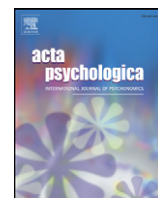




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Arousal modulates temporal preparation under increased time uncertainty: Evidence from higher-order sequential foreperiod effects

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ABSTRACT

When the foreperiod (FP) is unpredictably varied in reaction-time tasks, responses are slow at short but fast at long FPs (variable-FP effect), and further vary asymmetrically as a function of FP sequence (sequential FP effect). A trace-conditioning model attributes these phenomena to time-related associative learning, while a dual-process model views them as resulting from combined effects of strategic preparation and trial-to-trial changes in arousal. Sometimes, responses are slower in long–long than in short–long FP sequences. This pattern is not predicted from the trace-conditioning account, since FP repetitions should speed up, rather than slow down, responses (due to reinforcement). The effect, however, might indicate the contribution of arousal, which according to the dual-process model, is heightened after a short FP_{n-1} but decreased after a long FP_n . In five experiments, we examined higher-order sequential FP effects on performance, with a particular emphasis on analyzing performance in long- FP_n trials as a function of FP length in the two preceding trials, varying temporal FP context (i.e. average FP length) and reaction mode (simple vs. choice reaction). Slower responses in long–long–long (compared with short–short–long) FP sequences were not found within a short-FP context (Exps. 1 & 2) but clearly emerged within a long-FP context (Exps. 3–5). This pattern supports the notion that transient arousal changes contribute to sequential performance effects in variable-FP tasks, in line with the dual-process account of temporal preparation.

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1. Introduction

This study is concerned with potential mechanisms underlying variable-foreperiod phenomena, which arise in reaction-time (RT) experiments where the interval between warning signal and imperative stimulus (IS), usually termed foreperiod (FP), randomly varies within a block of trials. In such variable-FP paradigms, responses are usually slow in trials with a short FP and faster in trials with a longer FP, yielding the characteristic downward-sloping FP–RT function (cf. Niemi & Näätänen, 1981, pp. 137–141). This effect of variable FPs has been observed in both simple-RT and choice-RT tasks (e.g., Steinborn, Rolke, Bratzke, & Ulrich, 2008, 2009, 2010), has been demonstrated for different FP contexts (cf. Niemi & Näätänen, 1981; Steinborn et al., 2008). The precise mechanism underlying variable-FP effects is still unclear, however. Objectively, elapsing time during the FP is informative as to the imperative moment, since the

conditional probability of IS occurrence, given that it has not yet occurred, increases monotonously during the FP interval. Individuals appear capable to establish an internal prediction model of these conditional IS occurrence probabilities and convert them into a subjective expectation. How such (implicit or explicit) temporal expectancies are established and updated during FP is still unclear, although potential mechanisms have been proposed.

1.1. Current explanations of variable-FP phenomena

Historically, it has been claimed that individuals actively monitor the flow of time during the FP interval and adjust their preparatory state according to the time-related increase in conditional IS probability (cf. Näätänen, 1970; Nickerson & Burnham, 1969; Rabbitt & Vyas, 1980). Central to this view is the assumption that a high preparatory state is established by an effortful process of time-related preparation and can be maintained only for a brief duration (cf. Müller-Gethmann, Ulrich, & Rinke, 2003; Rolke & Ulrich, 2010). The concept of preparation is usually treated as non-selective, which means that a general state of optimal alertness is established in time, albeit selective temporal expectancies (of certain stimuli/

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responses) have also been demonstrated (e.g., Miller & Schröter, 2002; Thomaschke, Wagener, Kiesel, & Hoffmann, 2011; Wagener & Hoffmann, 2010). However, the classic strategic-preparation view cannot explain the sequential modulation of the FP–RT slope that also occurs across trials. In fact, it has been claimed that the typical FP–RT slope arises (at least to some degree) from this sequential modulation (Alegria & Delhayre-Rembaux, 1975; Los & Agter, 2005). This sequential FP effect refers to the fact that responses on short-FP trials are slower when preceded by a long FP than when preceded by an equally long or shorter one. The effect is asymmetric, since responses only vary on short-FP trials but are virtually unaffected by previous FP length on long-FP trials (e.g., Karlin, 1959; Klemmer, 1957; Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001; Steinborn & Langner, 2011; Steinborn et al., 2008, 2009, 2010; Van der Lubbe, Los, Jaskowski, & Verleger, 2004).

Los and colleagues (Los & Van den Heuvel, 2001; Los et al., 2001) challenged the classic view with an alternative model based on associative learning of temporally chained events during the FP. Essentially, it is assumed that the FP is represented as a sequence of time-tagged events, with each event being capable to acquire excitatory associations with representations of stimuli and/or motor activity. Hence, when the IS is presented at a particular time point and individuals respond to it, an excitatory time point–event connection is established or reinforced between the specific FP length and the co-occurring events, increasing “response strength” at this moment. This will have facilitatory effects when the IS occurs at the same moment on the subsequent trial (FP-repetition benefit). When, however, a critical (i.e. potentially imperative) moment is passed by without IS occurrence, response strength at this moment decreases due to extinction, which will have detrimental effects when the IS occurs at this (previously bypassed) moment on the subsequent trial. Responses therefore are particularly slow in the long–short FP sequence while they are consistently fast on long-FP_n trials, irrespective of FP_{n-1} length. Thus, the model explains the FP–RT slope as mainly arising from the asymmetric sequential FP effect.

Vallesi and colleagues (Vallesi, McIntosh, & Stuss, 2009; Vallesi & Shallice, 2007; Vallesi, Shallice, & Walsh, 2007) took a different view and developed the classic strategic model into a dual-process account of variable-FP phenomena, which can also explain the sequential FP effect. Their model maintains the idea of a strategic process based on conditional-probability monitoring to account for the typical FP–RT slope, while the sequential FP effect is assumed to arise from sequential fluctuations in arousal (i.e., the general readiness to respond, which is often termed “alertness” in other contexts, Langner et al., 2011). On short-FP_n trials, responses are assumed to be facilitated when following a short-FP_{n-1} trial, relative to a long-FP_{n-1} trial, due to the after-effects of deliberate preparation during the previous trial. Building on Näätänen’s (1970, 1971) notion of preparation-induced short-term exhaustion, the dual-process account supposes that prolonged preparation exhausts processing resources, leading to a decrease in general response readiness (Vallesi & Shallice, 2007). On long-FP_n trials, however, responses are fast irrespective of previous FP length, because the decrement in arousal following long-FP_{n-1} trials is compensated for by active preparation based on conditional-probability monitoring. Critical to the response slowing in long–short FP sequences, therefore, is not only the time between responses but also the time spent in a state of response preparation on trial_{n-1}.

According to this dual-process view, the asymmetry of the sequential FP effect arises from the combined impact of two different processes: an originally symmetric sequential effect, resulting from different transient arousal levels produced by prior preparation, is rendered asymmetric by effortful strategic preparation on long-FP_n trials. According to the dual-process model, the two processes combine to produce the standard RT pattern, although they can be dissociated from each other. For example, Vallesi, Shallice, and Walsh

(2007) demonstrated that the FP_n–RT slope but not the sequential effect is reduced after inhibiting the right dorsolateral prefrontal cortex (rDLPFC) via transcranial magnetic stimulation (TMS), suggesting that strategic processes putatively subserved by prefrontal cortex are not necessary for the emergence of the sequential FP effect. According to Vallesi, Shallice, and Walsh (2007), impaired rDLPFC functioning following TMS is equivalent to a reduction of those attentional resources that are required during the monitoring of time during FPs (cf. Helton, Dorahy, & Russell, 2011; Shallice, Stuss, Alexander, Picton, & Derksen, 2008; Stuss et al., 2005, for a theoretical discussion in related domains). In contrast, there is empirical evidence that the strategic process does not need the automatic, associative process to work, since patients with excision of premotor cortex show a normal FP–RT effect but no sequential FP effect (Vallesi et al., 2007).

1.2. Critical finding: faster responses in short–long than long–long FP sequences

Although both models (trace-conditioning and dual-process model) are often taken as competing views, the underlying mechanisms of associative learning, sequential arousal changes, and strategic preparation may not be mutually exclusive but may jointly contribute to the emergence of variable-FP phenomena. Therefore, a useful research strategy for revealing one of these mechanisms among the others is to use experimental manipulations that selectively affect one of the presumed mechanisms. Here we focused on the potential influence of sequential arousal changes (according to the dual-process model) on temporal preparation. In particular, it has often been observed in variable-FP experiments that responses are faster in short–long FP sequences than in long–long FP sequences (e.g., Langner et al., 2010; Los & Horoufchin, 2011; Steinborn & Langner, 2011; Steinborn et al., 2008, 2009, 2010; Van der Lubbe et al., 2004). This pattern would not be predicted from learning-based accounts of preparation or time-keeping. From the perspective of the trace-conditioning model, there is no reason for preparatory state to be lower at a long FP_n that was previously reinforced by an equally long FP_{n-1}, compared to a short FP_{n-1}. Instead, conditioned response strength at a late critical moment should increase (or at least remain stable) after a long FP_{n-1} through reinforcement. Thus, the model does not predict a decrease of response strength on long-FP repetition trials. Consequently, the available evidence favors the idea of sequential fluctuations in arousal, which is assumed to be at a higher level after a short FP_{n-1} than after a long FP_{n-1} (Vallesi & Shallice, 2007, p. 1386).

