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Revisiting variable-foreperiod effects: evaluating the repetition priming account

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Abstract

A warning signal preceding an imperative stimulus by a certain foreperiod can accelerate responses (foreperiod effect). When foreperiod is varied within a block, the foreperiod effect on reaction time (RT) is modulated by both the current and the prior foreperiods. Using a non-aging foreperiod distribution in a simple-reaction task, Capizzi et al. (*Cognition, 134*, 39-49, 2015) found equal sequential effects for different foreperiods, which they credited to repetition priming. The multiple-trace theory of Los et al. (*Frontiers in Psychology*, *5*, Article 1058, 2014) attributes the slope of the foreperiod-RT function to the foreperiod distribution. We conducted three experiments that examined these predicted relations. Experiment 1 tested Capizzi et al.'s prediction in a choice-reaction task and found an increasing foreperiod-RT function but a larger sequential effect at the shorter foreperiod. Experiment 2 used two distinct short foreperiods with the same foreperiod distribution and found a decreasing foreperiod-RT function. By increasing the difference between the foreperiods used in Experiment 2, Experiment 3 yielded a larger sequential effect overall. The experiments provide evidence that, with a non-aging foreperiod distribution, the variable-foreperiod paradigm yields unequal sequential-effect sizes at the different foreperiods, consistent with the multiple-trace theory but contrary to Capizzi et al.'s repetition-priming account. The foreperiod-RT functions are similar to those of the fixed-foreperiod paradigm, which is not predicted by the multiple trace theory.

Keywords Foreperiod · Variable-foreperiod effect · Non-aging foreperiod distribution · Repetition priming

Introduction

In a simple- or choice-reaction task, if a warning signal or cue always appears[1] before onset of the imperative stimulus, participants are able to utilize the relation between the two to prepare for the imperative stimulus before it appears (Shaffer, 1966). If the signal or cue does not provide any information about how to respond to the stimulus, then the warning signal is usually classified as neutral. A neutral warning signal only provides temporal information, which is the timing of imperative-stimulus onset. This temporal relation is marked by the foreperiod – the interval between termination of the former and onset of the latter. The foreperiod effect, which is how reaction time (RT) and error percentage (EP) are modulated by foreperiod duration, has been studied with two basic paradigms. In a fixed-foreperiod paradigm, the foreperiod remains constant across trials within a trial block, whereas in a variable foreperiod paradigm, different foreperiods are randomly intermixed in each block. Results show that in these two paradigms, the foreperiod modulates human performance in different ways.

The family of foreperiod effects

In the fixed-foreperiod paradigm, plotting RT as a function of foreperiod often yields a "U"-shaped curve (as in Fig. 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 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, 1981). Also, some research has provided evidence that, at

[1] In a case where an explicit cue is not available, participants are able to prepare for the imperative stimulus using the response of the previous trial as a warning signal (Niemi & Näätänen, 1981).

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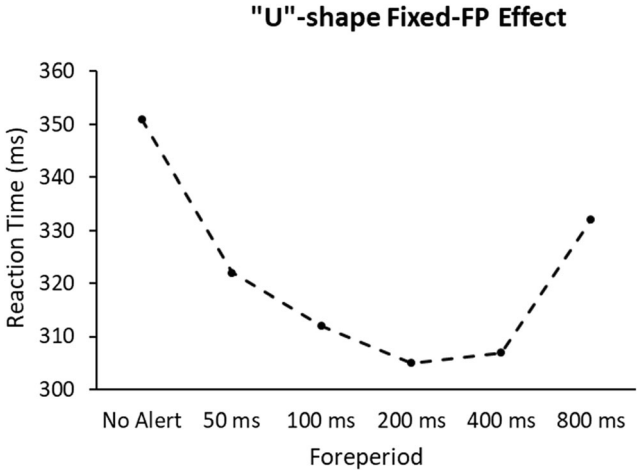

Fig. 1 Posner et al. (1973): Mean reaction time as a function of foreperiod condition for the spatially compatible mapping in Experiment 1

short foreperiods (< 300 ms), the effect is closely related to phasic arousal (Posner et al., 1973; Tona et al., 2016).

In the variable-foreperiod paradigm, the situation is more complex. The fact that more than one foreperiod may occur increases the participant's temporal uncertainty. In this case, the slope of the foreperiod-RT function is negative, regardless of the foreperiod length (Los et al., 2001; Steinborn et al., 2008, 2009, 2010; see Niemi & Näätänen, 1981, for a review). Moreover, when foreperiod varies across trials, RT is affected by the foreperiod of previous trials, especially the immediately preceding one, which is called the sequential foreperiod (SFP) effect. When the current foreperiod is short, responses are delayed by a preceding long foreperiod. In contrast, when the current foreperiod is long, RT is not affected by the prior foreperiod's length (as in Fig. 2). This asymmetric pattern is typical among studies of the SFP effect (Los et al., 2001; Steinborn et al., 2008, 2009, 2010; Vallesi & Shallice, 2007).

