REVISITING VARIABLE-FOREPERIOD EFFECTS: EVALUATING THE REPETITION PRIMING ACCOUNT

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ABSTRACT

A warning signal that precedes an imperative stimulus by a certain length of time (the foreperiod) can accelerate responses (foreperiod effect). Plotting reaction time (RT) as a function of foreperiod results in a "U"-shape curve when the foreperiod is fixed in a trial block but manipulated across blocks. When the foreperiod is varied within a block, the foreperiod-RT function is usually negative, with the foreperiod effect modulated by both the current foreperiod and the foreperiod in the prior trial (sequential foreperiod effect). This sequential effect was found to be robust at the shorter foreperiod while diminished at the longer foreperiod. Capizzi et al. (2015) used a non-aging foreperiod distribution and found an increasing foreperiod-RT function (consistent with that in a fixed-foreperiod paradigm) and a sequential effect equal for different foreperiods. They thus proposed a repetition priming account for the sequential foreperiod effect. I conducted three experiments, aiming to test this repetition priming account and to rebuild the connection between the fixed- and variable-foreperiod paradigms. Experiment 1 attempted to replicate Capizzi et al. in a choice-reaction task scenario and found an increasing foreperiod-RT function but a larger sequential effect at the shorter foreperiod. Experiment 2 examined the priming account in a short-foreperiod context and found a decreasing foreperiod-RT function with a larger sequential effect at the shorter foreperiod. Experiment 3 detected a larger sequential effect in general by increasing the difference in duration between the foreperiods that were used in Experiment 2. The current study provided converging evidence that with a non-aging foreperiod distribution the foreperiod-RT function in a variable-foreperiod paradigm shares the same direction as that in a fixed-foreperiod paradigm. However, instead of following Capizzi et al.'s account, the size of the sequential foreperiod effect in general was found to be modulated by the difference in duration between the foreperiods while the relative sizes were determined by the proportions of different foreperiods.

INTRODUCTION

In a simple- or choice-reaction task, when a warning signal always appears before onset of the imperative stimulus, participants are able to utilize the relation between them to get prepared before the imperative stimulus appears. If the former does not provide any information on how to respond to the latter, then the warning signal is usually called a neutral one. A neutral warning signal only provides temporal information, which is the timing of imperative-stimulus onset. This temporal relation between the warning signal and the imperative stimulus is marked by the foreperiod, the interval between the termination of the former and onset of the latter. Two basic paradigms have been used to study the foreperiod effect, which is how human performance, including reaction time (RT) and error percentage (EP), is modulated by foreperiod duration. In a fixed-foreperiod paradigm, the foreperiod is kept constant across trials within a trial block, whereas in a variable foreperiod paradigm, different foreperiods are randomly intermixed in each block. Researchers have found that in these two paradigms, the foreperiod modulates human performance in different ways.

The Family of Foreperiod Effects

In a fixed-foreperiod paradigm, plotting RT as a function of foreperiod leads to a "U"-shape curve (as in Figure 1). As foreperiod increases, RT first decreases, reaching its lowest point on the curve at about 250-ms foreperiod and then increases as the foreperiod gets even longer (see Niemi & Näätänen, 1981, for a review). The effect of a fixed foreperiod is believed to be determined by the ease of anticipating onset of the imperative stimulus with that interval (Niemi & Näätänen). Meanwhile, some research focusing on the decreasing side of the foreperiod-RT function argued that for short foreperiods (< 300 ms), the effect is closely related to phasic arousal (Posner et al., 1973; Tona et al., 2016). Although there is still debate about the mechanism behind this effect, researchers have considerable consensus about the "U"-shape foreperiod-RT function.

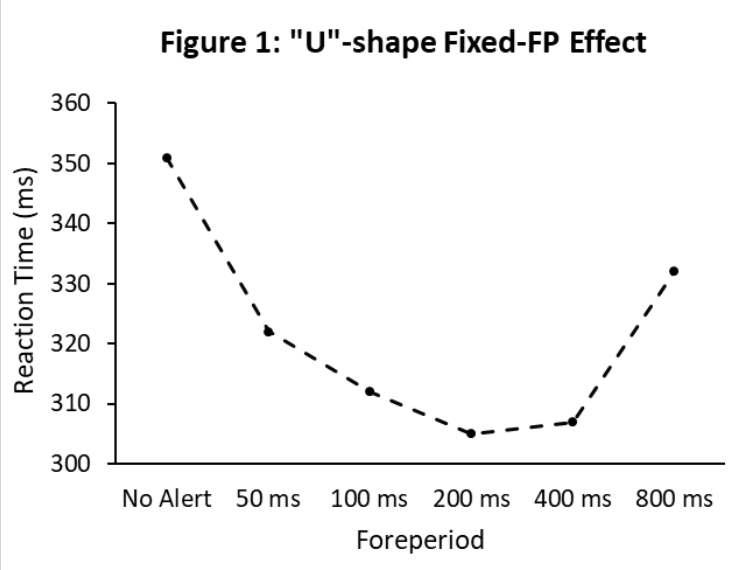

Figure 1. Posner et al. (1973): Reaction time (in ms) as a function of foreperiod condition for the spatially compatible mapping in Experiment 1.

In a variable-foreperiod paradigm, however, the situation is more complex. The fact that more than one foreperiod is involved increases the uncertainty that the participant faces. How different foreperiods are intermixed also matters. The most studied foreperiod distribution is the uniform distribution for which there are equal numbers of trials with each foreperiod in each block. In this case, when RT is plotted as a function of foreperiod, the slope is always negative, regardless of the lengths of the foreperiods. In other words, responses are always faster when the current foreperiod is the longest one in the distribution (Los et al, 2001; Niemi & Näätänen, 1981), which is the major difference between the fixed-foreperiod effect and the variable-foreperiod effect.

Moreover, when the foreperiod is varied across trials, RT is affected not only by the foreperiod of the current trial, but also by the foreperiod of previous trials, especially the immediately prior one, which is called the sequential foreperiod effect (SFP effect). When plotted as a function of both the current foreperiod and the preceding foreperiod, RT shows an asymmetry between short and long foreperiods (as in Figure 2). When the current foreperiod is short, responses are strongly delayed by a preceding long foreperiod. In contrast, when the current foreperiod is long, RT is not affected by the length of the previous foreperiod. This asymmetric pattern is typical among studies of the SFP effect (Los et al., 2001; Steinborn et al., 2008, 2009, 2010; Vallesi & Shallice, 2007).

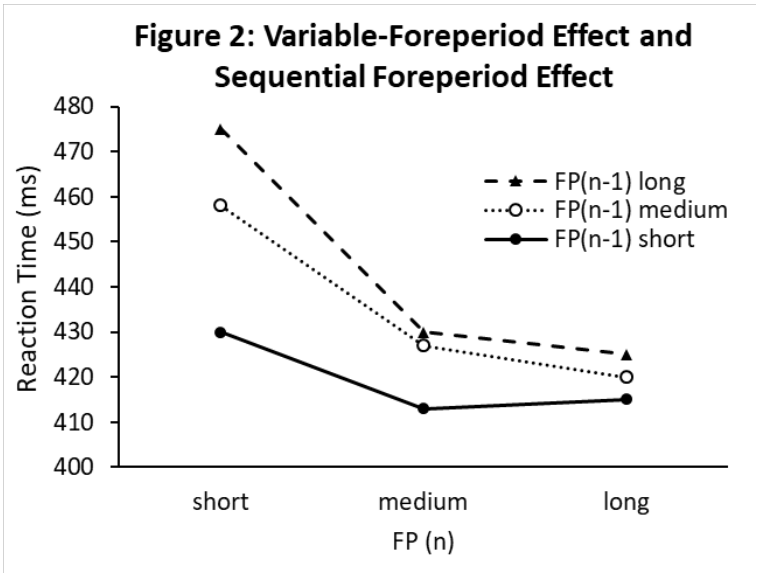

Figure 2. Steinborn et al. (2008): Reaction time (in ms) as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n) in Experiment 1 (long FP-set).

Prior Studies

Because both the variable-foreperiod effect and the SFP effect are observed in a variable-foreperiod paradigm, many researchers have attempted to investigate the connection between them instead of the link between the two foreperiod paradigms. In a typical variable-foreperiod paradigm, each foreperiod has a critical moment, which refers to its expected expiration, and each trial has an imperative moment, which refers to onset of the imperative stimulus. The number of critical moments in a trial depends on how many distinct foreperiods are intermixed within a trial block. At the start of a trial, because the foreperiod duration is uncertain, it is possible for each critical moment to become the imperative moment. However, as time passes after the end of the warning signal, if the imperative stimulus does not appear, the earlier critical moments will be bypassed and only the later ones are still possible to become the imperative moment. This relation between the critical moment and the imperative moment has been regarded as an important tool to explain the mechanism behind the SFP effect and the variable-foreperiod effect.

Niemi and Näätänen (1981) suggested that a combination of “expectancy hypothesis” and “repreparation hypothesis” would explain the phenomena in a variable-foreperiod paradigm. The “expectancy hypothesis” states that during the foreperiod, participants develop an expectancy on when the imperative stimulus will appear. If the imperative stimulus does not occur after the

critical moment of the shorter foreperiod, expectancy will decrease and initiate repreparation for the next critical moment. The peak of this adaptive expectancy is determined by the conditional probability of the imperative stimulus's onset.

An example would be a variable-foreperiod paradigm with two randomly intermixed foreperiods (400 ms and 1400 ms). After onset of the warning signal, before the first critical moment (400 ms after the end of the warning signal), the participant is uncertain about whether the imperative stimulus will appear at 400 ms or 1400 ms. The expectancy decreases when it passes the critical moment of the 400-ms foreperiod, and the participant starts to expect that the imperative stimulus will appear at 1400 ms. Because there are only two foreperiods, this expectancy does not suffer from uncertainty and thus gets higher, leading to better temporal preparation (the activity that causes the foreperiod effects). Thus, for the longer foreperiod, no matter whether the preceding foreperiod is short or long, the conditional probability is always equal to one after the earlier critical moment, which makes the participant always well-prepared for the later critical moment and perform better when the current trial has a long foreperiod. This assumed advantage explains why the response is always faster and not affected by the duration of the preceding foreperiod when the current foreperiod is long.

