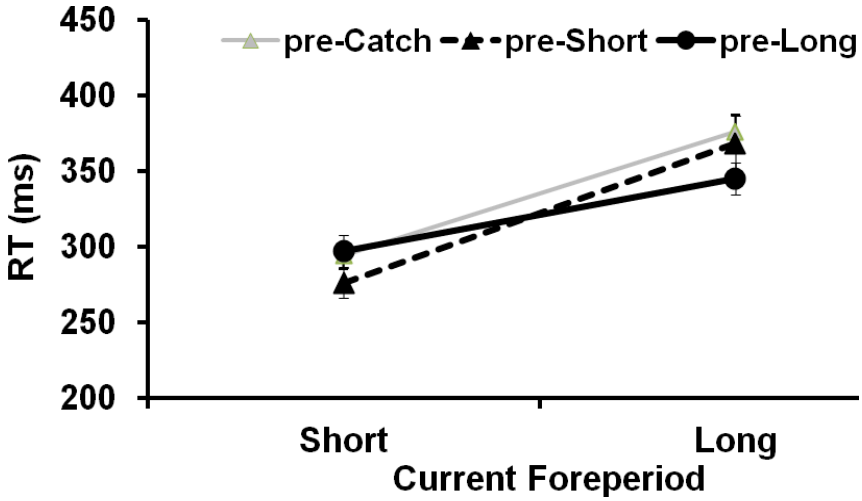


Figure 3. *Mean reaction time (RT) in Experiment 2 as a function of previous foreperiod (catch, 400-ms short, 1400-ms long) and current foreperiod (400-ms short, 1400-ms long). Vertical bars represent standard errors of the mean. RTs were shorter when durations of previous and current foreperiods were repeated rather than alternated. This repetition effect was of similar size in both current foreperiods.*

Planned comparisons for this interaction replicated the typical pattern of sequential effects at the current short foreperiod, $F(1,9)=20.39$, $p=.001$, with

shorter RTs when the previous foreperiod was short rather than long. More relevant, the inverse pattern was found at the current long foreperiod. That is, there was a significant effect of the previous foreperiod at the current long foreperiod, $F(1,9)=5.63$, $p=.04$, with shorter RTs for the current long foreperiod preceded by another long rather than short foreperiod.

In order to elucidate whether the current foreperiod by previous foreperiod interaction was due to opposite trends or to different effect sizes, we computed the sizes of sequential effects for both the current short foreperiod (RT-previous long minus RT-previous short) and the current long foreperiod (RT-previous short minus RT-previous long), and submitted them to a simple ANOVA with Current Foreperiod as factor. The results of this analysis were not significant (respectively 21 ms vs. 24 ms: $F<1$).

3.3. Discussion

The results of Experiment 2 showed that our manipulation of conditional probability by the introduction of catch trials was effective as participants' responses were lengthened at the current long foreperiod. More relevant, this manipulation led to significant sequential effects at the current long foreperiod with shorter RTs for long-long foreperiod sequences vs. short-long sequences. This finding does not support the dual-process model, which would predict the opposite pattern: longer RTs for the long-long foreperiod sequence as compared to the short-long sequence due to fatigue after having prepared in the previous trial for an exhausting long foreperiod.

Furthermore, we found sequential effects to be of similar size for both current short and long foreperiods. Although it might be argued that our sample was too small to capture potential differences between the sizes of sequential effects, if any, the trend pointed towards smaller effects at short vs. long foreperiods (RT difference between previous long and previous short foreperiod at the current short foreperiod: 21 ms, and RT difference between previous short and previous long foreperiod at the current long foreperiod 24 ms). This finding thus replicates Los and Agter's (2005) study, which also reported larger RT difference at the long foreperiod (16 ms) as compared to the short foreperiod (8 ms).

In order to strengthen the findings of Experiment 2, in Experiment 3 we increased the proportion of catch trials from 25% to 50%. This allowed another test of the influence of catch trials on sequential effects.

4. Experiment 3

Experiment 3 was similar to Experiment 2 except that the proportion of catch trials was increased from 25% to 50%.