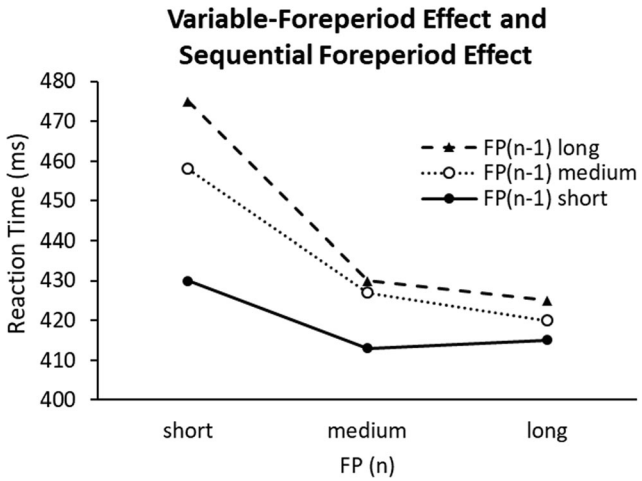

Fig. 2 Steinborn et al. (2008): Mean reaction time as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n) in Experiment 1 (long FP-set)

Prior studies

Because both the variable-foreperiod effect and the SFP effect are observed in the variable-foreperiod paradigm, the majority of the literature has focused on their connection instead of the link between the fixed- and variable-foreperiod paradigms. In a typical variable-foreperiod task, each foreperiod has a *critical moment*, which refers to its expected expiration. 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, it is possible for each critical moment to become the imperative moment. 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 remain as the candidates of the imperative moment. This relation between the critical moments and the imperative moment has been regarded as an essential tool to explain the mechanism behind the SFP effect and the variable-foreperiod effect.

Expectancy and repreparation

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

The other half of the picture, the robust sequential effect at the shorter current foreperiod, is explained by assuming that participants always anticipate 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 than foreperiod repetition (e.g., Los et al., 2001; Steinborn et al., 2008).

Trace conditioning and multiple trace theory

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 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 trial block. In contrast, the activation peaks of shorter foreperiods decrease, which leads to worse preparation in subsequent trials whenever their critical moments are bypassed by a later imperative moment. The model not only provides a plausible explanation for the presence of the sequential effect at a short current foreperiod and the absence at a long current foreperiod, but it also explains why in a variable-foreperiod paradigm, performance at the shorter foreperiod is no better, if not worse, than that at 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.

Despite its explanatory power, the trace-conditioning model has 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. Second, the model can only be applied readily to cases with a uniform foreperiod distribution (Los & Agter, 2005). To take advantage of the ability of the trace-conditioning model to account for the asymmetric SFP effect, while overcoming its difficulty in accounting for the effect of foreperiod distribution, Los et al. (2014) outlined a multiple trace theory of temporal preparation (MTP), which they described "as an adjustment of the trace-conditioning model" (p. 7). This account links temporal preparation to the multiple trace theory of memory, which has been used to explain a variety of memory-related phenomena (e.g., Hintzman, 1986). In MTP, each previous trial is stored as a memory trace. Within each memory trace, the strength of activation and inhibition related to each foreperiod still follows the trace-conditioning model, which ensures MTP's explanatory power on the short-term asymmetric SFP effect. But, whereas the trace-conditioning model focuses on how different foreperiods modify the same memory trace of temporal preparation, MTP assumes that the warning signal for the next trial serves as a retrieval cue for all previous memory traces. Those traces then contribute to the current preparatory state. MTP accounts for the foreperiod-distribution effect in the following manner. Because short-foreperiod trials are more frequent in an exponential distribution than in a uniform distribution, the number of short-foreperiod memory traces is larger. This larger number of traces results in greater trace weights for the short foreperiod, which leads to a higher level of preparation and shorter RTs.

For MTP, the variable-foreperiod effect and the SFP effect are the long- and short-term consequences, respectively, of the memory traces. Because it is assumed that both effects are influenced by the memory traces, but without a formalized model that specifies the relative strengths of the long-term and short-term weightings, the theory does not provide a complete account of the dissociation between the variable-foreperiod effect and the SFP effect. This is especially so for the results of studies that implicate a resource-consuming mechanism involving processing time and probability as the basis of the variable-foreperiod effect (Steinborn & Langner, 2011; Vallesi et al., 2014; but see Van Lambalgen & Los, 2008, for results counter to this implication). To explain the upward direction of the foreperiod-RT function in a fixed-foreperiod paradigm, Los et al. (2014) also assumed that the stored activation at each critical moment will be more dispersed if the critical moment is more remote from the warning signal. This assumption only predicts an upward direction and thus does not account for the entire "U"-shaped foreperiod-RT function in the fixed-foreperiod paradigm, especially the decreasing part of the curve at short foreperiods. Nevertheless, MTP provides a pathway for reconnecting the two foreperiod paradigms, as the fixed-foreperiod effect can be regarded as a baseline condition of the variable-foreperiod effect. This reasoning was adopted in interpreting the results of the current study.

Arousal-based dual-process model

Inspired by the dissociation found between the variable-foreperiod effect and the SFP effect, Vallesi (2010) proposed an arousal-based dual-process model, according to which the asymmetric SFP effect and the decreasing foreperiod-RT function are mainly caused by an additional endogenous preparation process. This process is similar to the combination of expectancy and repreparation mentioned by Niemi and Näätänen (1981). When the endogenous preparation process is absent (e.g., in early stages of cognitive development), the SFP effect is mainly driven by arousal, which is constantly changed by the current foreperiod and affects the response speed of the next trial. Short foreperiods promote arousal, whereas long foreperiods lower the arousal. This arousal-based SFP effect is symmetric in that shorter preceding foreperiods lead to shorter RTs regardless of the current foreperiod.

Vallesi and Shallice's (2007) Experiment 2 examined the variable-foreperiod and SFP effects in different age groups (4, 5 or 6 years) using a simple-reaction task. The foreperiods were 1, 3, and 5 s. The SFP effect emerged as early as the age of 4 years, whereas the decreasing foreperiod-RT function did not appear until age 5. For 4-year-old children, RT consistently increased as the foreperiod of the preceding trial increased, regardless of the current foreperiod, consistent with an arousal-based SFP effect. In contrast, the typical SFP asymmetry was found in 6-year-old children. These results imply that the mechanism behind the decreasing foreperiod-RT function and the asymmetry of the SFP effect were absent in 4-year-old children but developed by age 6. Vallesi et al.