According to Vallesi and Shallice (2007, p. 1386), decreased arousal after a long FP_{n-1} is compensated for by a strategic preparation process, which – strictly speaking – implies that no difference between short–long and long–long FP sequences should be observed. If, however, such an RT difference is obtained indeed (i.e., slower responses in long–long than in short–long FP sequences), this may indicate that the strategic preparation process did not fully compensate for the arousal decrement after a long FP_{n-1}, leaving a sign of decreased arousal on RT performance. In fact, there is electrophysiological evidence that Vallesi and Shallice (2007, p. 1386) viewed as a covert signature of arousal: Los and Heslenfeld (2005) examined sequential effects on the contingent negative variation (CNV), a slow cortical potential reflecting cortical excitability (Fischer, Langner, Birbaumer, & Brocke, 2008), using a time-cued variable-FP (temporal orienting) paradigm. Besides specific effects of time cues, the CNV amplitude in this study tended to be globally larger throughout the FP_n when FP_{n-1} was short compared to when FP_{n-1} was long, which should not be observed if one assumes that repeated exposure to the same FP length (i.e. response requirement at the same time point after the warning signal) facilitates performance by means of time-point-specific reinforcement learning. To reconcile these data with the trace-conditioning account, though, it may be argued that

heightened arousal due to a short FP_{n-1} somewhat adds to the conditioned response strength elicited at a long FP_n , rendering responses faster in short–long FP sequences, compared to long–long FP sequences.

Thus, observing faster responses in short–long than in long–long FP sequences may not falsify a learning-based account of temporal preparation but solely indicates that response speed at late imperative moments is affected by more than only reinforcement learning. A more in-depth analysis of experimental variables affecting RT in short–long, compared with long–long, FP sequences may thus add some bricks to the understanding of variable-FP phenomena. In the present study, we aimed to maximize the behavioral variance that is effectively produced by preceding short FPs on current RT performance by taking FP length *before* FP_{n-1} (i.e. FP_{n-2}) into account. Previous findings on such higher-order sequential FP effects (e.g., Alegria, 1975; Granjon & Reynard, 1977; Los et al., 2001; Possamai, Granjon, Reynard, & Requin, 1975) revealed a global speed-up of responses after a series of short FPs but a slowing of responses after a series of long FPs. Intuitively, one might argue that a series of short FPs may improve performance via two mechanisms: improved time estimation and increased alertness, which are difficult to disentangle. However, the important question is how the length of FP_{n-2} affects the RT patterning in variable-FP tasks. Los et al. (2001) demonstrated that the global speed-up originated from a flattened FP_n -RT slope after a short FP_{n-2} , while there was a steepening of the FP_n -RT slope after a long FP_{n-2} . This finding is consistent with the standard view that in any associative learning process the behavioral consequences of reinforcement/extinction develop across more than one trial, although the change of conditioned strength is subject to diminishing returns (cf. Rescorla & Wagner, 1972; Verguts & Notebaert, 2008).¹

1.3. Present study

Critical to our study was the question of whether we could reveal an increase in the effect of what we consider to be produced by arousal (faster responses in short–long, as compared to long–long, FP sequences) as a function of FP_{n-2} length (short vs. long). Further, the effect should be additionally moderated by temporal context (i.e., average length of a particular FP set), being larger under high (compared to low) temporal uncertainty, since it is certainly more difficult and exhausting to prepare during long (compared to relatively short) intervals. It may thus be important to consider effects of FP_{n-2} on RT at late critical moments for different FP contexts. These relations were systematically examined in the present study. In five experiments using the variable-FP paradigm with progressively increasing preparatory demand (i.e., average FP length), we analyzed sequential FP effects up to the second order (i.e., effects of FP_{n-2} , FP_{n-1} , FP_n). First of all, we expected to observe a flattening of the FP_n -RT slope after a short FP_{n-2} but a steepening after a long FP_{n-2} , using a rather short FP set (Los et al., 2001). Second, we expected that this effect becomes less pronounced with increasing FP context. Third, and most importantly, we asked whether and how second-order FP length affects responses at late critical moments.

As noted earlier, responses are often faster in short–long than long–long FP sequences, which is counterintuitive from a learning-based view, since a previously reinforced critical moment should yield faster responses over its non-reinforced counterpart. We, therefore, devoted particular emphasis on the effect of previous (short vs. long) FP_{n-2}/FP_{n-1} on RT in current long-FP trials by considering FP context (across experiments) as a moderator variable.

¹ It should be noted that a steepened FP_n -RT slope after a long FP_{n-2} could also be predicted from a dual-process model: According to this view, a long FP_{n-2} could probably increase refractory effects on response preparation in a similar but attenuated fashion as a long FP_{n-1} , whereby the FP_n -RT slope should be more pronounced after a long FP_{n-2} because of slowed responses on long–long–short FP sequences. Thus, we might not be able to discriminate between associative-learning and strategic-preparation processes by analysis of second-order FP effects.

The order of the five experiments corresponds to the degree of contextual temporal uncertainty as imposed by the FP set (i.e., the average scaling and range of FPs within a particular FP set). In Experiments 1–3, three (equiprobable) FPs were randomly varied within a block of trials using a two-choice RT task, with temporal uncertainty increasing progressively across experiments (FPs in Exp. 1: 300, 900, 1500 ms; in Exp. 2: 800, 1600, 2400 ms; in Exp. 3: 1200, 2400, 3600 ms). In Experiment 4, only two (instead of three) equiprobable FPs (1200, 3600 ms) were randomly varied within blocks of trials, using the same choice-RT task. In Experiment 5, two FPs (1200, 3600 ms) were again randomly varied but in a simple-RT task. Both Experiments 4 and 5 served to generalize results of Experiment 3 (high temporal uncertainty) to situations differing in the number of critical moments and the presence (Exps. 3 and 4) vs. absence (Exp. 5) of response uncertainty.

2. Experiment 1

In Experiment 1, we used a variable-FP situation that comprised only a moderate degree of temporal uncertainty (equiprobable FPs: 300, 900, 1500 ms). We employed a serial RT task in which the preparatory interval started immediately after responding to the IS in the previous trial. Strictly speaking, therefore, we used a variable response–stimulus interval but retained the term “foreperiod” throughout the manuscript. Notably, a response–stimulus interval (or interstimulus interval, respectively) has been regarded to produce an equivalent RT pattern as is typically observed in variable-FP situations (e.g., Granjon & Reynard, 1977; Rabbitt & Vyas, 1980; Stuss et al., 2005; Tucker, Basner, Stern, & Rakitin, 2009). We expected to replicate the results of Los et al. (2001), who observed a steepened FP_n -RT slope after a long FP_{n-2} within a similar temporal context. Further, we asked whether FP_{n-2} would affect response speed on long- FP_n trials. Due to the relatively low degree of temporal uncertainty imposed by the short FP set, we considered the possibility that arousal would not sufficiently vary within this temporal context to produce notable effects, albeit this is clearly an empirical question.

2.1. Method

2.1.1. Participants

Fifty (75% female) volunteers (mean age = 24.1 years, $SD = 5.5$) took part in this experiment. All participants reported to be in good health, and all of them had normal or corrected-to-normal vision.

2.1.2. Apparatus and stimuli

The experiment was run in a dimly lit and noise-shielded room; it was controlled by an IBM-compatible computer with color display (19 in., 150 Hz refresh rate) and programmed in MATLAB™ using the Psychophysics toolbox (Brainard, 1997). Participants sat at a distance of about 60 cm in front of the computer screen. A dot ($0.5^\circ \times 0.5^\circ$ angle of vision) in the middle of the screen served as fixation point and was constantly present throughout the experimental session. The letter “L” or “R” ($1.14^\circ \times 0.86^\circ$ angle of vision) served as the IS and was displayed in blue (7.1 cd/m^2) at the center of the computer screen.

² An experiment where time markers are given during the FP might be a way to dissociate the contributions of arousal and time estimation to the preparatory process (cf. Grondin, 2010; Rammesayer & Ulrich, 2001, for a tutorial). Using time markers equalizes the difficulty of time estimation across different FP lengths, so that the mechanism of dynamic temporal adaptation could be studied in its “pure” form (e.g. Ellis & Jones, 2010; Granjon, Requin, Durup, & Reynard, 1973; Hackley et al., 2009; Requin, Granjon, Durup, & Reynard, 1973; Sanabria, Capizzi, & Correa, 2011; Seifried, Ulrich, Bausenhardt, Rolke, & Osman, 2010; Simon & Slaviero, 1975).