The other half of the picture, the robust sequential effect at the shorter current foreperiod, is explained by assuming that participants always expect a repetition of the foreperiod in the next trial (Drazin, 1961). However, this assumption appears arbitrary, given that similar results have been found from studies using more than two foreperiods in which foreperiod switch is more likely to occur compared to foreperiod repetition (e.g., Los et al., 2001; Steinborn et al., 2008).

Los et al. (2001) proposed an alternative explanation based on trace conditioning. This memory-based model regards temporal preparation as a state of activation developed around each critical moment. The peaks of activation of each foreperiod change over the entire experiment. The peak of a certain foreperiod is increased when its critical moment matches the imperative moment. The peak stays the same as in the preceding trial when the imperative moment comes earlier than the corresponding critical moment and decreases when the imperative moment comes later. In a variable-foreperiod paradigm, the critical moment of the longest foreperiod is never bypassed by the imperative moment. Therefore, the activation peak of the longest foreperiod can approach its upper limit and never decrease throughout the whole block, whereas the activation peaks of shorter ones decrease and show worse temporal preparation in the subsequent trials

whenever their critical moments are bypassed by a later imperative moment. The model not only provides a reasonable explanation for the presence of the sequential effect at a short current foreperiod and absence of the effect at a long current foreperiod, it also explains why in a variable-foreperiod paradigm, performance with the shorter foreperiod is no better, if not worse, than that with the longer foreperiod. In other words, based on the trace-conditioning model, the variable-foreperiod effect (decreasing foreperiod-RT function) and the SFP effect are different facets of the same automatic and implicit mechanism.

The main advantage of Los et al.'s (2001) trace-conditioning model is that it predicts the patterns of both the variable-foreperiod effect and the SFP effect in a uniform foreperiod distribution. Steinborn et al. (2008) used shorter foreperiods (200 ms, 400 ms, and 600 ms) and found that although the overall SFP effect was smaller compared to that in the long-foreperiod scenario (1200 ms, 2400 ms, and 3600 ms), the pattern of the sequential effects still followed the prediction of the trace-conditioning model. The smaller SFP effect was attributed to less difference between foreperiods in the short-foreperiod scenario.

Steinborn et al. (2009, 2010) introduced a cross-trial shift of the warning signal and found that both a shift between different modalities and one between white noise and pure tone could modulate the SFP effect while maintaining the same asymmetric pattern. The SFP effect decreased with a warning-signal shift compared to a warning-signal repetition. They claimed that the warning-signal shift caused a discrepancy between encoding and retrieval, which compromised the influence of reinforcement and reduced the effect of repetition. The results of both studies were interpreted as evidence that the SFP effect is memory-based.

Despite its explanatory power, the trace-conditioning model has its limitations. First, the model does not make any assumption about the connection between the variable- and fixed-foreperiod paradigms, taking the phenomena produced by each as distinct. Although the two paradigms showed different results in terms of the foreperiod-RT function, it is not reasonable to separate them completely. Second, the model can only be readily applied to cases with a uniform foreperiod distribution. Los and Agter (2005) tested the trace-conditioning model in different foreperiod distributions and found that while the foreperiod-RT function varied across different distributions, only a very small proportion of the change could be accounted for by the change in the SFP effect. Because the trace conditioning model regards the foreperiod-RT function as a byproduct of the SFP effect, it is unable to explain this distribution effect. Los and Agter attributed

the part not explained by trace conditioning to temporal orienting, which is the allocation of resources to different critical moments through intentional or unintentional processes based on the foreperiod distribution. But evidence directly supporting this claim was not provided in the article.

Support for this implication of two separate factors controlling the SFP effect and the variable-foreperiod effect was found in later studies. Vallesi and Shallice (2007) investigated the variable-foreperiod effect and the SFP effect in different age groups (4, 5 or 6 years old) using a simple-reaction task in which the warning signal was a 1500-Hz pure tone lasting 50 ms and the imperative stimulus was a downward-pointing white arrow. The foreperiods adopted in the study were 1, 3, and 5 s. They found that the SFP effect emerged as early as at the age of 4 years, whereas the decreasing foreperiod-RT function did not appear until the age of 5. Moreover, no evidence was found to support an asymmetric SFP effect in 4-year-old children. RT consistently increased as the foreperiod of the preceding trial increased, regardless of the current foreperiod. In contrast, the typical asymmetry was found in 6-year-old children. This finding implies that the foreperiod-RT function and the asymmetry of the SFP effect were absent in 4-year-old children but later developed by the age of 6. The pattern found in 4-year-old children supports an arousal-based assumption of the SFP effect where arousal is constantly changed by the current foreperiod, and it affects the response speed of the next trial. Short foreperiods promote arousal while long foreperiods lower the arousal level. This arousal-based SFP effect is symmetric in that shorter preceding foreperiods lead to shorter RT regardless of the current foreperiod.

Vallesi, Shallice, and Walsh (2007) further investigated the finding of Vallesi and Shallice (2007), with the introduction of transcranial magnetic stimulation (TMS). They found that TMS on right dorsolateral prefrontal cortex (rDLPFC) diminished the decreasing trend of the foreperiod-RT function while leaving the SFP effect unchanged. This result serves as additional evidence that the mechanisms behind the variable-foreperiod effect and the SFP effect are different.

The findings of Vallesi and Shallice (2007) and Vallesi, Shallice and Walsh (2007) were summarized in Vallesi (2010) as a dual-process model. Based on this account, the asymmetric SPE and the decreasing foreperiod-RT function are mainly caused by an additional endogenous preparation process similar to the combination of expectation and repreparation mentioned by Niemi and Näätänen (1981). When this additional process is absent (e.g., in the early stages of cognitive development), the SFP effect is mainly driven by the arousal inherited from the preceding trial. RT decreases as the preceding trial's foreperiod decreases.

This dissociation between an intentional process and an unintentional process was supported by Steinborn and Langner (2011) and Vallesi et al. (2014). Steinborn and Langner examined the auditory filled-foreperiod effect, which refers to a performance decrement when the foreperiod is filled with irrelevant auditory stimulation compared to the case without additional distraction. They used different warning signal-imperative stimulus modality combinations in a variable-foreperiod paradigm and found consistent evidence that the filled-foreperiod effect mainly modulated the variable-foreperiod effect instead of the SFP effect, which supported the account that the variable-foreperiod effect involved processing of time or probability whereas the SFP effect is more implicit. Vallesi et al. made the participants perform a subtraction task during the foreperiod in a variable-foreperiod paradigm and showed that the dual-task manipulation mainly modulated the variable-foreperiod effect instead of the SFP effect. This result also supports a controlled, resource-consuming preparatory mechanism behind the variable-foreperiod effect and a more automatic one underlying the SFP effect.

Although the general dual-process account was supported by later studies, Vallesi's (2010) arousal-based model faces a major limitation. Evidence supporting the arousal-based account has usually been found in special groups (4-year-old children) or with intrusive task settings (e.g., TMS in rDLPFC). Critical evidence is absent with ordinary samples and usual task settings. Steinborn and Langner (2012) investigated a higher-order SFP effect and found that RT decreased as second-order (two-back) foreperiod decreased. This pattern was only found when longer foreperiods and a greater foreperiod range of the three foreperiods were used in a choice-reaction task scenario or when, with a simple-reaction task, two rather than three foreperiods were included. Again, although Steinborn and Langner's finding is consistent with the arousal-based model, direct support for the model is still missing.

On the other hand, to overcome the shortcoming of not being able to account for the effect of foreperiod distribution, Los et al. (2014), on the basis of the trace-conditioning model, proposed the multiple trace theory of temporal preparation, introducing the multiple trace theory, which has been used to explain a variety of memory-related phenomena, into temporal preparation. Based on this theory, each trial – which includes the warning signal, the foreperiod, the imperative stimulus and the corresponding response – is stored as a memory trace. Within each memory trace, the strength of activation and inhibition still follows the trace-conditioning model, which ensures the theory's explanatory power on the asymmetric SFP effect. While the trace-conditioning model

focuses on how different foreperiods modify the same memory trace of temporal preparation, the multiple trace theory assumes that, in the next trial, when the warning signal appears, it serves as a retrieval cue. At each foreperiod's critical moment, all previous memory traces contribute to the current preparatory state. It is also assumed that the more recent memory trace has a stronger effect on the current trial than older traces. With these assumptions, Los et al.'s multiple trace theory of temporal preparation is believed to be able to account for the foreperiod-distribution effect. An exponential foreperiod distribution in which short-foreperiod trials are the majority, based on this theory, is expected to have a less negative foreperiod-RT relation because more short-foreperiod trials lead to higher activation at the earlier critical moment corresponding to the short current foreperiod.

Based on the multiple trace theory, the variable-foreperiod effect and the SFP effect are two sides of one coin (memory trace). The theory does not provide a complete account for the dissociation between the variable-foreperiod effect and the SFP effect, especially from those studies that supported a resource-consuming mechanism that involves processing time and probability behind the variable-foreperiod effect (Steinborn & Langner, 2011; Vallesi et al., 2014). On the other hand, Los et al. (2014) attempted to use the multiple trace theory to explain the fixed-foreperiod effect. They assumed that without considering the activation-inhibition ratio when aggregating the memory trace values across trials, the stored activation at the critical moment of a fixed foreperiod will be more dispersed as the imperative moment is more remote from the warning signal, which explains the upward direction of the foreperiod-RT function in most fixed foreperiod cases. However, this simple assumption is not able to account for the whole "U"-shape curve caused by the fixed-foreperiod effect, especially the decreasing part at short foreperiods. Nevertheless it provides a pathway for reconnecting the two foreperiod paradigms. When the additional processes involved in the variable-foreperiod paradigm are excluded or inhibited, the foreperiod-RT function could go back to the same direction as that in a fixed-foreperiod paradigm. This reasoning was adopted in the current study.