(2007) further investigated the finding of Vallesi and Shallice (2007), with the introduction of transcranial magnetic stimulation (TMS). TMS on right dorsolateral prefrontal cortex 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.

This dissociation between intentional and unintentional processes 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 when it is not. 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 but not the SFP effect. Vallesi et al. had their participants perform a subtraction task during the foreperiod in a variable-foreperiod paradigm and showed that this dual-task manipulation also mainly modulated the variable-foreperiod effect instead of the SFP effect. Both studies support a controlled, resource-consuming preparatory mechanism behind the variable-foreperiod effect and a more automatic one underlying the SFP effect (see Van Lambalgen & Los, 2008, for a counterexample).

Although the general dual-process account was supported by later studies, Vallesi's (2010) arousal-based model faces a major limitation. Evidence supporting the symmetric SFP effect has usually been found in special groups (4-year-old children) or with intrusive task settings (e.g., TMS on right dorsolateral prefrontal cortex). Critical evidence is absent with ordinary samples and usual task settings.

Repetition priming account

In a variable-foreperiod paradigm without catch trials, every time after the critical moment of the second longest foreperiod is bypassed, the imperative stimulus will appear at the critical moment of the longest foreperiod, which provides the best chance to get prepared. This is regarded, according to the dual-process model, as the cause of the absence of the SFP effect at the longest current foreperiod. If that is the case, then by manipulating the foreperiod distribution and introducing catch trials, it is possible to keep the conditional probability of the imperative stimulus onset constant (non-aging distribution), which is supposed to diminish the effect from endogenous preparation.

Capizzi et al. (2015) tested this assumption using a simple-reaction task. In their Experiment 2, two foreperiods (400 and 1,400 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 predicted by the dual-process model, with a non-aging foreperiod distribution, the pattern of the SFP effect was found not to be asymmetric, and an increasing foreperiod-RT function was obtained, which is consistent with the function obtained with a fixed-foreperiod paradigm. Nevertheless, the SFP effect was symmetric in a different manner than in Vallesi (2010). 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) interpreted the evidence as supporting a dual-process model for which the other component in addition to endogenous preparation is repetition priming. This priming is memory-based rather than arousal-based as in Vallesi's (2010) model. According to the repetition priming account, the SFP effect on the current trial is 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 when the current trial has a different foreperiod than the prior one. This priming effect produces equivalent differences at different foreperiods regardless of the foreperiod duration, leading to a symmetric SFP-effect pattern (as in Fig. 3).

Although Capizzi et al.'s (2015) dual-process model seems an acceptable answer, at least two issues remain unresolved. First, studies supporting MTP (Los et al., 2017, 2021; Mattiesing et al., 2017) used a choice-reaction task, whereas Capizzi et al.'s participants were tested in a simple-reaction task. Even though the two types of tasks exhibit consistent patterns in general, previous studies have shown that using a simple- or choice-reaction task modulates the variable foreperiod effects (Steinborn et al., 2008, 2009, 2010;

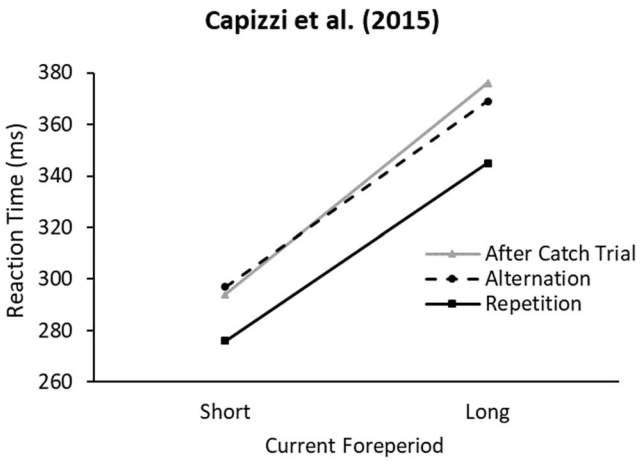

Fig. 3 Capizzi et al. (2015): Mean reaction time as a function of the foreperiod sequence and the current foreperiod in Experiment 2

Steinborn & Langner, 2012; Vallesi et al., 2013). This modulation is because response selection is minimal and motor preparation high in simple-reaction tasks, whereas response selection is a significant component of choice RT (Steinborn et al., 2008; Woods et al., 2015). So, it is informative to test Capizzi et al.'s repetition priming account in choice-reaction tasks to ensure its explanatory power on a broader range of temporal preparation phenomena. Second, Capizzi et al. (2015) regarded the nonsignificant, similar sizes of the sequential effects at 400 and 1,400 ms as an important finding (second paragraph, p. 45), which led them to propose the repetition priming account for the SFP effect (third and fifth paragraphs, p. 47). However, their acceptance of the null hypothesis – that the repetition priming effect is equivalent for short and long foreperiods – was based on sample sizes less than 15 (their Experiments 2 and 3). To assess the reliability of this crucial result, absence of interaction should be confirmed using a larger sample with adequate statistical power. If, instead, an interaction were obtained, the outcome would provide evidence against the repetition priming account.