2.1.3. Design and procedure

The three-factorial within-subject design contained the factors: second-order (2-back) previous-trial FP length (FP_{n-2} : short vs. medium vs. long), first-order (1-back) previous-trial FP length (FP_{n-1} : short vs. medium vs. long), and current-trial FP length (FP_n : short vs. medium vs. long). A trial started immediately after the response on the preceding trial, followed by the IS and the response. Besides these specifications, the task was similar to those used in our previous studies (Steinborn et al., 2008, 2009, 2010): Participants were instructed to respond with either the left shift-key (left index finger when “L” was presented) or the right shift-key (right index finger when “R” was presented). The IS was terminated either by response or when the response interval expired after 2000 ms. Participants were instructed to respond quickly and accurately to the IS. Feedback was given if an erroneous response had occurred or if the response interval had expired. In case of an erroneous response, the German word “falsch” (wrong) was presented for 300 ms, whereas in case of response interval expiration, the phrase “zu langsam” (too slow) was presented. Participants performed six warm-up trials and 600 experimental trials, with a break given after each block of 100 trials.

2.2. Results and discussion

Responses faster than 100 ms and slower than 1000 ms were considered outliers and corresponding trials (0.3%) were discarded (Ulrich & Miller, 1994). Correct responses were used to compute individual mean RT, while the percentage of incorrect responses (i.e., error percentage, EP) was used as an index of performance accuracy. Statistics are listed in Appendix A (Table 1), with the relevant effects being subsequently reported in more detail. Fig. 1 displays group-averaged RT and EP separately for short (panels A, D), medium (panels B, E), and long (panels C, F) FP_{n-2} .

2.2.1. Standard effects

As expected, the standard effects were obtained: a main effect of FP_{n-1} on RT indicated that responses were globally faster when the current trial was preceded by a short FP_{n-1} , as compared to a medium or long FP_{n-1} (RTs: 384, 390, 394 ms). The main effect of FP_n on RT indicated that responses became faster with increasing FP_n (i.e., downward-sloping FP_n -RT function; RTs: 406, 378, 383 ms), and the two-way ($FP_{n-1} \times FP_n$) interaction on RT indicated the asymmetric sequential FP effect.

2.2.2. Second-order FP effects

Responses were faster when the current trial was preceded by a short FP_{n-2} as compared to a medium or long FP_{n-2} (RTs: 384, 391, 393 ms), as indicated by a significant main effect of FP_{n-2} on RT. Evidently, this effect arose from response slowing at early critical moments, since the FP_n -RT slope was steeper for the case of a long FP_{n-2} compared to a shorter FP_{n-2} , as indicated by a significant $FP_{n-2} \times FP_n$ interaction on RT. The sequential FP effect was not modulated by second-order FP length (i.e., no significant $FP_{n-2} \times FP_{n-1} \times FP_n$ interaction).

2.2.3. Single-comparison analyses

To examine the isolated effects of previous (second- and first-order) FP length on responses at late critical moments (i.e., long- FP_n trials), we analyzed simple contrasts. As a reminder, critical to our study was the question of whether there were faster responses in short-long than long-long FP sequences (due to a smaller arousal decrease during preceding short FPs) and whether this difference varied as a function of a second-order FP_{n-2} length (short vs. long). First, responses were not faster but slower in short-long compared to long-long FP sequences [387 vs. 381 ms; $t(1, 49) = 2.8, p < 0.007$]. Second, responses on long- FP_n trials were not significantly faster after short FP_{n-2} , as compared to a long FP_{n-2} . Third, responses in the short-short-long FP sequence were not significantly faster than responses

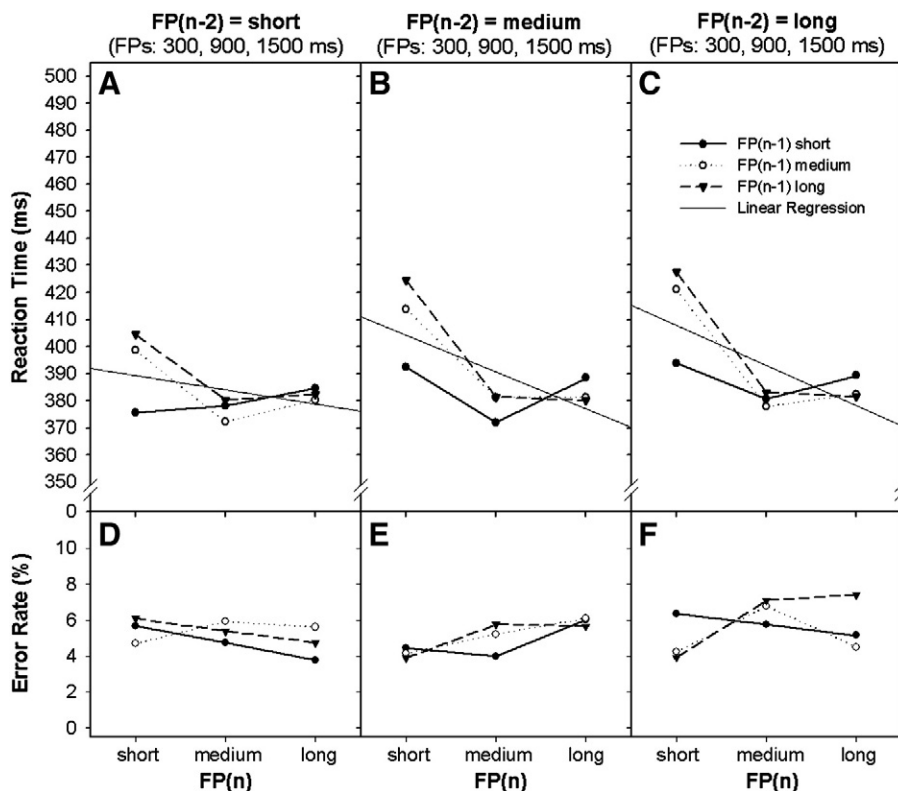


Fig. 1. Higher-order sequential foreperiod effects in Experiment 1. Reaction time and error rate as a function of the preceding (FP_{n-1}) and current (FP_n) foreperiod, separately displayed for short (panels A, D), medium (panels B, E), and long (panels C, F) foreperiods (FP_{n-2}) two trials previously.

in the long–long–long FP sequence. These results indicate no significant effects of arousal on temporal preparation, possibly because the short FP context provided insufficient contextual temporal uncertainty (i.e., preparatory demand). We argue that the expected effect of previous reinforcement dominated any (potentially small) sequential effects of arousal at this short temporal context.

3. Experiment 2

In Experiment 2 (choice-RT task; equiprobable FPs: 800, 1600, 2400 ms), we increased contextual temporal uncertainty in order to put higher demands on temporal preparation. Besides these changes, all features of the previous set-up were retained.

3.1. Method

3.1.1. Participants

Fifty young volunteers (63% females, mean age = 25.1 years, $SD = 7.6$), in good health and with normal or corrected-to-normal vision, took part in this experiment.

3.1.2. Apparatus and stimuli

The experimental situation was equal to the previous experiment.

3.1.3. Design and procedure

All design features but the FP set were retained; the three equiprobable FPs were 800, 1600, and 2400 ms.

3.2. Results and discussion

Data processing and statistical analyses were the same as in the previous experiment, and all statistical effects are listed in Appendix A (Table 1). Fig. 2 displays RT and EP separately for the case of a

short (panels A, D), medium (panels B, E), and long (panels C, F) FP_{n-2} .

3.2.1. Standard effects

The main effect of FP_{n-1} on RT indicated that responses were globally faster when a current trial was preceded by a short FP_{n-1} as compared to a medium or long FP_{n-1} (RTs: 391, 399, 406 ms). The main effect of FP_n on RT indicated that responses became generally faster with increasing FP_n (i.e., downward-sloping FP_n -RT function; RTs: 408, 393, 396 ms), and the two-way ($FP_{n-1} \times FP_n$) interaction on RT indicated an asymmetric sequential FP effect.

3.2.2. Second-order FP effects

Responses were again somewhat faster when a current trial was preceded by a short FP_{n-2} as compared to a medium or long FP_{n-2} (RTs: 396, 400, 400 ms), as indicated by a significant main effect of FP_{n-2} on RT. This effect again arose from a change of the FP_n -RT slope, which was steeper for the case of a long FP_{n-2} compared to a shorter FP_{n-2} , as indicated by a significant $FP_{n-2} \times FP_n$ interaction on RT. The sequential FP effect was again not modulated by second-order FP length.

3.2.3. Single-comparison analyses

First, responses tended to be faster in the short–long FP sequence compared to the long–long FP sequence [with marginal significance: 394 vs. 398 ms; $t(1, 49) = -1.8$, $p < 0.08$]. Second, responses on long- FP_n trials were not significantly faster after a short FP_{n-2} , compared to a long FP_{n-2} . Third, responses in the short–short–long FP sequence were not significantly faster than responses in the long–long–long FP sequence.