Based on the dual-process model by Vallesi (2010), the asymmetry of the SFP effect and the decreasing foreperiod-RT function were caused by endogenous preparation which, according to Niemi and Näätänen (1981), is related to the conditional probability of imperative stimulus onset. More specifically, due to the fact that in a variable-foreperiod paradigm without catch trials, when different foreperiods are equally distributed, the conditional probability of the imperative stimulus

appearing at the next critical moment will increase every time a shorter foreperiod's critical moment is passed. This increase means that after the critical moment of the second longest foreperiod is passed, the imperative stimulus will definitely appear at the critical moment of the longest foreperiod and this is where an uncertain event becomes certain, providing the best chance to get prepared. This is why, according to the dual-process model, one cannot find the effect of the previous foreperiod on performance when the current foreperiod is the longest. If this is the case, then by manipulating the foreperiod distribution and introducing catch trials, it is possible to keep the conditional probability of imperative stimulus onset constant (non-aging distribution), which is supposed to diminish the effect from endogenous preparation.

Capizzi et al. (2015) tried to test this assumption using a simple-reaction task. In their study, two foreperiods (400 ms vs. 1400 ms) were distributed in a 2-to-1 ratio with catch trials sharing the same proportion as the longer foreperiod, making the conditional probability of encountering the imperative stimulus equal before and after the critical moment of 400-ms foreperiod. As was predicted by the dual-process model, with a non-aging foreperiod distribution, the pattern of the SFP effect was not found to be asymmetric, and an increasing foreperiod-RT function was obtained, which is consistent with that obtained with a fixed-foreperiod paradigm. Nevertheless, the SFP effect was symmetric in a different manner than in Vallesi (2010). A repetition benefit was found at both the short and long foreperiods. Responses were faster when the current foreperiod and the preceding foreperiod were the same and slower when they were different, regardless of the duration of the current foreperiod. Moreover, from the data of Capizzi et al., the SFP effects at the shorter and longer foreperiods were estimated to be almost equal in size.

Based on these results, Capizzi et al. (2015) claimed that the evidence supported a dual-process model where the other component in addition to endogenous preparation was repetition priming, which is memory-based rather than arousal-based as in Vallesi's (2010) model. According to this account, the SFP effect on the current trial was caused by the memory of the preceding trial. When this memory matches the current trial (foreperiod repetition), the priming effect of this memory makes responses faster than the case where the current trial has a different foreperiod than the preceding one. This priming effect produces the equivalent differences at different foreperiods regardless of the foreperiod distribution, leading to a highly symmetric SFP-effect pattern (as in Figure 3).

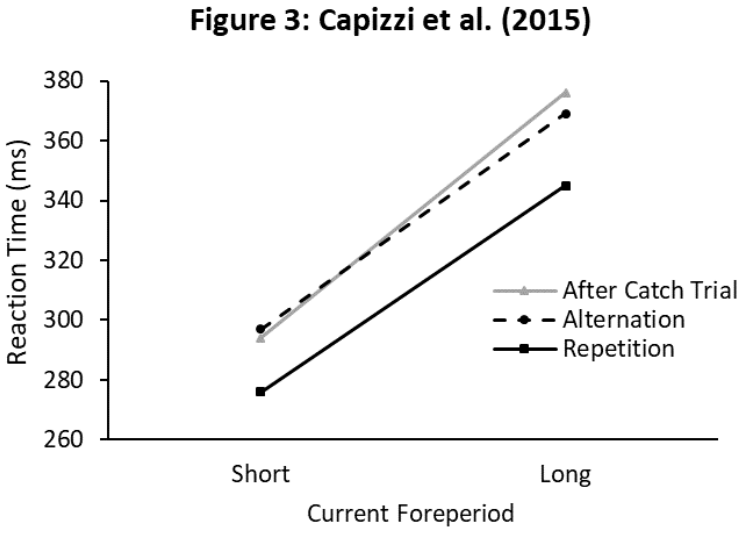

Figure 3. Capizzi et al. (2015): Reaction time (in ms) as a function of the foreperiod sequence and the current foreperiod in Experiment 2.

Although the dual-process model proposed by Capizzi et al. (2015) seems an acceptable answer, based on the data, several issues remain unsolved. First, a simple-reaction task was used by Capizzi et al. instead of a choice-reaction task. Previous studies have found that using a simple-reaction or choice-reaction task could influence the resulting pattern (Steinborn et al., 2008, 2009, 2010; Steinborn & Langner, 2012). Second, a strong inference was made that the repetition priming effect was equivalent between short and long foreperiods based on a nonsignificant result with a participant sample size smaller than 15. To justify the reliability of results, the equivalence for which Capizzi et al. argued should be tested with a larger sample size as well as in a choice-reaction task scenario.

Another interesting finding of Capizzi et al. (2015) was the increasing foreperiod-RT relation. There are several candidate explanations for the change from a decreasing function (as was found in the majority of previous studies) to an increasing one. It could be due to a relatively higher proportion of the shorter foreperiod. Based on the multiple trace theory, a higher proportion of short-foreperiod trials leads to better preparation at the corresponding critical moment. If this is the case, using a non-aging foreperiod distribution should always produce an increasing foreperiod-RT function, regardless of which foreperiods are involved in the distribution (e.g., short foreperiods like 50 ms or 200 ms).

Alternatively, the foreperiod-RT function could have been determined by the relative ease of anticipating the foreperiod duration, as in a fixed-foreperiod paradigm. It is assumed that with a non-aging foreperiod distribution, the endogenous preparation process is inhibited. Also, based on the repetition priming account, the SFP effect should modulate the variable-foreperiod effects of different foreperiods equally. Therefore, the variable-foreperiod effect in this scenario should mostly rely on the foreperiod duration itself, which is closely related to how easy it is for participants to anticipate stimulus onset, according to the studies of the fixed-foreperiod effect (Niemi & Näätänen, 1981). If this is true, then when using foreperiods on the decreasing side of the "U"-shape curve of the fixed-foreperiod effect but maintaining a non-aging distribution, the foreperiod-RT function should change its direction from increasing to decreasing.

Moreover, although the results of Capizzi et al. (2015) showed no support for Vallesi's (2010) arousal-based account, which predicts that a shorter preceding foreperiod should always lead to faster responses in the current trial regardless of the current foreperiod, they did not rule out the possibility that in particular circumstances, the dominance of repetition priming could be changed. For instance, when foreperiods are extremely short, the fixed-foreperiod effect is modulated by phasic arousal (Posner et al., 1973; Tona et al., 2016), which implies that the SFP effect in a short-foreperiod scenario could also be dominated by arousal. Therefore, it would be informative to replicate Capizzi et al. with a larger sample size and test the repetition priming account and the direction of the foreperiod-RT function in different foreperiod scenarios.

EXPERIMENT 1

Experiment 1 was a replication of the second experiment of Capizzi et al. (2015). Both the foreperiods and foreperiod distribution were the same, but a choice-reaction task instead of a simple-reaction task was used to generalize the finding of the original study. In Los et al. (2001), a choice-reaction task was used, whereas in Vallesi and Shallice (2007) and Capizzi et al., participants were tested in a simple-reaction-task scenario. Steinborn et al. (2008) found that the task scenario used (simple RT task vs. choice RT task) modulated both the variable-foreperiod effect and the SFP effect. Therefore, it is possible that Capizzi et al.'s repetition priming account might not apply to the results from a choice-reaction task. The first goal of the current experiment was to test the generalizability of Capizzi et al.'s finding.

The original study's reliability suffers from a small sample size. A simulation-based power analysis was conducted to estimate the appropriate sample size that has a probability of .9 to detect the main effects of the current foreperiod and the foreperiod sequence, and also the interaction between the two factors. The data (means, standard deviations and estimated correlations between conditions) from Experiment 2 of Capizzi et al. (2015) were assumed to represent the population, which is assumed to have a normal distribution. Then random samples (10000 samples) of a certain sample size were drawn from this distribution. Mean RTs in all conditions of each participant of a random sample were then submitted to a repeated-measures analysis of variance (ANOVA), which had two within-subject factors, Foreperiod Sequence (repetition vs. alternation) and Current Foreperiod (short vs. long), to test the significance of the two main effects and the interaction. Two separate one-way ANOVAs were also conducted to test the significance of the SFP effect at both foreperiods. For each sample size, the simulation reported the proportion of the random samples that showed significant results for both separate ANOVAs and for all three effects in the main ANOVA. This proportion was regarded as the statistical power corresponding to that particular sample size.

Through this method, a sample size of 75 participants was found to obtain a statistical power above .9. This result means that, based on the data of Capizzi et al. (2015), if Experiment 1 had failed to detect this difference, it would have been reasonable to be convinced that the SFP effects at different foreperiods are of similar size, which was the critical evidence supporting the repetition priming account.

Method

Participants

A total of seventy-six students (34 male, 42 female) participated. All participants in this and the remaining experiments (a) were enrolled in an introductory psychology course at Purdue University and received research credits, (b) reported having normal or corrected-to-normal vision and audition, and (c) were naïve to the purpose of the study. One participant under the age of 18 was excluded. This experiment and the others were conducted in accord with a protocol approved by the Purdue University Institutional Review Board and the ethical principles of the American Psychological Association, and all participants signed an approved informed consent form prior to participating.

Apparatus and Stimuli

Stimulus presentation and response recording were achieved by means of E-Prime software (Version 2.0, Psychology Software Tools, Inc.) installed on a PC workstation. Participants were seated in front of a 76-cm high table on which an E-Prime response box with a row of five response buttons was placed. Instructions, visual imperative stimulus, and response feedback were presented on a 17-in. LCD monitor in front of the participant, with an unconstrained viewing distance of approximately 63 cm in a dimly lit room. The response box was center aligned with the display, and participants responded with their left and right index fingers on the leftmost and rightmost buttons of the box.