Another noteworthy finding of Capizzi et al. (2015) is the increasing foreperiod-RT relation, acting as a direct response to the argument in Los et al. (2014) that "the approximately flat RT–FP function for non-aging FPs is problematic for the view of hazard-driven preparation rather than support for it" (p. 4). There are at least two possible reasons for the change from a decreasing function (as in the majority of prior studies) to an increasing one. For one, it could be due to a higher proportion of short foreperiod trials. According to MTP, a higher proportion of short-foreperiod trials leads to better preparation at the corresponding critical moment. If so, a non-aging foreperiod distribution should produce an increasing foreperiod-RT function, regardless of the specific foreperiods involved in the task. Alternatively, the foreperiod-RT function could be determined by the factor that produces the fixed-foreperiod effect. Capizzi et al. (2015) assumed that a non-aging foreperiod distribution inhibits the endogenous preparation process, in which case the variable-foreperiod effect in this scenario could rely on the foreperiod duration itself. If so, then the fixed-foreperiod effect could form the baseline of the variable foreperiod effect, supporting the possibility of linking the two paradigms. This latter account predicts that if two extremely short foreperiods (e.g. 50 ms vs. 200 ms) are used, the foreperiod-RT function should be decreasing.

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.

Although the effective power and test reliability is a function of several factors (Miller & Ulrich, 2013), the present study focused on replicating the original experiment with a more adequate sample size. A simulation-based power analysis was conducted to estimate the sample size that had a probability of .9 to detect the main effects of the current foreperiod and the foreperiod sequence, and also their interaction. The data (means, standard deviations, and estimated correlations between conditions) from Experiment 2 of Capizzi et al. (2015) were used to represent the population, which is assumed to have a normal distribution. Then, random samples (10,000 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), with two within-subject factors, Foreperiod Sequence (repetition vs. alternation) and Current Foreperiod (short vs. long). A significant two-way interaction in this main ANOVA is equivalent to a significant one-way ANOVA result on the sizes of sequential effects in Capizzi et al. (2015). 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 yield a statistical power above .9. This result means that, based on the data of Capizzi et al. (2015), if Experiment 1 did not detect this difference, it would be reasonable to be conclude that the SFP effects at different foreperiods are of similar sizes, as predicted by the repetition priming account.

Method

Participants

A total of 76 students (34 male, 42 female, age: 17–31 years, mean: 19.5 years, SD: 1.9 years) participated. All participants in this and the remaining experiments were enrolled in an introductory psychology course at Purdue University and received research credits. They reported having normal or corrected-to-normal vision and audition, and were naïve to the study's purpose. One participant under the age of 18 years 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 1,000 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 1,500 ms, the same as in Capizzi et al. (2015). After the inter-trial interval, the auditory warning signal was presented for 50 ms, following which, for a regular trial, a variable foreperiod of 400 ms (short) or 1,400 ms (long) started. After the foreperiod expired, the imperative stimulus was presented at the display center. Participants were told to press the left button when "**q**" appeared and to press the right button when "**p**" appeared. Both letters were in "Courier New" font. The imperative stimulus stayed on the display until a response was made.[2] Error feedback was provided after an incorrect response, 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 for 2,400 ms (1 s longer than the longer foreperiod), after which a reminder slide saying "No response is needed" was presented for 1,500 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 – eight with the shorter foreperiod, four with the longer foreperiod, and four 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 short foreperiod, eight with the long foreperiod, and eight catch trials. Trials with different foreperiods and catch trials were randomly mixed in each block.

Before the experiment, participants were told the average duration for the session (30–40 min) and the mapping they were to use. Participants were told to maintain their index fingers on the corresponding keys and not to use other fingers to respond. Speed and accuracy of 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 < 100 ms or > 1,000 ms were regarded as outliers and excluded (0.96%). To measure the SFP effects more precisely, the first trial of each block and trials following an incorrect response were also discarded (5.2%) from further data analysis. As for the power analysis simulation, trials following either a short-foreperiod trial or a long-foreperiod trial in all test blocks were submitted to a two-factor repeated-measures ANOVA (Foreperiod Sequence × Current Foreperiod) on mean RT of correct responses and error percentage (EP). Two additional one-way repeated-measures ANOVAs (Current Foreperiod) were conducted to test the significance of the SFP effect on RT at each foreperiod, with the purpose of confirming whether a significant SFP effect could be found at the longer current foreperiod as well as the shorter one. All effects were tested at an α level of .05. The mean RT data for this and the other two experiments have been posted online (Han, 2021).

Figure 4 shows RT of the correct responses (top) and EP (bottom) as a function of Current Foreperiod,[3] and Table 1 includes the mean RTs and SDs for all three experiments. EP

[2] In Capizzi et al. (2015), the imperative stimulus was only displayed for 100 ms and then replaced by a blank screen until the participant made a response or for a maximum duration of 2,000 ms.

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

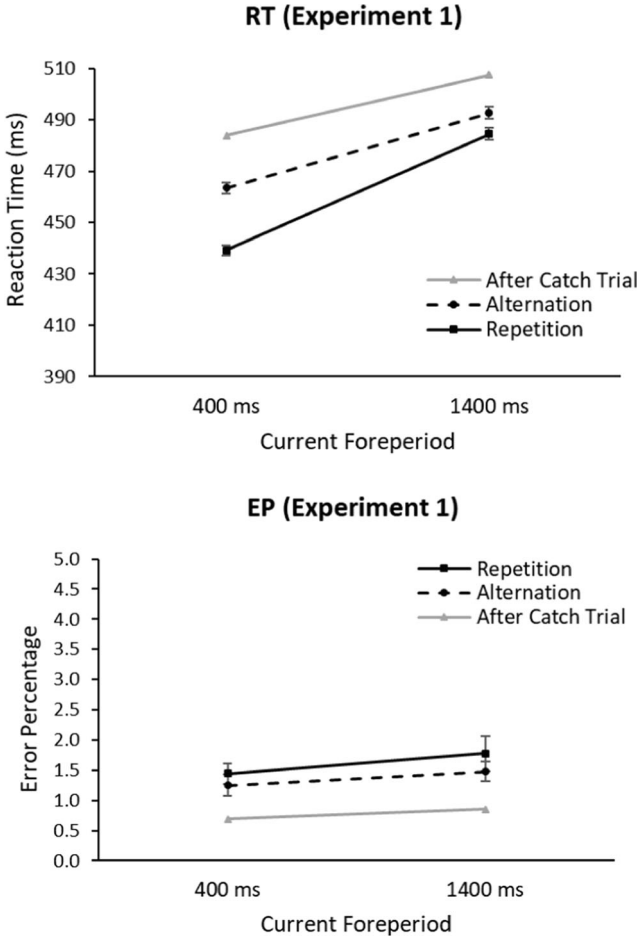

Fig. 4 Experiment 1: Mean reaction time as a function of Current Foreperiod (**top**); error percentage as a function of Current Foreperiod (**bottom**). Error bars in this and the other figures represent the adjusted standard errors for within-subject factors using the method described in O'Brien and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