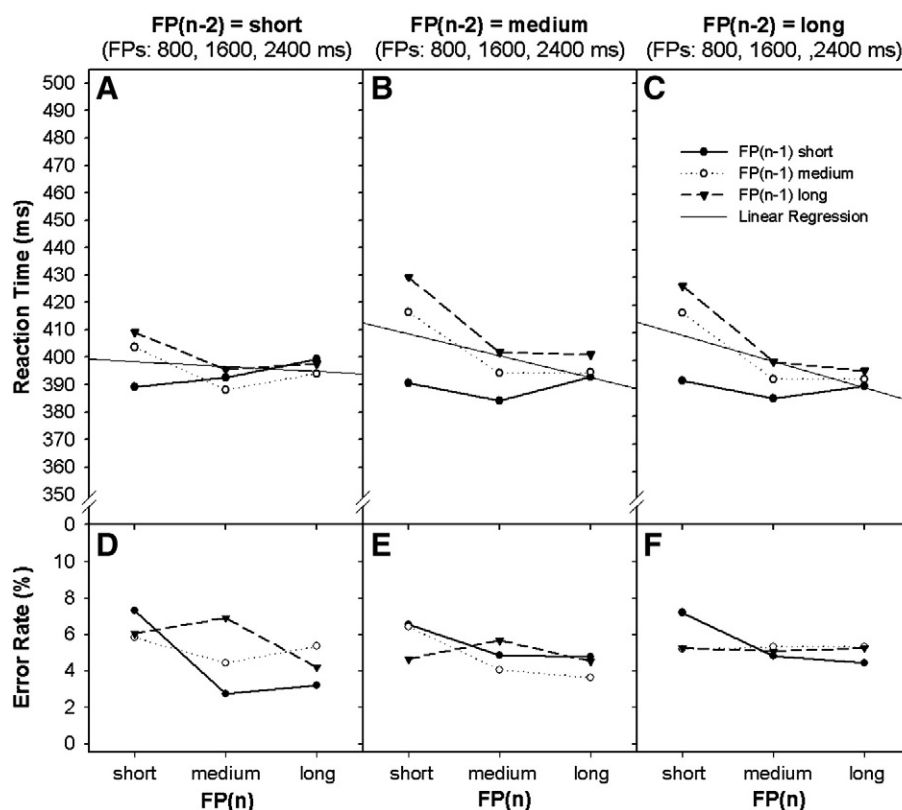


Fig. 2. Higher-order sequential foreperiod effects in Experiment 2. Reaction time and error rate as a function of the preceding (FP_{n-1}) and current (FP_n) foreperiod, separately displayed for short (panels A, D), medium (panels B, E), and long (panels C, F) foreperiods (FP_{n-2}) two trials previously.

4. Experiment 3

In Experiment 3 (choice-RT task, equiprobable FPs: 1200, 2400, 3600 ms), we further enhanced the demand on temporal preparation by increasing temporal uncertainty while retaining all other experimental features. Hypotheses were similar to the previous experiments.

4.1. Method

4.1.1. Participants

Fifty young volunteers (67% females, mean age = 24.3 years, $SD = 6.1$), in good health and with normal or corrected-to-normal vision, took part in this experiment.

4.1.2. Apparatus and stimuli

The experimental situation was equal to the previous experiments.

4.1.3. Design and procedure

All design features but the FP set were retained; the three equiprobable FPs were 1200, 2400, and 3600 ms.

4.2. Results and discussion

Data processing and statistical analyses were equal to the previous experiments, and all statistical effects are listed in Appendix A (Table 1). Fig. 3 displays RT and EP separately for the case of a short (panels A, D), medium (panels B, E), or long (panels C, F) FP_{n-2} .

4.2.1. Standard effects

The main effect of FP_{n-1} on RT indicated that responses were globally faster when the current trial was preceded by a short FP_{n-1} , compared to a medium or long FP_{n-1} (RTs: 421, 431, 440 ms). The main effect of FP_n on RT indicated that responses became faster with increasing FP_n (i.e., downward-sloping FP_n -RT function; RTs: 443, 423,

426 ms), and the two-way ($FP_{n-1} \times FP_n$) interaction effect on RT indicated a significantly asymmetric sequential FP effect.

4.2.2. Second-order FP effects

Responses were again faster when a current trial was preceded by a short FP_{n-2} as compared to a medium or long FP_{n-2} (RTs: 426, 431, 435 ms), as indicated by a significant main effect of FP_{n-2} on RT. This time, however, the FP_n -RT slope was not significantly affected by a long FP_{n-2} compared to a shorter FP_{n-2} , and the sequential FP effect was also not modulated by second-order FP length.

4.2.3. Single-comparison analyses

This time, responses were moderately but significantly faster in the short-long compared to the long-long FP sequence [422 vs. 428 ms; $t(1, 49) = -2.0, p < 0.05$]. Further, responses on long- FP_n trials were significantly faster after a short FP_{n-2} compared to a long FP_{n-2} [422 vs. 430 ms; $t(1, 49) = -3.8, p < 0.001$], indicating that a short FP two trials back produced a global speed-up of responses in a current long-FP trial. Finally, responses in the short-short-long FP sequence were significantly faster than responses in the long-long-long FP sequence [419 vs. 433 ms; $t(1, 49) = -3.2, p < 0.01$]. In sum, the results of Experiment 3 revealed detrimental effects of a preceding long FP under conditions of relatively great average FP length. We suggest that with greater preparatory demand from increased temporal uncertainty the sequential effects of previous reinforcement were overruled by the increased refractoriness of response preparation after long (vs. short) FPs, presumably mediated by a stronger decrease in arousal during a preceding long FP.

4.2.4. Between-subject analyses (Experiments 1–3)

In a final step, we compared the second-order FP sequence effect across experiments, using an aggregated between-subject ANOVA design that included the data of Experiments 1, 2, and 3. As mentioned earlier, the experiments were identical with respect to task

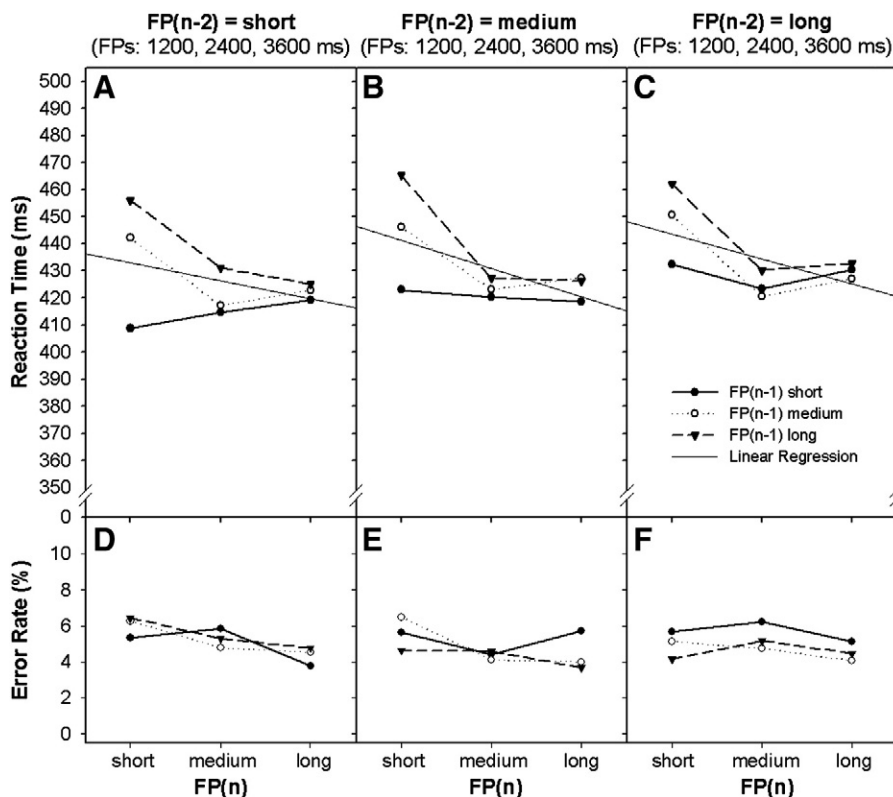


Fig. 3. Higher-order sequential foreperiod effects in Experiment 3. Reaction time and error rate as a function of the preceding (FP_{n-1}) and current (FP_n) foreperiod, separately displayed for short (panels A, D), medium (panels B, E), and long (panels C, F) foreperiods (FP_{n-2}) two trials previously.

and stimuli, with only contextual temporal uncertainty increasing from Experiment 1 to 3. Overall responses became significantly slower [$F(2, 147) = 7.5; p < 0.001$] across experiments (RTs: 389, 400, 431 ms), even though an identical two-choice RT task was employed. Thus, these costs can be attributed to the different degrees of temporal uncertainty across experiments. In addition, the effects of both FP_{n-1} [$F(4, 294) = 3.5; p < 0.01$] and FP_{n-2} [$F(4, 294) = 3.0; p < 0.019$] on RT became larger with temporal uncertainty across experiments. In fact, with growing between-experiment temporal uncertainty, responses became differentially slower after both a long first-order (1-back) and a long second-order (2-back) FP.