The background color of the monitor was black throughout the whole experiment with instructions, feedback and stimuli displayed in white. The imperative stimulus was a lower-case letter (either "**p**" or "**q**"), which appeared at the center of the display. The size of the stimulus was 0.5° × 0.3°. The warning signal was an 80-dBA pure tone of 1000 Hz transmitted through a pair of SONY headphones. The duration of the warning signal was 50 ms.

Procedure

Each trial began with a randomized (uniformly distributed) inter-trial interval ranging between 500 ms and 1500 ms, same as Capizzi et al. (2015). After the inter-trial interval, the

auditory warning signal was presented for 50 ms, after which, for a regular trial, the variable foreperiod started. The foreperiod was either 400 ms or 1400 ms. After the foreperiod expired, the imperative stimulus was presented at the center of the display. Participants were instructed to press the left button when "**q**" appears and to press the right button when "**p**" appears. Both letters were in "Courier New" font. The imperative stimulus stayed on the display until a response was made. Error feedback was provided only after an incorrect response was made, while a correct response would start the next trial without any feedback. In a catch trial, the warning tone was followed by a blank slide that lasted for 2400 ms (one second longer than the longer foreperiod), after which a reminder slide saying "No response is needed" was presented for 1500 ms before the next trial began.

The choice-reaction task used in Steinborn et al. (2008, 2009, 2010) and Steinborn and Langner (2012) requested a left-key response for letter "L" and a right-key response for letter "R", which was a semantically compatible mapping. Unlike "L" and "R" which look different in many aspects, "**q**" and "**p**" are the mirror version to each other (especially when presented in "Courier New" font). Although the spatial orientation of the letters is debatable (e.g., the head of "**q**" can be regarded as pointing to the left while the tail pointing to the right), the mapping used in the current study matches response tendency of typing in that left hand is used to type "q" and right hand is used to type "p". Therefore, this mapping should be easy to remember and not provide an advantage to either of the responses.

Each participant went through one practice block followed by 15 test blocks. The practice block contained 16 trials, 8 with the shorter foreperiod, 4 with the longer foreperiod and 4 catch trials to provide a general impression about the mapping and the structure of a block. Each test block contained 32 trials, 16 with the shorter foreperiod, 8 with the longer foreperiod, and 8 catch trials. Trials with different foreperiods and catch trials were randomly mixed in each block.

Before the experiment, participants were told about the average duration for the session (30~40 minutes) and the mapping they were to use. Participants were instructed to maintain their index fingers on the corresponding keys and not to use other fingers to respond. Speed and accuracy of the responses were equally emphasized to the participants. Mapping information was included in an introductory slide at the beginning of each block. The experimenter stayed in the room with the participant for all the trials.

Results

Prior to data analysis, all trials with RT shorter than 100 ms or longer than 1000 ms were regarded as outliers and excluded (0.96%). To measure the sequential foreperiod effects more precisely, the first trial of each block and trials following an incorrect response were also discarded (5.2%) from further data analysis. Trials following either a short-foreperiod trial or a long-foreperiod trial in all test blocks were submitted to a repeated-measures analysis of variance (ANOVA) on mean RT of correct responses and error percentage (EP), with Foreperiod Sequence (repetition vs. alternation) and Current Foreperiod (400 ms vs. 1400 ms) as within-subject factors. Two additional one-way repeated-measures ANOVA with Current Foreperiod as the only within-subject factor were then conducted to test the significance of the SFP effect on RT at each foreperiod, the purpose of which was to confirm whether a significant SFP effect could be found at the longer current foreperiod. All effects were tested at an α level of .05.

Figure 4 shows RT of the correct responses (top) and EP (bottom) as a function of Current Foreperiod[1]. EP was generally low with an average of about 1.5% and did not reveal any significant effects. The ANOVA on RT showed a main effect of Current Foreperiod, $F(1, 74) = 173.33$, $p < .001$, $\eta_p^2 = .70$. Responses were faster when the current foreperiod was 400 ms compared to 1400 ms. There was also a main effect of Foreperiod Sequence, $F(1, 74) = 76.40$, $p < .001$, $\eta_p^2 = .51$. Responses were faster when the current foreperiod was the same as the previous one compared to when they were different. In contrast with the result of Capizzi et al. (2015), the interaction between Current Foreperiod and Foreperiod Sequence was also significant, $F(1, 74) = 21.93$, $p < .001$, $\eta_p^2 = .23$, indicating a larger sequential effect when the current foreperiod was 400 ms (24 ms) compared to 1400 ms (8 ms).

[1] Gray lines in this and other figures represent the mean RTs or the error percentage following catch trials as a function of Current Foreperiod. The corresponding data were not involved in any data analysis.

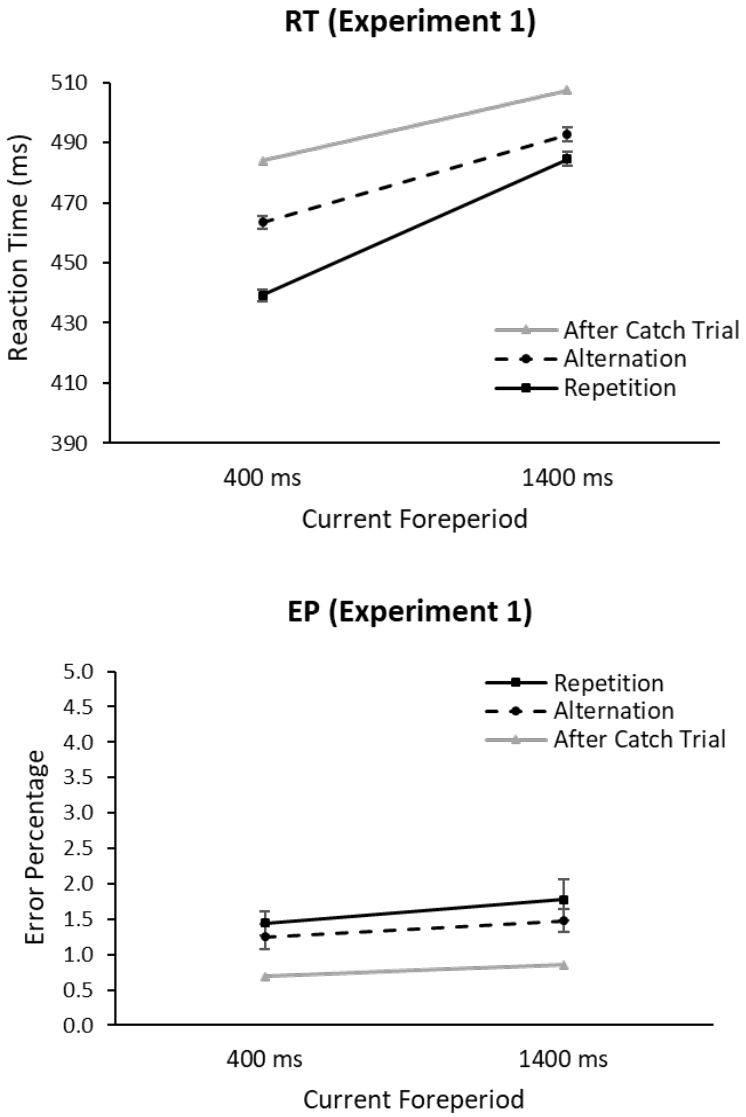

Figure 4. Experiment 1. Reaction time (in ms) as a function of Current Foreperiod (top); error percentage as a function of Current Foreperiod (bottom). Error bars in this and the other figures represent the adjusted standard errors for within-subject factors using the method described in O'Brien and Cousineau (2014), although in some cases they are small enough to not be visible.

Regarding the separate one-way ANOVAs, the effect of Foreperiod Sequence was significant at 400-ms foreperiod, $F(1, 74) = 123.59$, $p < .001$, $\eta_p^2 = .63$, and at 1400-ms foreperiod, $F(1, 74) = 8.63$, $p = .004$, $\eta_p^2 = .10$. Responses were faster for foreperiod repetition compared to alternation at both current foreperiods.

Discussion

Like Capizzi et al. (2015), Experiment 1 replicated the main effect of Current Foreperiod, showing a similar increasing foreperiod-RT function. The repetition benefit revealed in Capizzi et al. was represented as the main effect of Foreperiod Sequence. Separate one-way ANOVAs showed that the SFP effect was significant at both the shorter (400 ms) and the longer (1400 ms) foreperiods, as in Capizzi et al. The most important finding of Experiment 1 was the significant interaction between Current Foreperiod and Foreperiod Sequence, indicating that the SFP effect was larger at the shorter foreperiod compared to the longer foreperiod. This result is inconsistent with the repetition priming account by Capizzi et al., which claimed that the SFP effects should be equal at different foreperiods. Because the interaction detected in the current experiment is robust and the sample size was much larger than that of Capizzi et al., it is reasonable to argue that the difference was not detected in Capizzi et al. due to insufficient statistical power of their study.

Although the SFP effect was found to be different at the shorter and longer foreperiods, the pattern was still relatively more symmetric compared with previous research due to the detection of a significant SFP effect at the longer foreperiod. Based on the assumptions of a dual-process model (Capizzi et al., 2015; Vallesi, 2010), the asymmetry of the SFP effect was caused by the endogenous preparation, which should have been inhibited by the non-aging foreperiod distribution in the current study. Thus, based on this reasoning, there should be some other factor that influenced the size of the SFP effect. One possibility could be the proportion[2] of different foreperiods. Based on the multiple trace theory, the temporal preparation in the current trial is the aggregation of all the previous memory traces (Los et al., 2014). The closer that one trace is to the current trial, the larger effect it will have. In Experiment 1, because the longer foreperiod had a small proportion in the foreperiod distribution, when the current foreperiod was long, there were

[2] Because of using a non-aging foreperiod distribution, the longer foreperiod always had a smaller proportion in the foreperiod distribution. Consequently, none of the experiments in the current study were able to separate the influence of the proportions of foreperiods from the effect of the relative lengths of foreperiods.

likely not many adjacent memory traces that had the same foreperiod. The lack of help from previous traces also led to a smaller effect from a preceding memory trace of the other foreperiod because there was not much room to interfere.