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 1,400 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 1,400 ms (8 ms). For the separate one-way ANOVAs, the Foreperiod Sequence effect was significant at both the 400-ms foreperiod, $F(1, 74) = 123.59$, $p < .001$, $\eta_p^2 = .63$, and 1,400-ms foreperiod, $F(1, 74) = 8.63$, $p = .004$, $\eta_p^2 = .10$.

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 short (400 ms) and the long (1,400 ms) foreperiods, as in Capizzi et al. Most important, the interaction of Current Foreperiod × Foreperiod Sequence indicated that the SFP effect was larger at the short foreperiod than at the long foreperiod. This result is inconsistent with the repetition priming account of Capizzi et al., according to which the SFP effects should be of similar sizes at short and long foreperiods.

The larger SFP effect at short than long foreperiods is consistent with Los et al.'s (2014) multiple trace theory. This is because it assumes that a long previous foreperiod produces inhibition to the critical moment of the short foreperiod but a short previous foreperiod does not affect the preparation at the critical moment of the long foreperiod. Because the interaction in the current experiment is robust and the sample size was much larger than in Capizzi et al. (2015), the most likely possibility is that the difference was not detected by Capizzi et al. due to insufficient statistical power of their study. Alternatively, the nonsignificant difference in SFPs at short and long foreperiods in their study could be due to the reduced

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	1,400	50	200	400	1,400
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)	-

response-selection demand and preparation differences associated with simple-reaction tasks, although it is unclear how this general difference between task scenarios might modulate the repetition priming effect differently for different foreperiods. Langner et al. (2018) investigated how different stimulus-response event sequences in a choice-reaction scenario modulate the variable foreperiod effects. In their study (Experiment 2), stimulus-response event alternation, which is unique in choice tasks compared to simple-reaction tasks, made the sequential foreperiod effects less asymmetric compared to event repetition. This result suggests that symmetric sequential effects are more likely to be found in choice-reaction tasks compared to a simple-reaction scenario.

With regard to the variable-foreperiod effect, Experiment 1 was informative by revealing an increasing foreperiod-RT function that cannot be predicted from the trace-conditioning model. Based on the MTP, the larger proportion of shorter foreperiod trials could be the basis of that foreperiod's advantage in terms of response speed by having more previous memory traces contributing to the activation at the shorter foreperiod's critical moment. Alternatively, 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 the two foreperiod paradigms will be in the same direction. These explanations can be tested in a short-foreperiod scenario. When both foreperiods are less than 300 ms, based on the direction of the fixed-foreperiod effect, the foreperiod-RT function will be decreasing, whereas based on the foreperiod proportions, the function should be increasing.

Experiment 2

The second experiment resembled most of the settings in Experiment 1 except that two very 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 phasic arousal. However, in Steinborn et al. (2008), a typical but smaller asymmetry of the SFP effect 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. This prediction means that the shorter preceding foreperiod should produce faster responses regardless of the length of the current foreperiod.

However, if the SFP effect in a short-foreperiod scenario is determined by the same factor as in Experiment 1, then RT should be shorter for foreperiod repetition than for alternation. Moreover, based on the MTP, because the relative effect size is determined by the relative lengths 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. Los et al. (2014) argued, with regard to MTP, that "the theory should also account for the development of temporal preparation over very brief intervals" (p. 11). Based on the current assumptions of MTP, the preparation at any foreperiod is determined by the activation-inhibition states (strengths of activation and inhibition) stored in each memory trace, the strength of each memory trace (memory trace is more dispersed and weaker as the foreperiod gets longer), and the total number of previous memory traces with each foreperiod. In a uniform distribution, because the total number of previous memory traces is equal for different foreperiods, the activation-inhibition states overwrite the influence of trace strength, producing a decreasing foreperiod-RT function. However, to explain the increasing foreperiod-RT function in Experiment 1, it has to be assumed that in a non-aging foreperiod distribution, the influence from the number of memory traces and memory strength together is larger than that of the activation-inhibition states. If this is the case, then a similar distribution, but 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). Also, because of a shorter temporal distance between the critical moments, previous 200-ms foreperiod trials should produce less inhibition to the 50-ms critical moment compared to what 1,400-ms foreperiod trials produced to the 400-ms critical moment, which should contribute to the better temporal preparation at 50-ms foreperiod.

If, alternatively, without endogenous preparation, the foreperiod-RT functions from both fixed- and variable-foreperiod paradigms share the same trend (as has been shown in some previous studies; Bertelson & Tisseyre, 1968, and Lawrence & Klein, 2013), then the foreperiod-RT function in the current experiment should be the opposite direction from that in Experiment 1 (Han & Proctor, 2022; 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 sample size to detect all the expected effects in Experiment 2. It was assumed that the foreperiod-RT function and relative size of the SFP effect are 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 Experiment 2 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 1,400-ms foreperiod. 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 and 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 estimated to have a statistical power above .9 to detect all the effects matching those revealed in Experiment 1.