Moreover, the impression that a long FP_{n-2} steepened the FP_n -RT slope under low (Experiment 1) but not high (Experiment 3) temporal uncertainty (compare Figs. 1, 2, and 3) could also be validated statistically: including only two FPs (short vs. long) in the ANOVA to increase statistical power revealed a significant interaction between the factors contextual temporal uncertainty (Experiments 1 vs. 3), FP_{n-2} (short vs. long), and FP_n (short vs. long) on RT [$F(1, 98) = 6.0; p < 0.016$], indicating that the steepening of the FP_n -RT slope after a long FP_{n-2} became less pronounced with increasing temporal context. In fact, a long FP_{n-2} yielded a pronounced steepening of the FP_n -RT slope within a short FP set (Experiment 1), which became less pronounced within a relatively long FP set (Experiment 3).

5. Experiment 4

In Experiment 3, the effect of FP_{n-2} on the variable-FP effect (i.e., the FP_n -RT slope) was not significant, undermining a straightforward interpretation. We therefore asked whether we would obtain a clear-cut effect in a simpler experimental situation with only two FPs (short vs. long). Thus, instead of the 27 factorial conditions of Experiment 3, we now included only 8 conditions, enhancing statistical power. Predictions remained equal to the previous experiments.

5.1. Method

5.1.1. Participants

Thirty-five young volunteers (78% females, mean age = 24.0 years, $SD = 5.7$), in good health and with normal or corrected-to-normal vision, took part in this experiment.

5.1.2. Apparatus and stimuli

Task and stimuli were equal to the previous experiments.

5.1.3. Design and procedure

All design features but the FP set were retained; the two equiprobable FPs were 1200 and 3600 ms.

5.2. Results and discussion

Data processing and statistical analyses were equal to the previous experiments; all statistical effects are listed in Appendix A (Table 2). Fig. 4 displays RT and EP separately for the case of a short (panels A, B) and long (panels C, D) FP_{n-2} .

5.2.1. Standard effects

The main effect of FP_{n-1} on RT indicated that responses were globally faster when the current trial was preceded by a short as compared with a long FP_{n-1} (RTs: 436, 455 ms). The main effect of FP_n on RT indicated that responses became faster with increasing FP_n (i.e., downward-sloping FP_n -RT function; RTs: 454, 437 ms), and the two-way ($FP_{n-1} \times FP_n$) interaction on RT indicated an asymmetric sequential FP effect.

5.2.2. Second-order FP effects

Response speed was again faster when a current trial was preceded by a short as compared with a long FP_{n-2} (RTs: 442, 449 ms), as

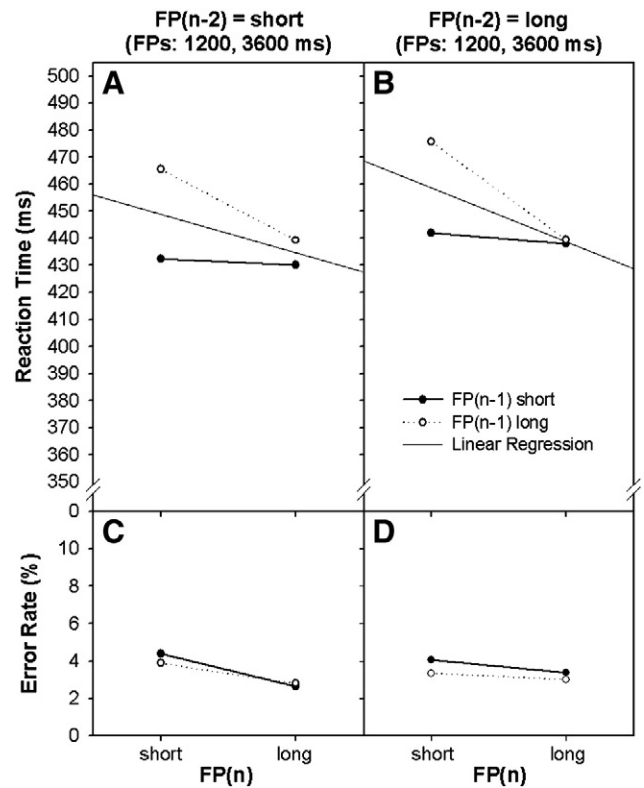


Fig. 4. Higher-order sequential foreperiod effects in Experiment 4. Reaction time and error rate as a function of the preceding (FP_{n-1}) and current (FP_n) foreperiod, separately displayed for short (panels A, B) and long (panels C, D) foreperiods (FP_{n-2}) two trials previously.

indicated by a main effect of FP_{n-2} on RT. This effect originated from a change of the FP_n -RT slope, which was steeper for a long than for a shorter FP_{n-2} , as indicated by the significant $FP_{n-2} \times FP_n$ interaction on RT. This time, even the asymmetric sequential FP effect was slightly modulated by second-order FP length, as indicated by a marginally significant $FP_{n-2} \times FP_{n-1} \times FP_n$ interaction on RT, and also by a comparison of the visual RT pattern of panels A and B in Fig. 4.

5.2.3. Single-comparison analyses

First, responses were faster in the short-long FP sequence compared to the long-long FP sequence [434 vs. 439 ms; $t(1, 34) = -3.2, p < 0.01$]. Second, responses on long- FP_n trials were significantly faster after a short than a long FP_{n-2} [435 vs. 439 ms; $t(1, 34) = -3.3, p < 0.01$], indicating that a short FP two trials back produced a global speed-up of responses in a current long-FP trial (irrespective of FP_{n-1} length). Third, responses in the short-short-long FP sequence were significantly faster than responses in the long-long-long FP sequence [430 vs. 439 ms; $t(1, 34) = -4.4, p < 0.001$]. Thus, when only two (instead of three) FPs were used, we observed a clear-cut detrimental effect of preceding long (vs. short) FPs under conditions of relatively great average FP length. In line with Experiment 3, these results indicate that longer preparatory activity on a given trial leads to suboptimal preparation on the next, suggesting that stronger sequential changes in arousal level might be able to outweigh the opposing effects of previous time-point-related reinforcement.

6. Experiment 5

Experiment 5 aimed to generalize the findings of Experiment 4 to a simple-RT task with similar contextual temporal uncertainty (FPs: 1200 and 3600 ms). Besides these changes, all features and hypotheses

of Experiment 4 were retained. By using a simple-RT paradigm, we aimed to estimate the degree to which our subject of study – variations in current preparatory efficiency due to previous short vs. long preparatory activity – is more sensitively detected when the task requires motor preparation without response uncertainty.

6.1. Method

6.1.1. Participants

Fifteen young volunteers (75% females, mean age = 25.2 years, $SD = 4.5$), in good health and with normal or corrected-to-normal vision, took part in this experiment.

6.1.2. Apparatus and stimuli

Task and stimuli were equal to the previous experiments, that is, the letters “L” and “R” served as the IS to which participants were to respond with the right shift-key by using their right index finger.

6.1.3. Design and procedure

All design features of Experiment 4 were retained (FPs: 1200, 3600 ms) except that a stimulus detection response (instead of a discriminative response) was required.

6.2. Results and discussion

Data processing and statistical analyses were equal to the previous experiments; all statistical effects are listed in Appendix A (Table 2). Fig. 5 displays RT and EP (i.e. anticipatory responses) separately for the case of a short (panels A, B) and a long (panels C, D) FP_{n-2} .

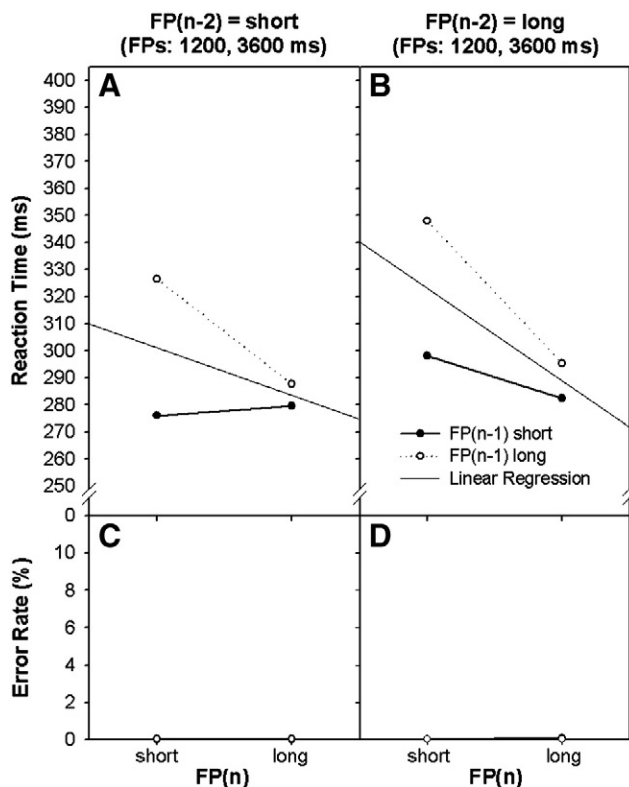


Fig. 5. Higher-order sequential foreperiod effects in Experiment 5. Reaction time and percentage of anticipatory responses as a function of the preceding (FP_{n-1}) and current (FP_n) foreperiod, separately displayed for short (panels A, B) and long (panels C, D) foreperiods (FP_{n-2}) two trials previously.