4.1. Method

4.1.1. Participants

Fourteen new undergraduate psychology students (three males, all right-handed, age range: 22-36 years, mean: 25.1 years, SD: 4.2 years) from the University of Bangor participated in Experiment 3 in exchange for cash payment of £6.

4.1.2. Stimuli and Procedure

The stimuli and procedure were the same as those used in Experiment 2. Participants were presented with one practice block of 24 trials and 15 experimental blocks of 48 trials each. Experimental trials were distributed according to the following foreperiod durations: 16 short foreperiods, 8 long foreperiods and 24 catch trials.

4.1.3. Design and data analysis

Practice trials, the first trial of each block, trials with premature responses (i.e., responses before target onset), trials without responses and trials with responses to catch trials were not analysed. RTs within each condition were normally distributed (Shapiro-Wilk test, *ps*>.6). The RT analysis included mean correct RTs between 100 and 1000 ms (1.8% of rejected trials in total), which were submitted to a repeated-measures ANOVA with Previous Foreperiod (short, long) and Current Foreperiod (short, long) as within-participants factors (see Table 1 and Figure 4 for detailed data on previous catch trials condition).

4.2. Results

The results replicated a significant main effect of Current Foreperiod, $F(1,13)=161.12$, $p<.0001$, partial $\eta^2=.9$, and a significant Previous Foreperiod by

Current Foreperiod interaction, $F(1,13)=34.18$, $p<.0001$, partial $\eta^2=.7$ (see Figure 4).

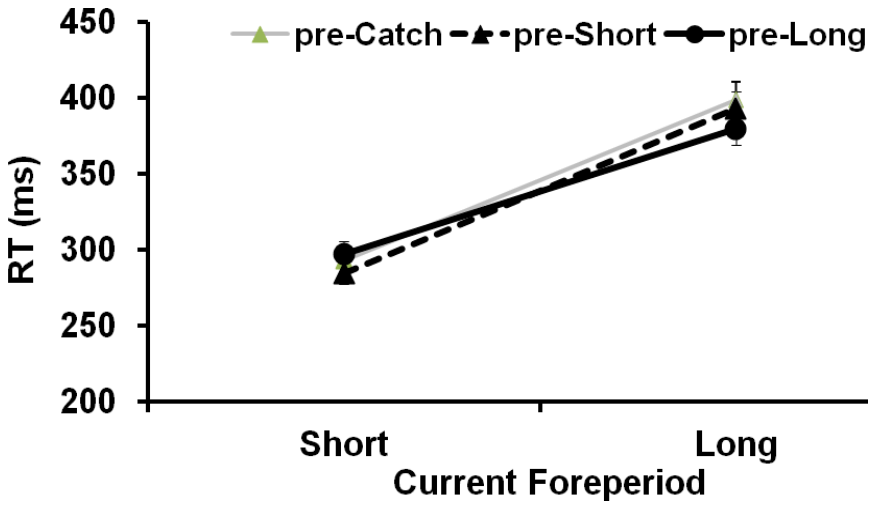


Figure 4. *Mean reaction time (RT) in Experiment 3 as a function of previous foreperiod (catch, 400-ms short, 1400-ms long) and current foreperiod (400-ms short, 1400-ms long). Vertical bars represent standard errors of the mean. RTs were shorter when durations of previous and current foreperiods were repeated rather than alternated. This repetition effect was of similar size in both current foreperiods.*

Planned comparisons for this interaction showed sequential effects for both the current short foreperiod, $F(1,13)=57.001$, $p<.001$, with shorter RTs when the previous foreperiod had been short rather than long, and for the current long foreperiod, $F(1,13)=9.63$, $p=.008$, with shorter RTs when the previous foreperiod had also been long rather than short. As in Experiment 2, we computed the sizes of sequential effects for both the current short (RT-previous long minus RT-previous short) and the current long foreperiod (RT-previous short minus RT-previous long), and submitted them to a simple ANOVA with Current Foreperiod as factor.

The results of this analysis did not reach statistical significance (respectively 13 ms vs. 14 ms: $F < 1$).