Method

Participants

One hundred and thirty-three students (48 male, 85 female, age range: 17–22 years, mean: 18.5 years, SD: 0.9 years) from the same participant pool participated, none of whom had participated in Experiment 1. Three participants were excluded because of some problem with the experiment process, and four others because their ages were under 18 years of age.

Apparatus, stimuli, and procedure

The apparatus, stimuli and procedure 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, eight with the shorter foreperiod, four with the longer foreperiod and four 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, eight with the longer foreperiod, and eight 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 pandemic protocol, which was not in effect when Experiment 1 was conducted.

Results

Outliers (0.32%) were excluded using the same criteria as in Experiment 1. To measure the SFP effect 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- or long-foreperiod trial in all test blocks were analyzed as in Experiment 1.

Figure 5 shows RTs 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, $F(1, 125) = 4.62$, $p = .034$, $\eta_p^2 = .04$. Participants were more likely to make errors when encountering foreperiod repetition compared to alternation. The main effect of Current Foreperiod was not significant, $F(1, 125) = 3.36$, $p = .069$, $\eta_p^2 = .03$, but the EP was numerically smaller at the 50-ms than 200-ms foreperiod. The interaction between Foreperiod Sequence and Current Foreperiod was not significant, $F(1, 125) = .23$, $p = .636$, $\eta_p^2 < .01$.

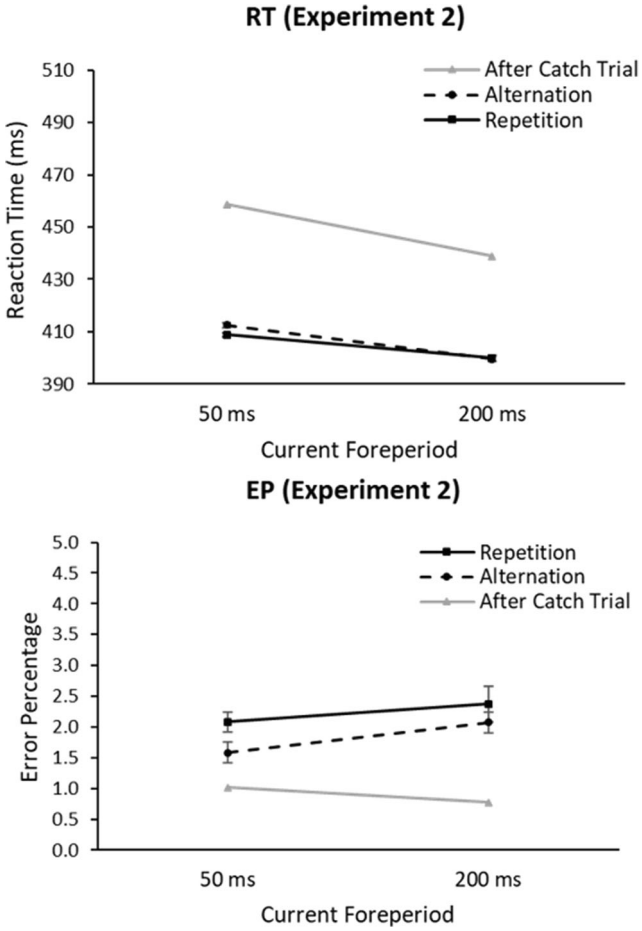

Fig. 5 Experiment 2: Mean reaction time as a function of Current Foreperiod (**top**); error percentage as a function of Current Foreperiod (**bottom**)

The RT ANOVA showed a main effect of Current Foreperiod, $F(1, 125) = 98.49$, $p < .001$, $\eta_p^2 = .44$. Responses were faster when the current foreperiod was 200 ms compared to 50 ms. The main effect of Foreperiod Sequence was not significant, $F(1, 125) = 2.88$, $p = .092$, $\eta_p^2 = .02$. Consistent with Experiment 1, 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 was 50 ms (4 ms) rather than 200 ms (nearly 0 ms). For 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, $F(1, 125) = .08$, $p = .777$, $\eta_p^2 < .01$.

Discussion

Experiment 2 tested the findings of the prior experiment and provided an answer to some of the questions raised by it. First, the main effect of Current Foreperiod was found, indicating a decreasing foreperiod-RT function in the short-foreperiod scenario. This direction is consistent with the prediction based on the fixed-foreperiod effect but this foreperiod-RT function, especially its opposite direction from that observed in Experiment 1, cannot be predicted from the current assumptions of the MTP. Together, Experiments 1 and 2 provide evidence 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, indicating in general that foreperiod repetition did not lead to faster responses than foreperiod alternation. A small interaction was found between Current Foreperiod and Foreperiod Sequence, with separate ANOVAs indicating a significant SFP effect at the 50-ms foreperiod but not the 200-foreperiod. These results are consistent with the predictions of MTP, which also indicates that the activation-inhibition states in a short-foreperiod scenario are similar to those in a long-foreperiod scenario. However, the combination of a similar sequential effect pattern and the opposite foreperiod-RT relation implies that the two effects could be based on distinct mechanisms.

It is worth noting that participants were more likely to make errors when the current foreperiod matched the previous one compared to when it did not. Although the effect was small, it does indicate that 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. This outcome is consistent with some previous studies using the fixed foreperiod paradigm (Han & Proctor, 2022; McCormick et al., 2019; Posner et al., 1973).