6.2.1. Standard effects

The main effect of FP_{n-1} on RT indicated that responses were globally faster when the current trial was preceded by a short FP_{n-1} as compared with a long FP_{n-1} (RTs: 284, 314 ms). The main effect of FP_n on RT indicated that responses became faster with increasing FP_n (i.e., downward-sloping FP_n -RT function; RTs: 312, 286 ms), and the two-way ($FP_{n-1} \times FP_n$) interaction on RT indicated the typical asymmetric sequential FP effect.

6.2.2. Second-order FP effects

Response speed was again faster when a current trial was preceded by a short FP_{n-2} as compared with a long FP_{n-2} (RTs: 292, 306 ms), as indicated by a significant main effect of FP_{n-2} on RT. As in previous experiments, this effect originated from a change of the FP_n -RT slope, which was steeper after a long than after a shorter FP_{n-2} , as indicated by a significant $FP_{n-2} \times FP_n$ interaction. The sequential FP effect was not modulated by second-order FP length.

6.2.3. Single-comparison analyses

First, responses were faster in the short–long FP sequence compared to the long–long FP sequence [281 vs. 291 ms; $t(1, 14) = -4.6$, $p < 0.001$]. Second, responses on long- FP_n trials were significantly faster after a short FP_{n-2} compared with a long FP_{n-2} [284 vs. 289 ms; $t(1, 14) = -2.3$, $p < 0.05$], indicating that a short FP two trials back produced a speed-up of responses in a current long-FP trial (irrespective of FP_{n-1}). Third, responses in the short–short–long FP sequence were significantly faster than responses in the long–long–long FP sequence [279 vs. 295 ms; $t(1, 14) = -4.0$, $p < 0.01$]. In sum, the results of Experiment 5 extend the findings from Experiment 4 to a simple-RT task, indicating that certainty about the upcoming response does not alleviate the detrimental effect of a preceding long FP on current preparatory efficiency. This is further indirect evidence for the nonspecific nature of the underlying mechanism, supporting our interpretation of the effect in terms of differential changes in arousal brought about by short-term exhaustion from previous preparatory activity.

7. General discussion

Two explanations have been proposed for the finding that responses in variable-FP experiments are especially slow in short- FP_n trials but fast in long- FP_n trials, as reflected in the typical downward-sloping FP_n -RT function. The dual-process account (Vallesi, Shallice, & Walsh, 2007) assumes that response speed depends on (i) arousal, which is thought to decrease with an increasing duration of the preceding preparatory interval, and (ii) the degree of strategic preparation for the moment of IS occurrence, which should improve with increasing FP duration (at least up to a certain FP length). The typical asymmetric sequential FP effect is assumed to result from the parallel action of both mechanisms (Vallesi, McIntosh, & Stuss, 2009; Vallesi & Shallice, 2007; Vallesi, Shallice, & Walsh, 2007). The trace-conditioning account alternatively suggests that an implicit trial-by-trial learning of implicit temporal expectancies is the source of the variable-FP effect (Los & Van den Heuvel, 2001; Los et al., 2001). Across five variable-FP experiments with progressively increasing contextual temporal uncertainty, we analyzed first- and second-order sequential FP effects to examine the potential influence of arousal from previous responding on performance. Central to our study was the question of whether there is an increase in the detrimental effect of the previous trial's FP length (i.e., faster responses in short–long compared with long–long FP sequences) as a function of FP_{n-2} length and contextual temporal uncertainty (i.e., average FP length).

We observed longer overall RTs after a long than after a short FP_{n-2} . These costs and benefits selectively accrued at early imperative moments, since we observed a steepening of the FP_n -RT slope after a long FP_{n-2} , while a flattening of the FP_n -RT slope was found after a short FP_{n-2} . In addition, with the increase in temporal-preparation demands across Experiments 1–3 (due to increased average FP length),

the global effect (i.e., the overall RT increase after a long FP_{n-2}) grew, while the selective effect (change of the FP_n -RT slope) became less pronounced. The results of Experiments 4 and 5 then provided evidence that higher-order sequential effects are stronger with two (compared with three) FPs and with a simple-RT task (compared with a choice-RT task). Yet, the asymmetry of the sequential FP effect was not significantly affected by FP_{n-2} length. In summary, the detrimental effect of previous preparatory activity on current preparation efficiency (slower responses in the long-long compared with the short-long FP sequence) increased with temporal uncertainty (between experiments) and as a function of higher-order FP sequence (i.e., comparison of short-short-long and long-long-long FP sequences). Also, the effect was numerical-ly stronger with a simple-RT (vs. choice-RT) task.

7.1. Implications for models of dynamic temporal preparation

The results of our five experiments are consistent with previous studies on higher-order sequential FP effects (e.g., Alegria, 1975; Granjon & Reynard, 1977; Los et al., 2001; Possamai et al., 1975) but extend those studies by explicitly considering the temporal FP context as critical variable. Starting with a relatively narrow temporal context in Experiment 1, we showed a pronounced increase in the FP_n -RT slope after a long FP_{n-2} , thus replicating prior results of Los et al. (2001). This effect was sensitive to preparatory difficulty (i.e. average FP length), being most pronounced within a narrow temporal context (Exp. 1: FPs: 300, 900, 1500 ms), as compared to a wide one (Exp. 3, FPs: 1200, 2400, 3600 ms). These results indicate that the contribution of mechanisms considered to produce the variable-FP effect (i.e. sequential arousal changes, associative learning, and/or strategic preparation) may change with contextual temporal uncertainty. We thus consider it necessary to first discuss the implications of our results for current models of dynamic temporal preparation, that is, the trace-conditioning model (Los & Van den Heuvel, 2001; Los et al., 2001) and the dual-process model (Vallesi, Mussoni, et al., 2007; Vallesi & Shallice, 2007; Vallesi, Shallice, & Walsh, 2007), and then to delineate the role of energetic factors (i.e., arousal) on the efficiency of temporal preparation under time uncertainty.

From an associative-learning perspective, it is assumed that a series of long FPs yields a decrease of the strength of temporal target-response connections at all critical moments but the latest (i.e., longest FP), since the earlier moments are repeatedly bypassed without responding. In line with this view, a steepening of the FP_n -RT slope was observed after a long FP_{n-2} , as any previously bypassed critical moment was subject to extinction, whereas a flattening of the FP_n -RT slope was observed after a short FP_{n-2} , as the previous imperative moment was subject to reinforcement. This explanation also involves the assumption that long-term associations are progressively acquired through repeated reinforcement, although the immediately preceding FP arguably has the strongest impact on current performance. The decrease of this effect with increasing average FP length (compare Figs. 1–4) indicates a decline in the impact of time-related learning (reinforcement vs. extinction), presumably due to a compound decrease of arousal and temporal precision (Näätänen, Muranen, & Merisalo, 1974). According to Los and Van den Heuvel (2001), individuals will acquire a sharp-peaked conditioned response if a critical moment can be timed with high temporal precision but a round-peaked conditioned response under low temporal precision. Given that a round preparatory peak effectively leads to reduced response strength at a given imperative moment, the effects of FP_{n-2} length on the FP_n -RT slope under low vs. high temporal uncertainty may be consistent with the trace-conditioning view.

From a strategic-preparation perspective, efficient monitoring of time and probability information during the FP is considered a deliberate mental act that is subjectively experienced as effortful. It requires individuals to sustain attention to an internal representation of temporal events until IS occurrence (cf. Ansari & Derakshan, 2011; Falkenstein, Hoormann, Hohnsbein, & Kleinsorge, 2003; Gottsdanker, 1984; Näätänen & Merisalo, 1977; Rabbitt & Vyas,

1980; Vallesi, Shallice, & Walsh, 2007). The finding of a steepened FP_n -RT slope after a long FP_{n-2} may also be integrated into the dual-process view if one considers the possibility that the after-effects of deliberate preparation during a long FP accumulate over trials. Precisely, if one assumes that a long FP_{n-2} increases refractory effects on response preparation cumulatively (i.e., in addition to a long FP_{n-1}), then the FP_n -RT slope should be steepened after a series of long-FP trials. This hypothesis was tested via comparing RT in the short-long-short and the long-long-short FP sequence. Across experiments, RT was significantly ($p < 0.01$) faster in the former compared to the latter sequence, consistent with the prediction (Exp. 1: 404/428 ms; Exp. 2: 409/427 ms; Exp. 3: 456/462 ms; Exp. 4: 465/476 ms; Exp. 5: 326/348 ms).