Another possibility is that the SFP effect reflected how much benefit temporal preparation was able to obtain from foreperiod repetition. An extreme case of this would be the fixed-foreperiod paradigm where only foreperiod repetition exists. Therefore, the size of the SFP effect could be related to how fast responses could be in a fixed-foreperiod paradigm. When foreperiods are kept constant within a trial block, people are faster at the 400-ms foreperiod than the 1400-ms foreperiod; therefore, the benefit from repetition could also follow this relation. The two explanations above could be tested in a short-foreperiod (< 300 ms) scenario because people are faster at a 200-ms foreperiod compared to a 50-ms foreperiod when the foreperiod is fixed. By using a non-aging foreperiod distribution, the 50-ms foreperiod would have a larger proportion in the distribution. In this case, the two explanations would predict the opposite patterns.

With regard to the variable-foreperiod effect, the current experiment was informative by revealing an increasing foreperiod-RT function that cannot be predicted from the trace-conditioning model. Based on the multiple trace theory, the larger proportion of shorter foreperiod trials could be the basis of that foreperiod's advantage in terms of the response speed by having more previous memory traces contributing to the activation at the shorter foreperiod's critical moment. On the other hand, the increasing foreperiod-RT function in Experiment 1 shared the same direction as in a fixed-foreperiod paradigm. It is reasonable to argue that without the effect from the additional processes in a variable-foreperiod paradigm, the foreperiod-RT relation in two foreperiod paradigms will be in the same direction. These two explanations can also be tested in a short-foreperiod scenario as in the case of the SFP effect. When both foreperiods are shorter than 300 ms, based on the direction of the fixed-foreperiod effect, foreperiod-RT function will be decreasing, whereas based on the proportions, the function should also be increasing.

EXPERIMENT 2

The second experiment resembled most of the settings in Experiment 1 except that extremely short foreperiods (50 ms and 200 ms) were used. According to Posner et al. (1973) and Tona et al. (2016), the fixed-foreperiod effect on RT is determined by arousal. However, in Steinborn et al. (2008), a typical but smaller asymmetry of the SPE was observed in a short-foreperiod scenario with a uniform foreperiod distribution. According to Vallesi (2010), this asymmetry should be due to, in a uniform foreperiod distribution, the endogenous preparation that dominates the data pattern. Thus, based on the arousal-based dual-process model, when a non-aging foreperiod distribution is adopted in a short-period scenario where endogenous preparation is inhibited, the SFP effect should follow an arousal-based account, which means that the shorter preceding foreperiod should produce faster responses no matter how long the current foreperiod is.

However, if the SFP effect in a short-foreperiod scenario is determined by the same factor as in the prior experiment, then RT is expected to be shorter for foreperiod repetition compared to alternation. Moreover, if the relative size of the SFP effect is determined by the ease of anticipating the foreperiod, then a larger SFP effect is expected to occur at the 200-ms foreperiod. On the contrary, if the relative effect size is determined by the proportions of foreperiods, then the 50-ms foreperiod should produce a larger SFP effect. Therefore, the directions and the relative sizes of the SFP effects in Experiment 2 would indicate which factor determines the SFP effect in a short-foreperiod scenario.

Experiment 2 was also informative with regard to the foreperiod-RT function and the relation between the two foreperiod paradigms. If the foreperiod-RT function is determined by the proportions of foreperiods, with a similar distribution, using short foreperiods (50 ms vs. 200 ms) should lead to the same increasing pattern, because the larger proportion is taken by the shorter foreperiod (50 ms). If, alternatively, without endogenous preparation, the foreperiod-RT functions from both fixed- and variable-foreperiod paradigms share the same trend, then based on previous studies, the foreperiod-RT function in the current experiment should be the opposite direction from that in Experiment 1 (McCormick et al., 2019; Niemi & Näätänen, 1981; Posner et al., 1973).

Another simulation-based power analysis similar to that used for the prior experiment was conducted to find the appropriate sample size to detect all the expected effects in the current

experiment. I assumed that both the foreperiod-RT function and the relative size of the sequential foreperiod effect is determined by the ease of anticipating the corresponding foreperiod, which is the same mechanism behind the fixed-foreperiod effect. Consequently, the 200-ms foreperiod in the current experiment was assumed to resemble the case of the 400-ms foreperiod in Experiment 1, whereas the 50-ms foreperiod was assumed to resemble the case of the 1400-ms foreperiod. Therefore, instead of the data pattern in Capizzi et al. (2015), the means and standard deviations of the reversed data pattern of Experiment 1 were used as the population parameters in the simulation. For each sample size, the simulation reported the proportion of the random samples that showed all the effects detected in Experiment 1 (including the main ANOVA and the separate ANOVAs). The proportion was then regarded as the statistical power corresponding to that particular sample size. Through this method, a sample size of 129 was found to have a statistical power above .9 to detect all the effects corresponding to those revealed in Experiment 1.

Method

Participants

One hundred and thirty-three students (48 male, 85 female) from the same participant pool participated. None of the participants had participated in the prior experiment. Three participants were excluded because of some problem with the experiment process. Four others were excluded because their ages were under 18.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli and procedure of Experiment 2 were the same as those of Experiment 1, except that a different pair of foreperiods (50 ms and 200 ms) was used. There was one practice block followed by 15 test blocks. The practice block contained 16 trials, 8 with the shorter foreperiod, 4 with the longer foreperiod and 4 catch trials to provide a general impression about the mapping and the structure of a block. Each test block contained 32 trials, 16 with the shorter foreperiod, 8 with the longer foreperiod, and 8 catch trials. Unlike the prior experiment, after vocally introducing the experiment procedure and requirements, the experimenter stayed out of the room to obey the social distancing guidance of the Covid-19 protocol, which was not in effect when Experiment 1 was conducted.

Results

Prior to data analysis, all trials with RT shorter than 100 ms or longer than 1000 ms were regarded as outliers and excluded (0.32%). To measure the sequential foreperiod effects more precisely, the first trial of each block and trials following an incorrect response were also discarded (5.8%) from further data analysis. Trials following either a short-foreperiod trial or a long-foreperiod trial in all test blocks were submitted to a repeated-measures analysis of variance (ANOVA) on mean RT of correct responses and EP, with Foreperiod Sequence (repetition vs. alternation) and Current Foreperiod (50 ms vs. 200 ms) as within-subject factors. Two additional one-way repeated measures ANOVA were then conducted to test the significance of the SFP effect on RT at the shorter and longer foreperiod. All effects were tested at an α level of .05.

Figure 5 shows RT of the correct responses (top) and EP (bottom) as a function of Current Foreperiod. EP was in general numerically higher than that of Experiment 1 with an average of about 2.0%. The ANOVA on EP revealed a main effect of Foreperiod Sequence, $F(1, 125) = 4.62$, $p = .034$, $\eta_p^2 = .03$. Participants were more likely to make errors when encountering foreperiod repetition compared to alternation. The main effect of Current Foreperiod was not significant, $F(1, 125) = 3.36$, $p = .069$. The EP at 50-ms foreperiod was numerically lower than that at 200 ms. The interaction between Foreperiod Sequence and Current Foreperiod was not significant, $F(1, 125) = .23$, $p = .636$.

The ANOVA on RT showed a main effect of Current Foreperiod, $F(1, 125) = 98.49$, $p < .001$, $\eta_p^2 = .44$. Response were faster when the current foreperiod was 200 ms compared to 50 ms. The main effect of Foreperiod Sequence was not significant, $F(1, 125) = 2.88$, $p = .092$. Consistent with the result of the prior experiment, a significant interaction was revealed, $F(1, 125) = 5.56$, $p = .020$, $\eta_p^2 = .04$, indicating a larger sequential effect when the current foreperiod is 50 ms (4 ms) compared to 200 ms (nearly 0 ms).

Regarding the separate one-way ANOVAs, the effect of Foreperiod Sequence was significant at 50-ms foreperiod, $F(1, 125) = 13.14$, $p < .001$, $\eta_p^2 = .10$, but not at 200-ms foreperiod, $F(1, 125) = 0.08$, $p = .777$. For the 50-ms current foreperiod, responses were faster for foreperiod repetition compared to alternation.

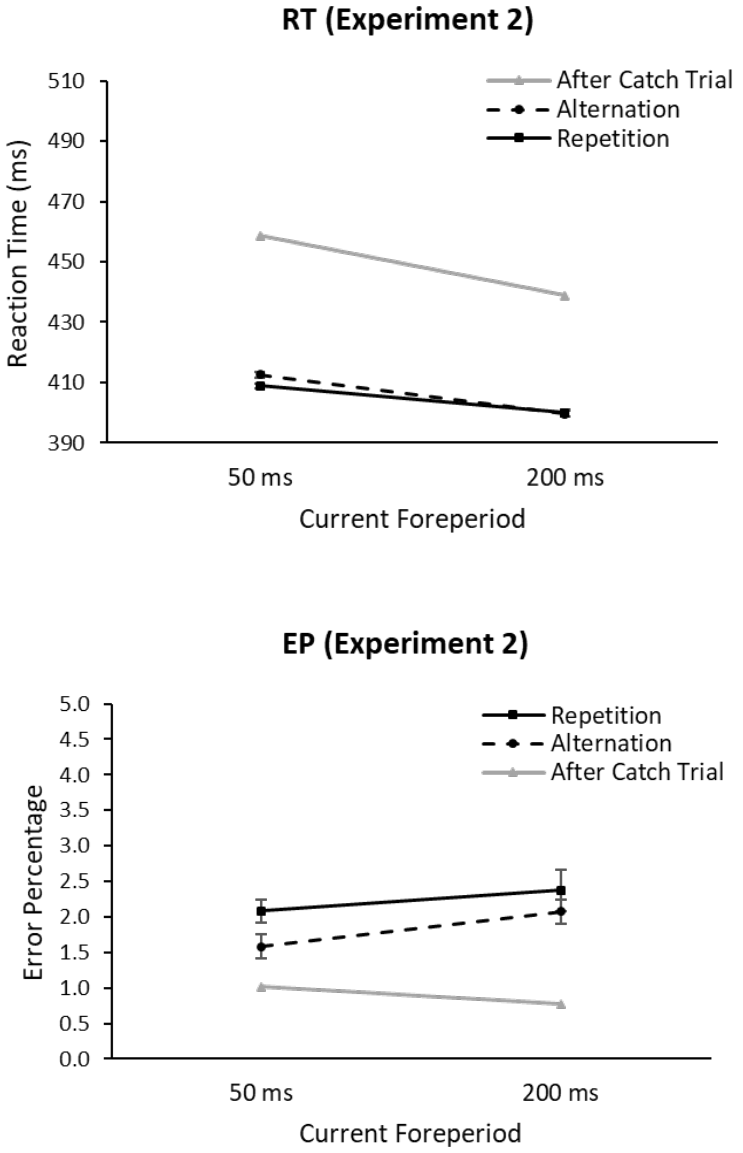

Figure 5. Experiment 2: Reaction time (in ms) as a function of Current Foreperiod (top); error percentage as a function of Current Foreperiod (bottom).