4.3. Discussion

Experiment 3 replicated the main findings of Experiment 2 with significant sequential effects at both current short and long foreperiods. Taken together, these results contradict the dual-process model, which would predict symmetric sequential effects. Rather, they lend support to the trace-conditioning model which also reported sequential effects at the long foreperiod when catch trials were intermixed along the block. On Los' view, the introduction of catch trials would have favoured reinforcement of the previous long foreperiod, which could have speeded up participants' responses in the case of a long-long sequence as compared to a short-long sequence (Los & Agter, 2005).

However, an alternative explanation to account for sequential effects at the long foreperiod may be related to the loss of participants' expectation of target onset. Namely, the fact that catch trials influence preparation by inducing uncertainty about target occurrence (Näätänen, 1972) might have contributed to the emergence of sequential effects (faster responses for repeated rather than for alternated foreperiod durations) at the current long foreperiod. Support for this hypothesis comes from a prior temporal orienting study by Correa and colleagues (2006), who also reported significant sequential effects at the long foreperiod in a group including 12.5% of catch trials. The discouragement of the strategic process underlying conditional probability monitoring by catch trials in non-aging

distributions could thus explain why sequential effects do not occur at the long foreperiod in aging distributions. Aging distributions lead to a strong foreperiod effect that may obscure the expression of sequential effects at the long foreperiod, whereas non-aging distributions with catch trials may reveal *pure* sequential effects similarly for both current short and long foreperiod durations (i.e., short-short and long-long RT benefits).

5. General discussion

A basic finding in temporal preparation research is that sequential effects are typically asymmetric, such that a previous experience of preparation has a strong impact on the subsequent preparation for a short but not for a long foreperiod. The aim of the present study was to understand the source of this asymmetry and to contrast trace-conditioning and dual-process models of sequential effects.

The key question concerned whether the use of a non-aging distribution, with or without catch trials, might alter the asymmetry of sequential effects. The dual-process model would predict symmetric sequential effects under non-aging distributions, as preparation guided by conditional probability monitoring should be prevented by the non-aging distribution and the arousal process would be the only determinant of sequential effects. By contrast, the trace-conditioning model would predict sequential effects only at the current short foreperiod in the context of a manipulation without catch trials (persistence vs. reinforcement of the long foreperiod) and significant sequential effects at the current long foreperiod in the presence of catch trials (extinction vs. reinforcement of the long foreperiod due to

the effects of extra-long catch trials). Overall, the results of our study challenged the dual-process model lending support to the trace-conditioning model. According to the former, RTs should be speeded-up for the short-long foreperiod sequence vs. the long-long sequence once the process of conditional probability monitoring was controlled for by the inclusion of catch trials. On the contrary, Experiments 2 and 3 showed participants' responses to be faster for a long-long foreperiod sequence than for a short-long sequence.

What then is the cause of the RT benefit observed for repeated vs. alternated foreperiods at the current long foreperiod? Los' model explains it in terms of conditioning by assuming that catch trials would behave as extra-long trials thus enabling the conditioned strength associated with a long foreperiod to be either reinforced (if a previous long foreperiod has been responded to) or extinguished (if the current long foreperiod has been bypassed by a preceding catch trial). Although plausible, however, Los and Agter' s (2005) results further imply the possibility that trace-conditioning principles may be overruled by strategic temporal preparation when the foreperiod distribution deviates from an aging function (see also Los, 2010). On this view, it is possible that the finding of sequential effects at the current long foreperiod may be due to the influence of catch trials on temporal preparation. Catch trials impair strategic preparation at the long foreperiod by changing the conditional probability function and decreasing participants' certainty about target occurrence at the long foreperiod (Correa et al., 2004). The use of catch trials would hence favour the emergence of sequential effects also at the current long foreperiod.