Given the possibility that higher-order FP sequences have transient effects on both learning-based and strategic preparation processes, neither theoretical model of implicit temporal preparation is unequivocally favored by our results. However, given that demands on deliberate preparation increase with temporal context (Karlin, 1959; Steinborn et al., 2008), one could argue from the dual-process perspective that the accumulation of motor refractoriness should become more pronounced with increasing demands on preparatory processes. Testing this hypothesis, however, yielded exactly the opposite effect: the RT difference between short-long-short and long-long-short FP sequences decreased from Experiments 1–3 (Exp. 1 = 24 ms; Exp. 2 = 18 ms; Exp. 3 = 6 ms), which was statistically supported by a between-subject ANOVA ($p < 0.01$). Note that all features but FP set were identical in the three experiments. Importantly, after visual inspection of Figs. 1–3, it becomes clear that this effect arises from the fact that the initial RT decrement after a long FP_{n-1} was small in Experiment 1 but especially large in Experiment 3, so that there was simply more room for the refractory effect to emerge after a series of long FPs.

7.2. Signatures of arousal effects on long-foreperiod trials

Central to the present study was estimating the effect of the preceding FP's duration in situations with optimal temporal preparation, i.e. in current long-FP trials. Long-FP trials should show the fastest responses according to both theoretical accounts, since at the latest critical moment, there never is extinction, and conditional probability is maximal. However, despite optimal conditions for response preparation, previous studies often reported responses to be faster in short-long FP sequences than in long-long ones (cf. Section 1.2). As mentioned in the introduction, this effect is not predicted from the trace-conditioning view, since current preparatory state at the latest critical moment should increase rather than decrease after a long- FP_{n-1} trial through reinforcement.³ Therefore, we consider the detrimental effect of a preceding long FP as resulting from a short-term decline in arousal that comes along with the transiently exhausting preparatory activity on the previous trial, in line with the dual-process account (Vallesi & Shallice, 2007).

Our results further revealed an important boundary condition: temporal FP context. We considered a comparison of short-short-long and long-long-long FP sequences as critical to our question, since arousal differences between these conditions should be maximal, with arousal on the current trial being significantly higher in the former than in the latter condition (cf. Vallesi & Shallice, 2007, p. 1386). Our results revealed no effect of arousal under conditions

³ It should be noted that Los et al.'s (2001) formal modeling of the conditioning processes thought to underlie sequential FP effects was able to produce this RT pattern (i.e., slightly slower responses in long-long than in short-long FP sequences) with at least one set of plausible parameter values. Los et al. assumed that a short delay in peak readiness relative to the critical moment reinforced on the previous trial produced a slight net benefit at late imperative moments (cf. Los et al., 2001, pp. 140–141). In our view, however, the benefit from such shifts of peak time should be maximal in narrow FP contexts (i.e., low average FP length), whereas our data revealed this phenomenon to be especially pronounced in wide FP contexts (i.e., great average FP length).

of low temporal uncertainty (Exps. 1 & 2) but a clear-cut effect under high temporal uncertainty (Exps. 3–5). In particular, Experiments 3–5 revealed that responses in the short–short–long FP sequence were significantly faster compared to the long–long–long FP sequence (Exp. 1: 419/433 ms, Exp. 2: 430/439 ms, Exp. 3: 280/295 ms), while no such effect occurred in Experiments 1 and 2. We interpret this finding as further support for assuming arousal as the underlying mechanism, which comes to outweigh opposing reinforcement effects only within a rather wide FP context that produces sufficiently great differences in short-term exhaustion between the different FP lengths (Fig. 6).

From the perspective of a dual-process model, arousal and, thus, responsiveness will decrease over the course of an FP. Since, however, normal individuals are assumed to engage in a compensatory process of strategic preparation that capitalizes on the hazard-rate increase during the FP, responses are predicted to be fast on long-FP trials even when preceded by a long FP_{n-1}. While this may essentially be true, our data show that there is a slight tendency to being better prepared in short–long than long–long FP sequences, an effect that is even more pronounced in short–short–long FP sequences compared to long–long–long ones. On the one hand, this could mean that preserved arousal after a short FP_{n-1} aids the strategic preparation process and thus adds somewhat to RT performance on long-FP_n trials. Such a perspective has been offered by Correa, Trivino, Perez-Duenas, Acosta, and Lupiáñez (2010, p. 236) within the context of FP effects, who referred to a process termed “arousal inertia,” and, more broadly, by Dietrich and Audiffren (2011, pp. 1309–1312), who proposed that bodily induced arousal (e.g., during physical exercise) energizes cognition. On the other hand, and more in line with the dual-process model, the strategic component might not fully succeed in compensating for a stronger arousal decrease on preceding long-FP_{n-1} trials. This might be the case because the strategic preparatory process does not directly aim at compensatory arousal regulation but rather at turning objective hazard-rate changes into subjective expectancy and associated response preparation. Thus, its compensatory effect might only be a by-product. This view agrees with the well-known fact that any kind of preparation for speeded action also entails an increase in arousal (cf. Langner et al., 2011). And after one or more preceding long FPs, this arousal component of the strategic preparatory process might simply not be able to reach its optimum level.

The beneficial effect of multiple preceding short FPs on performance in long-FP_n trials was especially pronounced when a simple-

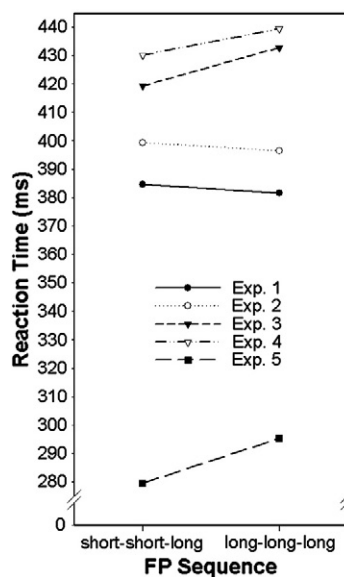


Fig. 6. Comparison of reaction times (RTs) between short–short–long and long–long–long foreperiod (FP) sequences, displayed separately for Experiments 1 to 5 (FPs in Exp. 1: 300, 900, 1500 ms; Exp. 2: 800, 1600, 2400 ms; Exp. 3: 1200, 2400, 3600 ms; Exp. 4: 1200, 3600 ms; Exp. 5: 1200, 3600 ms; Exps. 1–4: choice-RT task, Exp. 5: simple-RT task).

RT (instead of a choice-RT) task was used (compare Exps. 4 and 5). This apparently greater sensitivity of the simple-RT (vs. choice-RT) task to the effects of temporal preparation in the variable-FP situation is consistent with previous studies (e.g., Correa, Lupiáñez, Milliken, & Tudela, 2004; Steinborn et al., 2008) and may result from several reasons. First, probably parts of time-related response activation at a critical moment are absorbed during decision time of a choice-RT task. Kiesel et al. (2010, pp. 854–855), for example, argued that temporal preparation plays a rather minor role in more complex tasks such as task switching. Second, in simple-RT tasks, stimulus processing and motor response can be prepared completely, potentially leading to arousal- and/or learning-related modulations along the whole sensorimotor processing chain. This predictability might thus enable input- and effector-specific preparation and/or time-point associations beyond the nonspecific preparation/associations possible in choice-RT tasks.

Finally, although the trace-conditioning model (Los & Van den Heuvel, 2001) does not incorporate arousal as a relevant factor, it is certainly not inconsistent with the model to assume that arousal can modulate conditioning processes in a way that might produce effects as observed here. For example, Killeen, Hanson, and Osborne (1978) argued that heightened levels of an animal's cortical arousal lowers the threshold for exhibiting an over-conditioned response to a target. Therefore, less associative strength would be needed to evoke an overt response under states of heightened arousal. In the classical-conditioning literature, effects of arousal on response threshold are regarded as biasing the measurement of “true” associative-strength values, but some authors even argue that arousal may also affect the associative-learning process itself. According to Gallistel and Gibbon (2002), for instance, decreased arousal impairs both memory encoding and retrieval, thus hampering the acquisition of conditioned responses at long timing intervals. Our results may therefore not be interpreted as inconsistent with a learning-based view of temporal preparation but rather as suggesting a moderating influence of arousal on learning-based performance.

7.3. Future directions and conclusion

One question that remained open in our study concerns the potentially dissociable effects of average FP length and FP range. In our design, these factors could not be disentangled, but previous research showed independent effects of both variables on performance (see Niemi & Näätänen, 1981, for a review). Another challenge for future research is to better characterize and potentially differentiate the presumed monitoring mechanisms running during the FP. The dual-process model assumes that temporal event monitoring is guided by a supervisory attentional system (cf. Shallice, 1988; Shallice et al., 2008; Stuss et al., 2005; Vallesi, McIntosh, Shallice, & Stuss, 2009), which should be impaired by any variable that produces an imbalance between supply and demand of cognitive resources. In situations with low contextual temporal uncertainty (Exps. 1 & 2), the critical (i.e., resource-demanding) processes may be to monitor the conditional probabilities. In a wider temporal context (Exps. 3–5), however, an additional resource-demanding process emerges, namely the need to monitor and re-establish an appropriate level of general arousal, or energization, respectively. Posner (1978), for example, originally attributed the increase in RT with very long (> 10 s) FPs to difficulties in maintaining vigilance, considered by some authors to be counteracted by means of a resource-demanding process of arousal regulation (cf. Bratzke, Rolke, Steinborn, & Ulrich, 2009; Fischer et al., 2008; Flehmig, Steinborn, Westhoff, & Langner, 2010; Helton et al., 2010; Langner et al., 2011; Matthews & Davies, 2001; O'Connell et al., 2008).