Discussion

Experiment 2 tested the findings of the prior experiment and provided an answer to some of the questions raised in Experiment 1. First, the main effect of Current Foreperiod was found, indicating a decreasing foreperiod-RT function in the short-foreperiod scenario. This direction was consistent with the prediction based on the fixed-foreperiod effect while contradicting the prediction based on the multiple trace theory and the proportion of different foreperiods. The evidence from Experiments 1 and 2 demonstrate that when a non-aging foreperiod distribution is used, the foreperiod-RT functions in a variable-foreperiod paradigm will share the same direction as in a fixed-foreperiod paradigm.

With regard to the SFP effect, the picture is more complex. The main effect of Foreperiod Sequence was absent in the current experiment, indicating in general that foreperiod repetition did not lead to significantly faster responses compared to foreperiod alternation. A small interaction was found between Current Foreperiod and Foreperiod Sequence, indicating a larger SFP effect at the shorter foreperiod (50 ms) compared to the longer one (200 ms). Separate ANOVAs revealed a significant SFP effect at the 50-ms foreperiod but not at the 200-ms foreperiod, consistent with the significant interaction and the nonsignificant main effect of Foreperiod Sequence. These results do not support the assumption that the foreperiod with which responses are faster benefits more from foreperiod repetition. Although serving as an incomplete piece of evidence, the findings of Experiment 2 support the explanation that the foreperiod with a larger proportion in the foreperiod distribution is modulated more by the foreperiod sequence. This conclusion further implies that the SFP effect and the variable-foreperiod effect are based on distinct mechanisms instead of being two sides of one coin, as indicated by the multiple trace theory (Los et al., 2014).

It is worth noting that in Experiment 2, participants were more likely to make errors when the current foreperiod matched the previous one compared to when they are different. Although the effect was small, it does indicate that the performance was modulated by the foreperiod sequence. Combined with the marginally significant main effect (p = .069) of Current Foreperiod on EP, the results of Experiment 2 imply that in a short-foreperiod scenario, faster responses are likely to be accompanied by a higher probability of making mistakes, which is consistent with some previous studies using the fixed foreperiod paradigm (McCormick et al., 2019; Posner et al., 1973).

One critical issue in the results of Experiment 2 was that the general effect of Foreperiod Sequence was much smaller than that detected in Experiment 1. One explanation could lie in the smaller difference between the pair of foreperiods in Experiment 2 (50 ms vs. 200 ms) compared to those in Experiment 1 (400 ms vs. 1400 ms). If the SFP effect originated from the immediate priming from the preceding trial (repetition priming account) or the aggregation of all previous memory traces (multiple trace theory), then using a less distinct pair of foreperiods (e.g., 50 ms and 200 ms) could impair the contribution from memory. Based on this reasoning, a more distinct pair of foreperiods should lead to a more pronounced SFP effect.

EXPERIMENT 3

The first aim of the current experiment was to test the hypothesis that the size of the SFP effect in general is determined by how distinct the foreperiods are from each other. Steinborn et al. (2008) found that when using a dense foreperiod distribution for which the foreperiods were close to each other (400 ms, 500 ms, and 600 ms) diminished the SFP effect. By increasing the difference between the shorter and the longer foreperiods, the current experiment should be able to enlarge the small SFP effect found in Experiment 2. Therefore, instead of 50 ms and 200 ms, 50 ms and 400 ms were used to fulfill this purpose, with everything else kept the same as in Experiment 2.

The second goal of Experiment 3 was to confirm the connection between the two foreperiod paradigms in Experiments 1 and 2. It is implied from the prior experiments that when a non-aging foreperiod distribution is used, the foreperiod-RT function in a variable-foreperiod paradigm should have the same direction as that in a fixed-foreperiod paradigm. In the foreperiod-RT function of a fixed-foreperiod paradigm, the 50-ms foreperiod is on the decreasing side while 400 ms is on the increasing side. Therefore, when pairing the two foreperiods together, it is unclear whether the foreperiod-RT function should be increasing or decreasing. To form a baseline, two fixed-foreperiod trial blocks were added in the current experiment and the data of the fixed- and variable-paradigm were analyzed separately. The result would have been regarded as conflicting evidence if the direction of Current Foreperiod effect had been the opposite directions.

Because the purpose of the current experiment was to increase the size of the general SFP effect, the simulation-based power analysis for Experiment 3 was designed to find the sample size appropriate for detecting an enlarged SFP effect at the current short foreperiod (50 ms). Thus, only the data of the two relevant conditions (foreperiod repetition and foreperiod alternation at 50-ms foreperiod) were used as the population parameters of the simulation. The difference between these two conditions was then enlarged to twice its original size. For each sample size, the simulation reported the proportion of the random samples that showed a significant difference between the two conditions of Foreperiod Sequence at 50 ms. The proportion was then regarded as the statistical power corresponding to that particular sample size. Through this method, a sample size of 60 was found to have a statistical power above .9 to detect a difference between foreperiod repetition and alternation twice as large as that at 50-ms foreperiod in Experiment 2. In other words,

a failure to detect this SFP effect should be at least regarded as evidence that the SFP was not as large as predicted in the current experiment.

Method

Participants

Sixty students (27 male, 33 female) from the same participant pool participated. None of the participants had participated in the prior experiments. One participant under the age of 18 was excluded.

Apparatus, Stimuli, and Procedure

The apparatus, stimuli and procedure of Experiment 3 were the same as those of Experiment 2, except the following changes. First, a different pair of foreperiods (50 ms and 400 ms) was used. There was one practice block followed by 17 test blocks. The practice block contained 16 trials, 8 with the shorter foreperiod, 4 with the longer foreperiod and 4 catch trials to provide a general impression about the mapping and the structure of a block. 15 of the test blocks were variable-foreperiod blocks, each containing 32 trials, 16 with the shorter foreperiod, 8 with the longer foreperiod, and 8 catch trials.

After finishing all variable-foreperiod blocks, participants went through two fixed-foreperiod blocks, each containing 32 trials with the same foreperiod (50 ms or 400 ms). The sequence of the fixed-foreperiod blocks was counterbalanced among the participants. Similar to the prior experiment, after vocally introducing the experiment procedure and requirements, the experimenter stayed out of the room to obey the social distancing guidance of the Covid-19 protocol.

Results

Prior to data analysis, for the variable-foreperiod blocks, all trials with responses shorter than 100 ms or longer than 1000 ms were regarded as outliers and excluded (0.72%). To measure the sequential foreperiod effects more precisely, the first trial of each block and trials following an incorrect response were also discarded (6.3%) from further data analysis. Trials following either a

short-foreperiod trial or a long-foreperiod trial in all test blocks were submitted to a repeated-measures analysis of variance (ANOVA) on mean RT of correct responses and EP, with Foreperiod Sequence (repetition vs. alternation) and Current Foreperiod (50 ms vs. 400 ms) as within-subject factors. Two additional one-way repeated measures ANOVA were then conducted to test the significance of the sequential foreperiod effect on RT for each foreperiod. Moreover, a between-experiment comparison was performed to compare the SFP effect at 50-ms foreperiod in Experiments 2 and 3. All effects were tested at an α level of .05.

For the fixed-foreperiod blocks, all trials with RT shorter than 100 ms or longer than 1000 ms were regarded as outliers and excluded (0.85%). The rest of the trials were submitted to a one-way repeated-measures ANOVA on mean RT of correct responses and EP to test the significance and the direction of the Current Foreperiod effect at an α level of .05.

Figure 6 shows RTs of the correct responses (top) and EP (bottom) as a function of Current Foreperiod. For the variable-foreperiod condition, EP was at a similar level as that of Experiment 2 with an average of about 2.1% and did not reveal any significant effects. The ANOVA on RT showed a main effect of Foreperiod Sequence, $F(1, 58) = 16.79$, $p < .001$, $\eta_p^2 = .22$. Responses were faster when the current foreperiod was the same as the previous one. The main effect of Current Foreperiod was not significant, $F(1, 58) = 3.06$, $p = .085$. Neither was the interaction between Current Foreperiod and Foreperiod Sequence, $F(1, 58) = 2.42$, $p = .125$. The separate one-way ANOVAs revealed a significant Foreperiod Sequence effect at 50-ms foreperiod, $F(1, 58) = 18.12$, $p < .001$, $\eta_p^2 = .24$, but not at 400-ms foreperiod, $F(1, 58) = 2.23$, $p = .140$. For the 50-ms current foreperiod, responses were faster for foreperiod repetition compared to alternation.