The general effect of Foreperiod Sequence was much smaller than in Experiment 1. One explanation could lie in the smaller difference between the pair of foreperiods used in Experiment 2 (200 ms – 50 ms = 150 ms) than in Experiment 1 (1,400 ms – 400 ms = 1,000 ms). If the SFP effect originated from the retrieval of the previous trial (repetition priming account & MTP), 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 Experiment 3 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 the SFP effect was diminished when using a dense foreperiod distribution for which the foreperiods were close to each other (400, 500, and 600 ms). By increasing the difference between the longer and shorter 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. The prior experiments imply that when a non-aging foreperiod distribution is used, the foreperiod-RT function in a variable-foreperiod paradigm has the same direction as that in a fixed-foreperiod paradigm. In the fixed-foreperiod paradigm, the 50-ms foreperiod is on the decreasing side of the RT function, whereas the 400-ms foreperiod is on the increasing side. Thus, when pairing the two foreperiods, it is unclear whether the foreperiod-RT function should be increasing or decreasing. Consequently, as a baseline, fixed-foreperiod trial blocks for each of the foreperiods were added in Experiment 3, and the data of the fixed- and variable-paradigm were analyzed separately. If the Current Foreperiod effect was in the opposite direction in the fixed- and variable-foreperiod conditions, this would provide evidence counter to the hypothesis of a common basis for the effects in each.

Because the purpose of Experiment 3 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 in Experiment 2 (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, age range: 17–23 years, mean: 18.7 years, SD: 1.0 years) from the same participant pool participated. None had participated in the prior experiments. One participant under the age of 18 years 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, eight with the shorter foreperiod, four with the longer foreperiod, and four catch trials to provide a general impression about the mapping and the structure of a block. Fifteen of the test blocks were variable-foreperiod blocks, each containing 32 trials, 16 with the shorter foreperiod, eight with the longer foreperiod, and eight 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 < 100 ms or > 1,000 ms were regarded as outliers and excluded (0.72%). To measure the SFP effects more precisely, the first trial of each block and trials following an incorrect response were also discarded (6.3%) from further analysis. Trials following either a 50- or 400-ms foreperiod trial in all test blocks were analyzed as in the prior experiments. Also, 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 < 100 ms or > 1,000 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 RT 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, $F(1, 58) = 3.06$, $p = .085$, $\eta_p^2 = .05$, neither was the interaction between Current Foreperiod and Foreperiod Sequence, $F(1, 58) = 2.42$, $p = .125$, $\eta_p^2 = .04$. However, the separate one-way ANOVAs revealed a significant Foreperiod Sequence effect at 50-ms foreperiod (9 ms), $F(1, 58) = 18.12$, $p < .001$, $\eta_p^2 = .24$, but not at 400-ms foreperiod (4 ms), $F(1, 58) = 2.23$, $p = .140$, $\eta_p^2 = .04$. For the 50-ms current foreperiod,

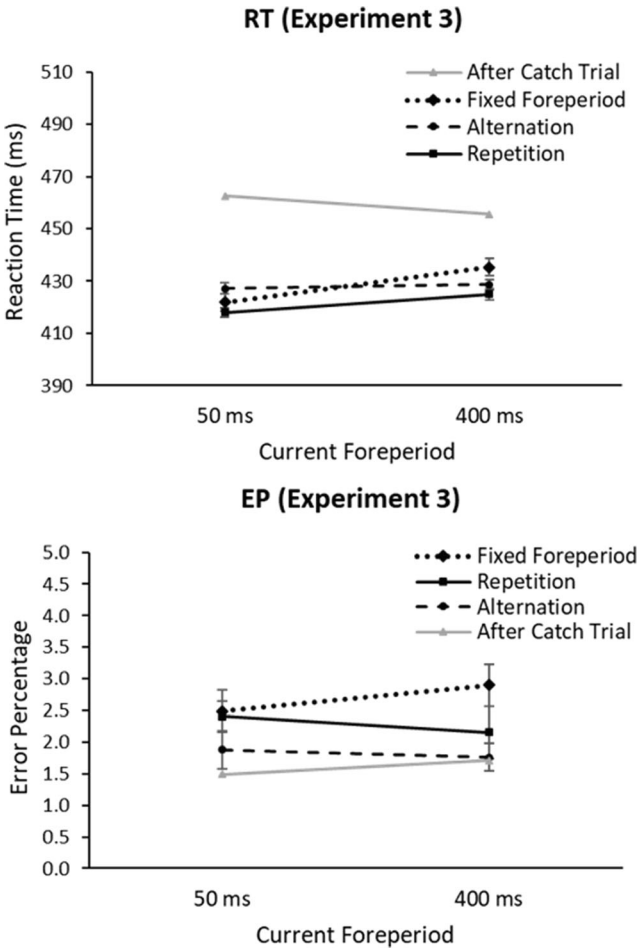

Fig. 6 Experiment 3: Mean reaction time as a function of Current Foreperiod (**top**); error percentage as a function of Current Foreperiod (**bottom**)

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, $F(1, 58) = .74$, $p = .393$, $\eta_p^2 = .01$. In contrast, the ANOVA on RT showed a 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.

Regarding the between-experiment comparison, for the data of Experiments 2 and 3, the SFP effect at the 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 difference between groups was found, $F(1, 183) = 6.32$, $p = .013$, indicating that the SFP effect at 50-ms foreperiod was larger in Experiment 3 than in Experiment 2.