In conclusion, our study revealed sequential effects of prolonged preparatory activity during the preceding trial(s) that are detrimental to temporal preparation under conditions of increased contextual time uncertainty, i.e. great average FP length and range. This pattern argues for an explanation in terms of a short-term exhaustion from

effortful preparation that lowers arousal (i.e. response readiness) to suboptimal levels and cannot fully be compensated for by strategic (or conditioning-based) preparation on the current trial. This reasoning agrees very well with the dual-process account but could also be incorporated into the trace-conditioning model. Future studies, therefore, are required to further disentangle the complex interplay between energetic and computational processes that mediate temporal preparation under different degrees of time uncertainty.

Appendix A

Table 1
ANOVA results for Experiments 1, 2, and 3.

Source	dfs	Reaction time			Error percentage		
		F	p	η^2	F	p	η^2
<i>Experiment 1 (FPs: 300, 900, 1500 ms, choice reaction)</i>							
1 FP _{n-2}	2,98	22.0	0.000	0.31	3.1	0.050	0.06
2 FP _{n-1}	2,98	23.3	0.000	0.32	1.0	0.401	0.02
3 FP _n	2,98	55.3	0.000	0.53	2.0	0.142	0.04
4 FP _{n-2} × FP _{n-1}	4,196	0.5	0.749	0.01	0.9	0.496	0.02
5 FP _{n-2} × FP _n	4,196	14.7	0.000	0.23	4.0	0.005	0.08
6 FP _{n-1} × FP _n	4,196	38.0	0.000	0.44	3.3	0.013	0.06
7 FP _{n-2} × FP _{n-1} × FP _n	8,392	1.5	0.155	0.03	1.6	0.155	0.03
<i>Experiment 2 (FPs: 800, 1600, 2400 ms, choice reaction)</i>							
1 FP _{n-2}	2,98	4.2	0.019	0.08	0.4	0.682	0.01
2 FP _{n-1}	2,98	51.8	0.000	0.51	0.0	0.699	0.01
3 FP _n	2,98	24.8	0.000	0.34	8.0	0.001	0.14
4 FP _{n-2} × FP _{n-1}	4,196	5.5	0.001	0.10	1.7	0.154	0.03
5 FP _{n-2} × FP _n	4,196	6.2	0.000	0.11	0.9	0.478	0.02
6 FP _{n-1} × FP _n	4,196	25.2	0.000	0.34	4.8	0.001	0.09
7 FP _{n-2} × FP _{n-1} × FP _n	8,392	0.5	0.939	0.01	1.6	0.131	0.03
<i>Experiment 3 (FPs: 1200, 2400, 3600 ms, choice reaction)</i>							
1 FP _{n-2}	2,98	21.0	0.000	0.30	0.8	0.435	0.02
2 FP _{n-1}	2,98	52.3	0.000	0.52	1.5	0.232	0.03
3 FP _n	2,98	32.0	0.000	0.40	4.7	0.011	0.10
4 FP _{n-2} × FP _{n-1}	4,196	2.9	0.027	0.06	1.7	0.161	0.03
5 FP _{n-2} × FP _n	4,196	1.9	0.114	0.04	1.8	0.135	0.04
6 FP _{n-1} × FP _n	4,196	26.1	0.000	0.35	1.2	0.316	0.02
7 FP _{n-2} × FP _{n-1} × FP _n	8,392	0.9	0.463	0.02	0.8	0.539	0.02]

Note. Effect size: partial η^2 ; Experimental factors: FP_{n-2}/FP_{n-1}/FP_n: 2-back/-1-back/-current-trial foreperiod (short vs. medium vs. long).

Table 2
ANOVA results for Experiments 4 and 5.

Source	dfs	Reaction time			Error percentage		
		F	p	η^2	F	p	η^2
<i>Experiment 4 (FPs: 1200, 3600 ms; choice reaction)</i>							
1 FP _{n-2}	1,34	65.6	0.000	0.66	0.2	0.899	0.00
2 FP _{n-1}	1,34	124.0	0.000	0.79	3.5	0.069	0.09
3 FP _n	1,34	37.0	0.000	0.52	10.6	0.003	0.24
4 FP _{n-2} × FP _{n-1}	1,34	3.5	0.069	0.09	0.8	0.387	0.02
5 FP _{n-2} × FP _n	1,34	9.2	0.005	0.21	4.9	0.034	0.13
6 FP _{n-1} × FP _n	1,34	110.2	0.000	0.76	1.2	0.282	0.03
7 FP _{n-2} × FP _{n-1} × FP _n	1,34	3.4	0.073	0.09	0.2	0.664	0.01
<i>Experiment 5 (FPs: 1200, 3600 ms; simple reaction)</i>							
1 FP _{n-2}	1,14	41.1	0.000	0.75	–	–	–
2 FP _{n-1}	1,14	113.1	0.000	0.89	–	–	–
3 FP _n	1,14	13.6	0.002	0.49	–	–	–
4 FP _{n-2} × FP _{n-1}	1,14	0.2	0.630	0.02	–	–	–
5 FP _{n-2} × FP _n	1,14	10.9	0.005	0.44	–	–	–
6 FP _{n-1} × FP _n	1,14	60.9	0.000	0.81	–	–	–
7 FP _{n-2} × FP _{n-1} × FP _n	1,14	1.0	0.336	0.07	–	–	–]

Note. Effect size: partial η^2 ; Experimental factors: FP_{n-2}/FP_{n-1}/FP_n: 2-back/-1-back/-current-trial foreperiod (short vs. long). For Experiment 5, effects on anticipatory responses could not be analyzed, since not all factor cells contained sufficient responses.

Table 3
Mean reaction time (RT) and standard error of the mean (SE) as a function of second-order previous foreperiod (FP_{n-2}), first-order previous foreperiod (FP_{n-1}), and current foreperiod (FP_n), displayed for Experiments 1 to 3.

	Factor levels			Experiment 1		Experiment 2		Experiment 3	
	FP _{n-2}	FP _{n-1}	FP _n	RT	SE	RT	SE	RT	SE
1	1	1	1	376	8.1	389	8.0	409	8.6
2	1	1	2	378	5.8	393	7.4	415	8.1
3	1	1	3	385	6.5	399	7.9	419	9.5
4	1	2	1	399	8.0	404	8.2	442	10.9
5	1	2	2	372	6.2	388	8.5	417	9.1
6	1	2	3	380	6.5	394	7.4	423	9.6
7	1	3	1	404	8.2	409	8.6	456	9.8
8	1	3	2	380	7.0	395	8.6	431	10.7
9	1	3	3	382	7.3	398	7.3	425	10.2
10	2	1	1	393	8.3	390	8.3	423	10.1
11	2	1	2	372	6.0	384	7.0	420	9.5
12	2	1	3	388	7.1	393	8.2	419	8.6
13	2	2	1	414	8.3	416	8.7	446	9.1
14	2	2	2	381	6.7	394	8.5	423	8.7
15	2	2	3	381	7.0	394	8.9	427	10.7
16	2	3	1	425	8.8	429	9.4	465	10.8
17	2	3	2	381	7.3	402	8.5	427	10.6
18	2	3	3	380	6.2	401	8.5	426	10.9
19	3	1	1	394	7.9	393	7.9	432	9.2
20	3	1	2	381	7.0	387	7.8	423	9.0
21	3	1	3	389	7.5	391	7.6	430	9.8
22	3	2	1	421	8.6	417	9.5	451	9.9
23	3	2	2	378	6.9	393	7.9	421	9.0
24	3	2	3	382	7.5	393	8.4	427	10.1
25	3	3	1	428	9.7	427	9.1	462	10.7
26	3	3	2	383	6.7	400	8.7	430	9.4
27	3	3	3	382	7.8	396	8.6	433	10.6]

Notes. Factor levels of the experimental conditions (FP_{n-2}, FP_{n-1}, FP_n): 1 = short FP, 2 = medium FP, and 3 = long FP.

Table 4
Mean reaction time (RT) and standard error of the mean (SE) as a function of second-order previous foreperiod (FP_{n-2}), first-order previous foreperiod (FP_{n-1}), and current foreperiod (FP_n), displayed for Experiments 4 and 5.

	Factor levels			Experiment 4		Experiment 5	
	FP _{n-2}	FP _{n-1}	FP _n	RT	SE	RT	SE
1	1	1	1	432	9.2	276	8.2
2	1	1	2	430	9.7	280	8.0
3	1	2	1	465	9.9	326	10.2
4	1	2	2	439	9.7	288	9.6
5	2	1	1	442	9.4	298	12.7
6	2	1	2	438	9.7	282	8.9
7	2	2	1	476	9.5	348	12.4
8	2	2	2	439	9.7	295	8.3]

Notes. Factor levels of the experimental conditions (FP_{n-2}, FP_{n-1}, FP_n): 1 = short FP, 2 = long FP.

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