For the fixed-foreperiod condition, the ANOVA on EP did not reveal a significant effect of Current Foreperiod, $F(1, 58) = .74$, $p = .393$. In contrast, the ANOVA on RT showed a significant Current Foreperiod effect, $F(1, 58) = 8.18$, $p = .006$, $\eta_p^2 = .12$. Responses were faster when the foreperiod was 50 ms rather than 400 ms.

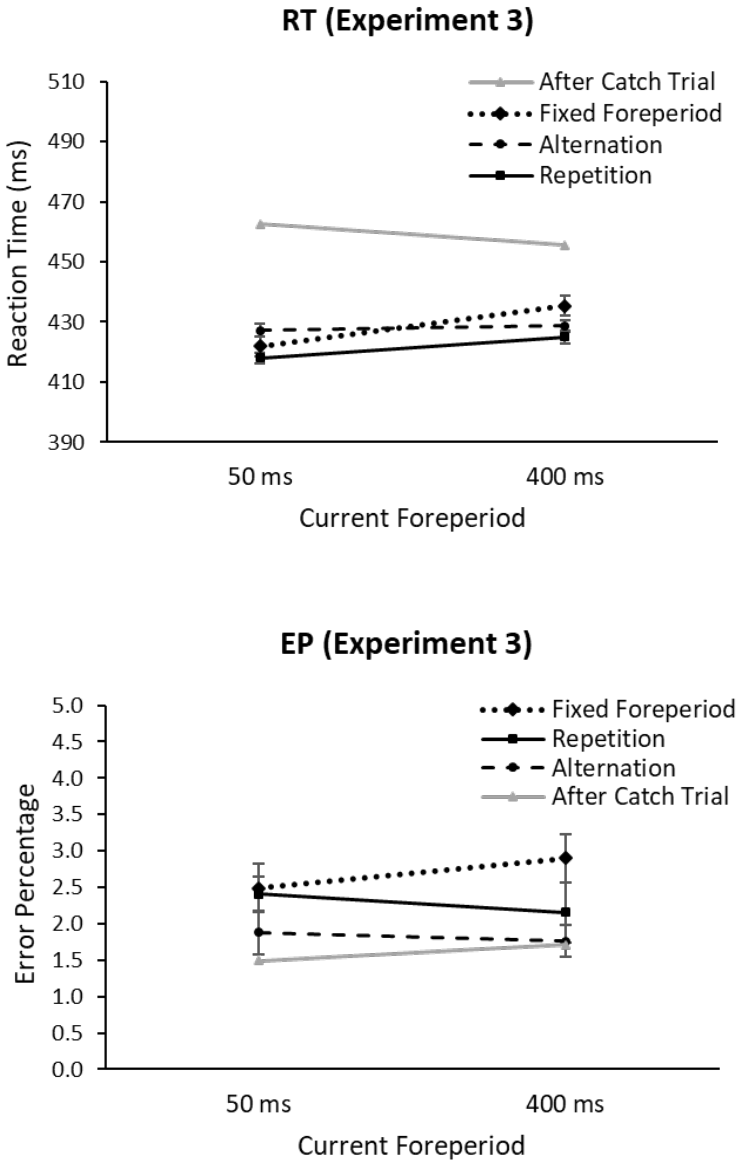

Figure 6. Experiment 3: Reaction time (in ms) as a function of Current Foreperiod (top); error percentage as a function of Current Foreperiod (bottom).

Regarding the between-experiment comparison, for the data of Experiments 2 and 3, the SFP effect at 50-ms foreperiod was calculated for each participant by subtracting the RT of foreperiod repetition from that of foreperiod alternation. Then the calculated differences were submitted to a one-way ANOVA with Experiment (2 vs. 3) as the between-subject factor. A significant difference between groups was found, $F(1, 183) = 6.32$, $p = .013$. The SFP effect at 50-ms foreperiod was larger in Experiment 3.

Discussion

Compared to the two prior experiments, Experiment 3 demonstrated a relatively unclear picture. The only significant effect from the main ANOVA was the main effect of Foreperiod Sequence, which, consistent with the findings of Experiments 1 and 2, showed that responses were faster for foreperiod repetition compared to alternation. Separate one-way ANOVAs found a significant SFP effect at the shorter foreperiod (50 ms) but not at the longer one (200 ms). The between-experiment comparison showed that the SFP effect at the 50-ms foreperiod in Experiment 3 (9.17 ms) was larger than that in Experiment 2 (3.82 ms). These results regarding the SFP effect are in agreement with the assumption that the general size of the SFP effect is modulated by how distinct the foreperiods are from each other. This difference between the durations of foreperiods could also be regarded as the distinctiveness of the previous trial's memory trace. The more distinct this memory trace is from that of the trials with the other foreperiod, the larger difference it would produce on the RT of the current trial. Therefore, consistent with the conclusion of Experiment 2, this enlarged main effect of Foreperiod Sequence also supports a memory-based account for the SFP effect.

As for the relative size of the SFP effect at different foreperiods, Experiment 3 did not provide solid evidence supporting the conclusion from the prior experiments due to the absence of a significant interaction between Current Foreperiod and Foreperiod Sequence. This nonsignificant interaction does not support that the sizes of the SFP effects were different while on the other hand, the results from the one-way ANOVAs showed that the SFP effect was significant at the 50-ms foreperiod but was not at the 400-ms foreperiod. The fact that the results from the main ANOVA and the one-way ANOVAs lead to different implications probably indicates that both the interaction and the SFP effect at the 400-ms foreperiod, if they really exist, were small effects, making the statistical power of the current experiment insufficient to have a

high probability of detecting any of them. Assuming the existence of these two effects, a post-hoc simulation was conducted, based on the data obtained from Experiment 3 to estimate the appropriate sample size. The results showed that to have a probability of .8 of detecting the SFP effect at the 400-ms foreperiod, the sample size should be larger than 160. To detect both of the assumed effects, more than 250 participants would be needed to maintain a statistical power higher than .8.

With regard to the variable-foreperiod effect, although a significant main effect was not detected (p = .085), the numerical difference in RT at the two foreperiods pointed to the same direction as the significant fixed-foreperiod effect. The result that the fixed-foreperiod effect appeared to be more robust could be related to the fact that the fixed-foreperiod blocks were placed after all the variable-foreperiod blocks where the 50-ms foreperiod was the majority in the foreperiod distribution. Los et al. (2017) used a visual warning signal and a visual imperative stimulus and found that blocks with the same foreperiod distribution (exponential or anti-exponential) induced a short-term carryover effect on the foreperiod-RT function in subsequent blocks with a uniform distribution. Crowe and Kent (2019) used an auditory pair of stimuli and found a similar but more limited carryover effect (lasting for only one block). These finding implied that having the fixed-foreperiod blocks performed immediately after the variable-foreperiod blocks could have made it more difficult to measure the fixed-foreperiod effect precisely, which could be a potential limitation of the current design.

GENERAL DISCUSSION

In the present study, I examined Capizzi et al.'s (2015) repetition priming account of SFP effect and attempted to seek a possible reconnection between fixed- and variable- foreperiod paradigms in three experiments. The repetition priming account argued that the SFP effect is caused by the memory of the preceding trial and that this effect should be of equal size for different foreperiods regardless of the foreperiod duration or the foreperiod distribution. This highly symmetric pattern of the SFP effect detected in Capizzi et al. has seldom been found in other studies.

With regard to the variable-foreperiod effect, an increasing foreperiod-RT function, which cannot be predicted by either the trace-conditioning model or the multiple trace theory, was found in Capizzi et al. (2015). A non-aging foreperiod distribution was used, which was assumed to inhibit the endogenous expectation process. Without the influence from this process, the variable-foreperiod effect and the SFP effect were hypothesized to resume their baseline. In this situation, the SFP effect, according to Capizzi et al., should follow the repetition priming account, whereas for the variable-foreperiod effect, their discussion was insufficient. One suggested explanation was that the faster responses were due to the larger proportion of the shorter foreperiod, which was not further tested.

Experiment 1 adopted a sample size with more statistical power to detect a possibly existing difference between the SFP effects at the shorter and the longer foreperiods. The result showed that although the SFP effect at the longer foreperiod was detected, its size was significantly smaller than that at the shorter foreperiod. This pattern was replicated in Experiment 2, when shorter foreperiods were used, and partially indicated by the result of Experiment 3. Therefore, the present study provided sharp evidence against the over-simplified repetition priming account of the SFP effect.

The foreperiod-RT function corresponding to the variable-foreperiod effect was the other main focus of the current study. Experiments 1 and 2 used the same distribution for the shorter and longer foreperiods while using different pair of foreperiods on either the increasing or the decreasing side of the foreperiod-RT function in a fixed-foreperiod paradigm. The results from the variable-foreperiod paradigm in the present study followed the direction of the foreperiod-RT function in a fixed-foreperiod paradigm, which means that the direction of the variable-foreperiod

effect was not determined by the proportions of different foreperiods. Rather, it was determined by the corresponding direction of the fixed-foreperiod effect. Solid evidence was not found in Experiment 3, but the data point to the same rule behind the variable-foreperiod effect with a non-aging foreperiod distribution. The results further indicated that the direction of the variable-foreperiod effect was independent from the general or relative size of the SFP effect, implying a dissociation between the two effects.

A Memory-Based Sequential Foreperiod Effect

Before the trace-conditioning model was proposed, the SFP effect was thought to be driven by the expectation of having a foreperiod repetition in the next trial. This account was straightforward but could not explain the asymmetry of the SFP effect. Los (1996, p. 178) abandoned this intentional account and linked temporal preparation to classical conditioning in non-human species, which is a more implicit and unintentional process. The formal trace-conditioning model was proposed by Los et al. (2001); it assumed that the SFP effect is caused by the memory trace that contains the activation peaks of critical moments corresponding to each foreperiod. The change of activation is determined by the relative lengths of the foreperiods. This model predicts the asymmetric SFP effect in a uniform foreperiod distribution, but it has limited explanatory power when dealing with other foreperiod distributions.