This idea is bolstered by prior studies that successfully used catch trials to unveil other temporal preparation phenomena at long intervals, otherwise hidden by the presence of a strong foreperiod effect. For example, a similar logic as in the present study was previously followed in temporal-orienting research to explain why predictive temporal cues were mainly effective at short foreperiods (Coull & Nobre, 1998). In several experiments, we have found temporal-orienting effects (i.e., RT benefit by valid temporal cues as compared to invalid cues) to be significant at the long foreperiod only when catch trials were included (Correa, Lupiáñez, Milliken, & Tudela, 2004; Sanabria, Capizzi, & Correa, 2011). We argued that catch trials prevented the process of re-preparation or re-orienting (i.e., if the target did not appear early, it will surely appear later), which was hiding temporal-orienting effects at the long foreperiod. In other words, a very similar design with catch trials was powerful in revealing temporal-orienting effects at the long foreperiod. Along the same line, in another study we showed that temporal preparation driven by regular presentation of auditory rhythms reached significance at the long foreperiod only when catch trials introduced temporal uncertainty about target onset (Sanabria, Capizzi, & Correa, 2011; Experiment 3).

Taking the above evidence into account, we thus propose that the development of strong expectations about the appearance of the target in aging distributions of foreperiods can prevent sequential effects from occurring at the current long foreperiod. Support for this claim comes also from a recent study by Steinborn and Langner (2011), who reported shorter RTs for long-long foreperiod sequences when introducing auditory distraction during the foreperiod (Experiments 3 and 4). In line with our working hypothesis, this study showed that impairing time-monitoring processes by distracting participants with an irrelevant sound over the

course of the foreperiod contributed to the development of sequential effects at the current long interval.

An additional argument for the idea that hindering participants' expectation of target onset during the task may influence the asymmetry of sequential effects is provided by a recent variable-foreperiod experiment (Los, 2013), in which target identity indicated either to execute a response (go condition) or to withhold it (no-go condition). Los' s (2013) study showed that the asymmetry of sequential effects was absent after a no-go trial, a result that was driven by longer RTs for foreperiod repetitions as compared to foreperiod alternations. The finding of a modified pattern of sequential effects following a no-go trial was interpreted within a new theoretical formulation of the trace-conditioning model, according to which extinction and reinforcement would be mediated by inhibitory and excitatory processes, respectively (see also Correa et al., 2010). Response inhibition would be in charge of preventing participants from releasing a premature response during the foreperiod and would thus lead to extinction. Response execution instead would reinforce the foreperiod duration in which the target is presented and responded to. Hence, the fact that a preceding no-go trial, which required strong response inhibition, nullified the asymmetry of sequential effects was interpreted by Los (2013) as evidence that inhibition (i.e., extinction) applied in the previous trial influenced performance on the current trial.

It should be noted that only using catch trials, as in our study, but not manipulating response requirements with no-go trials, as in Los' s (2013) study, favoured the emergence of sequential effects at the current long foreperiod. It makes sense to speculate that the different outcome between the two studies could be due to the

fact that, despite neither catch nor no-go trials required a response, only the latter relied on time-monitoring efficiency as the identity of the target (go or no-go) was unknown until its onset, whereas catch trials discouraged time-monitoring processes because of the low probability of target occurrence. Future studies should explore this suggestion by directly comparing the influence of catch trials and no-go requirements on temporal preparation processes.

To sum up, the results reported here, together with the evidence coming from the above-mentioned studies, lead us to suggest that our finding of similar sequential effects for both current short and long foreperiods in Experiments 2 and 3 could be explained in terms of repetition priming. Repetition priming of foreperiods implies that RTs are shorter when durations of previous and current foreperiods are repeated rather than alternated. We assume that in the absence of strategic temporal preparation processes, as is the case of our non-aging distribution with catch trials, the RT facilitation due to foreperiod repetition can be observed to a similar extent in both current short and current long foreperiods. However, this latter effect (i.e., shorter RTs for long-long repetitions as compared to short-long alternations) is rarely found in the literature probably because research on sequential effects mainly relies on the use of aging distributions of foreperiods.

Broadly consistent with this interpretation, Yashar and Lamy (2013) recently demonstrated that repetition priming is one of the mechanisms that give rise to sequential effects. The authors used a rapid serial visual presentation (RSVP) task, in which participants had to search for a target that was embedded within a visual stream of distractors. In order to contrast participants' expectation of target onset during the trial, Yashar and Lamy (2013) introduced a non-aging distribution of

the target temporal position with 33% of catch trials and found a temporal position priming (i.e., shorter RTs for repeated target positions) and a repetition priming (i.e., shorter RTs for repeated foreperiods) for both the short and the long target positions. That is, RTs at the current long foreperiod were speeded up when the previous foreperiod had also been long. On the basis of these results, Yashar and Lamy (2013) concluded that sequential effects "asymmetry results from an interaction between a "pure" sequential effect and effects of conditional probability" (page 12).