Discussion

Compared to the two prior experiments, Experiment 3 demonstrated a less clear picture. The only significant result from the overall ANOVA was the main effect of Foreperiod Sequence, which, as in Experiments 1 and 2, showed that RT was shorter for foreperiod repetition compared to alternation. Separate one-way ANOVAs found a significant SFP effect at the 50-ms foreperiod but not at the 400-ms foreperiod. The between-experiment comparison showed that the SFP effect at the 50-ms foreperiod in Experiment 3 (9 ms) was significantly larger than that in Experiment 2 (4 ms). This result agrees 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 RT difference it would produce on the current trial. Thus, consistent with the conclusion of Experiment 2, this enlarged main effect of Foreperiod Sequence also agrees with 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 unambiguous 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. In contrast, the results from the one-way ANOVAs showed that the SFP effect was significant at the 50-ms foreperiod but not the 400-ms foreperiod. The fact that the results from the main ANOVA and the one-way ANOVAs lead to different inferences probably indicates that the interaction and SFP effects at the 400-ms foreperiod, if they exist, are small, making the statistical power of the current experiment insufficient to have a high probability of detecting 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 in 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, in which 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 findings imply 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

The present study 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. This highly symmetric pattern of the SFP effect in Capizzi et al.'s experiment has seldom been found in other studies.

With regard to the variable-foreperiod effect, an increasing foreperiod-RT function was found in Capizzi et al. (2015). They used a non-aging foreperiod distribution, which was assumed to inhibit the endogenous preparation process. Without the influence from this process, the variable-foreperiod effect and the SFP effect were hypothesized to resume their baseline levels. 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 they provided was that the faster responses at the short foreperiod were due to the larger proportion of short foreperiod trials (p. 43), a relation consistent with predictions of Los et al.'s (2014) MTP, but which was not further tested by Capizzi et al.

Experiment 1 adopted a sample size with more statistical power than Capizzi et al.'s (2015) study to detect a possible difference between the SFP effects at the shorter (400 ms) and long (1,400 ms) foreperiods. The results showed that although the SFP effect at the 1,400-ms foreperiod was detected, its size was significantly smaller than that at the 400-ms foreperiod. This asymmetric pattern was replicated in Experiment 2, in which 50-ms and 200-ms foreperiods were used, and partially indicated by the results of Experiment 3 that used 50- and 400-ms foreperiods. Therefore, the experiments provide evidence against the 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. The MTP (Los et al., 2014) suggests that the slope of the foreperiod-RT function is mainly determined by the proportions of foreperiods in a foreperiod distribution. Experiments 1 and 2 used similar distributions for the shorter and longer foreperiods while using different pairs of foreperiods on either the increasing or decreasing side of the foreperiod-RT function in a fixed-foreperiod paradigm. The results from the variable-foreperiod paradigm 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. This result is counter to Capizzi et al.'s (2015) suggestion and to what the MTP would seem to predict. This consistent foreperiod effect direction between the two paradigms suggests that, as in the fixed foreperiod paradigm, the foreperiod effect in a variable foreperiod paradigm is largely impacted by the absolute duration of the foreperiod, not just the relation between different foreperiods. As the endogenous preparation process is inhibited by a non-aging foreperiod distribution, the variable foreperiod effect can also produce a U-shaped foreperiod-RT curve, which applies to both short and long foreperiod scenarios. Incontrovertible evidence was not found in Experiment 3, but the data again point to the same rule behind the variable-foreperiod effect with a non-aging foreperiod distribution. The results further indicate 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 considered 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. Los et al. (2001) proposed the formal trace-conditioning model; 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 relative lengths of the foreperiods determine the change of activation-inhibition states. This model predicts the asymmetric SFP effect in a uniform foreperiod distribution. The prediction based on the activation-inhibition states is consistent with the current findings of a larger sequential effect at the shorter foreperiod, and of a large sequential effect caused by a greater distance between the critical moments. However, to predict a sequential effect at the longer foreperiod (as in Capizzi et al., 2015, and the current Experiment 1), the trace-conditioning model and the MTP (Los et al., 2014) have to assume that catch trials serve as an extremely long foreperiod and cause inhibition at the later critical moment, which leaves space for a SFP effect to appear at the actual long foreperiod. Though we did not conduct any statistical test on the RTs after catch trials, the numerical differences in the current study show that when focusing on the current short foreperiod, catch trials caused a different effect than a long foreperiod did, which is not consistent with the trace-conditioning model or the MTP.

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 result 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. In Steinborn et al. (2009) and Steinborn et al. (2010), without changing the actual foreperiod, an inter-trial change of the warning signal modulated the SFP effect, indicating that any component of that memory trace could modulate its effect on the current trial, not just the foreperiod itself, which raises the question whether it is necessary to assume a specific activation-inhibition mechanism just for the temporal relation between the warning signal and the target stimulus in a task.

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 key step of reconnecting the two foreperiod paradigms was taken by Los et al. (2014), in which a simplified version of the MTP without the activation-inhibition ratio was used to account for the fixed-foreperiod effect. A lower maximum and greater temporal dispersion as the imperative moment is moved further from the warning signal were added to predict a shorter RT at the short foreperiod. These assumptions, however, were not able to produce a "U"-shaped curve of the fixed-foreperiod effect. When Lawrence and Klein (2013) adopted a foreperiod distribution similar to a non-aging one in a variable foreperiod paradigm, the whole "U"- shaped foreperiod-RT function rather than a decreasing one was found.

The results of the present 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 preparation based on conditional probabilities (whether explicit or implicit), which was assumed to be inhibited by using a non-aging foreperiod distribution, is responsible for the deviation of the variable-foreperiod effect from the fixed-foreperiod effect.

Conclusion

The results of this study suggest that the SFP effect reflects a benefit of repetition, which can be attributed to the memory of prior trials. Counter to the repetition priming account of Capizzi et al. (2015), which predicts SFP effects of equal sizes at different foreperiods, the SFP effect was larger at the shorter foreperiod, which is consistent with MTP. On the other hand, we 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 foreperiod-RT relation in a fixed foreperiod paradigm. This consistency between different foreperiod paradigms is not predicted by the MTP, which attributes the foreperiod-RT function to the proportions of foreperiods. These findings provide a basis for future studies that aim to integrate the two foreperiod paradigms and provide a complete account of general temporal preparation effects.

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