The multiple trace theory (Los et al., 2014) was built on the basis of the trace-conditioning model. Based on this theory, each previous trial is stored in a single memory trace, including the activation and inhibition values. The aggregation of all previous memory traces determines the RT of the current trial. Adding multiple memory traces to the theory was intended to predict the variable-foreperiod effects in different foreperiod distributions, not about the SFP effect. However, sticking to the activation-inhibition ratio made the theory incapable of predicting a significant SFP effect at the longer foreperiod, which was found in the present study.

Sanabria and Correa (2013) introduced a preceding regular rhythm before stimulus onset, using the last tone in the rhythm sequence as the warning signal. They found that the interval between the tones in the rhythm could serve as the preceding foreperiod and produced a pattern similar to the SFP effect. Responses were faster when the rhythm matched the foreperiod, at both the shorter and the longer foreperiods. This finding implies that the SFP effect could be driven by something as simple as the memory of a rhythm rather than the inhibition or activation values

marked on the memory trace. In Steinborn et al. (2009) and Steinborn et al. (2010), an inter-trial change of the warning signal also modulated the SFP effect without changing the actual foreperiod, indicating that any component of that memory trace could modulate its effect on the current trial, not necessarily changing the foreperiod.

Capizzi et al. (2015) and the present study showed that with a non-aging foreperiod distribution, it is not unusual to find a significant SFP effect at the longer foreperiod. Moreover, the current research pointed out that the relative sizes of the SFP effects were closely related to the proportions of different foreperiods rather than the absolute foreperiod durations. The results support a multiple-memory-trace account where previous memory traces aggregate to promote the temporal preparation of the current trial. Instead of the activation-inhibition ratio, the distance and identity of the memory trace can function together to produce the SFP effect. The same memory improves preparation, whereas a different memory trace (different foreperiod) interferes the preparation. With these assumptions, the account should be able to predict the SFP effect at the longer foreperiod and produce different sizes of the SFP effect in a non-aging foreperiod distribution.

Reconnecting the Two Foreperiod Paradigms

One of the first attempts to integrate the fixed- and variable-foreperiod paradigms was made by Bertelson and Tisseyre (1968). They used a click as the warning signal prior to onset of one of two lamps, to which participants were to respond by pressing a left or right key with the index or middle finger of their preferred hand. Bertelson and Tisseyre compared results obtained with the fixed- and variable-foreperiod paradigms and found that for the foreperiods up to 300 ms, temporal preparation was similar regardless of whether the foreperiod was predictable (fixed foreperiod) or not (variable foreperiod).

However, as additional variable-foreperiod studies were conducted using longer foreperiods, an increasing number of differences were found between the results for the two foreperiod paradigms, including the difference in foreperiod-RT function and the SFP effect. Consequently, the two foreperiod paradigms came to be regarded as two distinct phenomena instead of having the same origin.

The important step of reconnecting the two foreperiod paradigms was taken by Los et al. (2014), in which a simplified version of the multiple trace theory without the activation-inhibition

ratio was used to account for the fixed-foreperiod effect. A lower maximum and a greater temporal dispersion as the imperative moment is moved further from the warning signal were added to predict a shorter RT at the shorter foreperiod. These assumptions, however, were not able to produce a "U"-shape curve of the fixed-foreperiod effect. In the current study, on the contrary, I did not attempt to propose an account to explain both foreperiod paradigms. The results of the three experiments indicated that by using a non-aging foreperiod distribution, the variable-foreperiod effect would get back to its baseline, which is the foreperiod-RT function in a fixed-foreperiod paradigm. This reconnection further implies that the endogenous expectation, which was assumed to be inhibited by using a non-aging foreperiod distribution, should be responsible for the deviation of the variable-foreperiod effect from the fixed-foreperiod effect.

A New Construct

Currently, the most powerful tool to explain the variable-foreperiod effect and the SFP effect is the multiple trace theory by Los et al. (2014). The main issue with the multiple trace theory and the trace-conditioning model is that they strictly reject any strategic or intentional factor in the construct. Based on these accounts, all results related to the variable-foreperiod effect and the SFP effect should be implicit and unintentional. Mattiesing et al. (2017) similarly rejected a strategic account. They conducted their study in two sessions separated by seven days. Different groups of participants went through a variable-foreperiod experiment with different foreperiod distributions in Session 1. In the second session, all the participants performed with a uniform foreperiod distribution. The study detected a modulation from the foreperiod distribution in Session 1 on the variable-foreperiod effect in Session 2, which was regarded as evidence supporting a memory-based account for the variable-foreperiod effect instead of a strategy-based one.

This conclusion of Mattiesing et al. (2017) provided evidence that long-term memory could modulate the variable-foreperiod effect. However, it did not completely rule out the possibility that a strategic factor could still play a role. Moreover, Steinborn and Langner (2011) and Vallesi et al. (2014) supported an intentional-unintentional dissociation between the variable-foreperiod effect and the SFP effect, respectively. Without an intentional component, any construct attempting to explain the phenomena in a variable-foreperiod paradigm would not be able to

explain why the variable-foreperiod effect is modulated by other resource-consuming processes while the SFP effect is not affected.

Therefore, based on the results of the current study and the knowledge from prior research, I propose a new construct to explain the phenomena in a variable-foreperiod paradigm, which regards the fixed-foreperiod effect as the baseline of the variable-foreperiod effect, and integrates both the endogenous expectation from dual-process models and the a multiple-trace account from the multiple trace theory.

Compared to the fixed-foreperiod paradigm, a variable-foreperiod paradigm is a more complex scenario. Although within a trial, the task could be identical between the foreperiod paradigms, because of a varied foreperiod across trials, the uncertainty faced with the participants is increased, which allows other mechanisms to have significant influences. The most critical modulation is from the endogenous expectation assumed in many dual-process models (e.g., Capizzi et al., 2015; Vallesi, 2010). This process reflects an intentional strategic mechanism that participants use to deal with cross-trial uncertainty of the foreperiod. It is assumed to be closely related to the conditional probabilities of the imperative stimulus appearing at different critical moments. In each block, participants gradually picked up the experience of this changing probability and change their expectation accordingly. When a uniform foreperiod distribution is used, this expectation provides better preparation for the longer foreperiod, thus turning the foreperiod-RT function to decreasing and diminishing the effect of previous trials on the performance of long-foreperiod trials. However, when a non-aging foreperiod distribution is used, because the conditional probability is kept as .5 for all critical moments, this process is inhibited. In this case, the response speed at each foreperiod is mainly modulated by the foreperiod duration, which is the same as in a fixed-foreperiod paradigm.

Apart from the intentional strategic mechanism, a memory-based unintentional process also plays a role in a variable-foreperiod paradigm. After each trial, the warning signal, the target stimulus, and the temporal relation between them form an individual piece of memory. When the warning signal in the subsequent trial appears, it automatically serves as a retrieval cue. Through this process, the retrieval of a preceding experience of the same foreperiod improves the preparation of responding to the imperative stimulus while the retrieval of a different experience harms the preparation, which leads to the SFP effect. This effect is less pronounced when the foreperiods are similar because a decreased distinctiveness of memory makes it more difficult to

retrieve any particular memory trace. On the other hand, retrieval is easier when a certain foreperiod has a larger proportion in the foreperiod distribution, which leads to different sizes of the SFP effect. Compared to the endogenous expectation, this memory-based mechanism is more automatic and less demanding on mental resources. The current study showed that with a non-aging foreperiod distribution, while the variable-foreperiod effect returned to the same direction as the fixed-foreperiod effect, the foreperiod sequence still modulated response speed. The fact that the relative sizes of the SFP effect were determined by the proportions of foreperiods rather than the fixed-foreperiod effect supports a dissociation between the variable-foreperiod effect and the sequential foreperiod effect.

This proposed construct has some implications which should be investigated by future research. First, the SFP effect is assumed to be based on the memory of prior trials, which means that this effect should be changing across trials within a block. Trial-level data instead of condition-level data should be used in this case to see whether an enlarged SFP effect could be found at the end of a block compared to the beginning. Second, because the current construct assumes a close relation between the fixed- and variable-foreperiod paradigms, it is still possible for arousal to play a role in a short-foreperiod scenario. The arousal-based SFP effect at the longer current foreperiod is assumed to be the opposite direction as the memory-based SFP effect, which perhaps was the reason for the absence of a significant SFP effect at the long current foreperiod in Experiments 2 and 3. To address this problem, both trial-level data and model comparison between one without the arousal component and another with it are probably needed.

The current study also suffered from some limitations. Because in a non-aging foreperiod distribution, the shorter foreperiod always takes a larger proportion, it is impossible to separate the effect of the proportions from that of the relative lengths of foreperiods. Moreover, direct evidence supporting the presence of the endogenous expectation cannot be found in the current study. The concept of an endogenous expectation process still needs more clarification. A more precise definition of this process is demanded before the proposed construct can become a formalized model.

Conclusion

The current study found another piece of the jigsaw puzzle of the mysterious distinction between the fixed and variable foreperiod paradigms. Different from Vallesi (2010) but consistent

with Capizzi et al. (2015), the results suggest that the sequential foreperiod effect reflects a benefit of repetition, with this benefit due to the influence of the memory traces of prior trials. I showed that in a variable foreperiod paradigm, when the conditional probability of the imperative stimulus appearing at the next foreperiod stays constant over time, the foreperiod-RT function follows the same direction as that in a fixed foreperiod paradigm. This finding will encourage future studies that aim to integrate the two foreperiod paradigms and provide a complete account of general temporal preparation effects.

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APPENDIX

Table 1. Mean Reaction Times (ms) with Standard Deviations in the Parentheses as a Function of Foreperiod Sequence and Current Foreperiod in Experiments 1-3

Experiment	Current Foreperiod (ms)							
	Foreperiod Repetition				Foreperiod Alternation			
	50	200	400	1400	50	200	400	1400
1	—	—	439(55)	484(64)	—	—	463(63)	492(60)
2	409(52)	400(51)	—	—	413(51)	400(48)	—	—
3	418(57)	—	425(56)	—	427(57)	—	429(50)	—