Extending Yashar and Lamy's (2013) results to a variable foreperiod paradigm, our study reinforces the idea that sequential effects would be similar to other intertrial priming effects. The proposal of repetition priming of foreperiods as the source of sequential effects is also compatible with the dynamic attending model developed by Jones and colleagues (Jones, Moynihan, MacKenzie, & Puente, 2002; Large & Jones, 1999), by which attention is conceived of as an endogenous oscillatory process that can be entrained by external rhythms. That is, an environmental sound with a fast regular pace can "entrain" our attentional rhythm to *expect* a relevant event to occur early, so that the focus of attention will be directed to an early point in time. Likewise, a sequence of short-short foreperiods could well be considered as a fast-pace rhythm entraining preparation for early target onsets, whereas a sequence of long-long foreperiods could constitute a slow-pace rhythm entraining preparation for late target onsets (see also Steinborn & Langner, 2012, Experiments 1 and 2, for a similar argument on entrainment of foreperiods based on the analysis of second order sequential effects).

Although the dynamic attending model was originally developed on research presenting a rhythm within a trial (but see also Ellis & Jones, 2010, for evidence on rhythmic patterns), it could be possible to extend the model to instances like sequential effects by thinking of them as rhythms across trials. This idea could be tested in future experiments comparing the effects of within-trial rhythms vs. sequential effects, with the aim of elucidating whether repetition priming of foreperiods and rhythmic entrainment are based on similar or dissociable mechanisms.

The proposal that repetition priming could be involved in sequential effects is also compatible with the finding that such effects are mediated by automatic processing and that automaticity and repetition priming would arise from a common underlying mechanism (Logan, 1990). In previous studies (Capizzi, Correa, & Sanabria, 2013; Capizzi, Sanabria, & Correa, 2012; see also Vallesi, Arbula, & Bernardis, 2014), we showed that sequential effects were not reduced by the addition of a concurrent secondary task, in line with the idea that performance based on automatic processing does not rely on attentional resources and is not hence diminished by extra processing demands (e.g., Logan, 1979). In the same vein, it is worth noting that temporal preparation guided by regular rhythms is also resistant to working memory interference (De la Rosa, Sanabria, Capizzi, & Correa, 2012), suggesting that both sequential effects and rhythmic patterns may induce temporal preparation automatically.

An interesting question is whether automaticity in sequential effects is the result of learning or trial-by-trial carry-over processes (Logan, 1990). Steinborn et al. (2009; 2010)'s studies support a learning-based mechanism by showing

attenuated sequential effects when the warning signal modality is shifted from one trial to another, in line with the reasoning that "successful retrieval of the previously encountered trial episode would depend on the similarity between stimuli (i.e., warning and target) in the encoding and the test situation" (Steinborn et al., 2009, page 41). On the other hand, sequential effects could be also due to some trial-by-trial carry-over mechanisms, as Vallesi, Lozano and Correa (2013) showed that increasing the inter-trial interval up to 20 sec reduced sequential effects, probably, by hampering carry-over mechanisms across subsequent trials. Vallesi (2007) has also shown that sequential effects do not follow a learning process across task blocks, but they are indeed present from the first block of trials. In sum, there is evidence of both learning-based and carry-over mechanisms in the expression of sequential effects. Determining the exact contribution and the functioning of the two mechanisms would be an interesting topic for future research.

To conclude, by manipulating conditional probability using a non-aging distribution with catch trials (Experiments 2 and 3), we have shown that temporal certainty about target onsets is relevant to explain the typical asymmetry of sequential effects. The finding of sequential effects of similar sizes in both foreperiods fits in well with the proposal of repetition priming of foreperiods (e.g., Yashar and Lamy, 2013). The current proposal can account for a variety of results in the literature about temporal preparation and it relates sequential effects to other intertrial priming effects.

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