

Sequential effects within a short foreperiod context: Evidence for the conditioning account of temporal preparation

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ABSTRACT

Responses to an imperative stimulus (IS) are especially fast when they are preceded by a warning signal (WS). When the interval between WS and IS (the foreperiod, FP) is variable, reaction time (RT) is not only influenced by the current FP but also by the FP of the preceding trial. These sequential effects have recently been proposed to originate from a trace conditioning process, in which the individuals learn the temporal WS–IS relationship in a trial-by-trial manner. Research has shown that trace conditioning is maximal when the temporal interval between the conditioned and unconditioned stimulus is between 0.25 and 0.60 s. Consequently, one would predict that sequential effects occur especially within short FP contexts. However, this prediction is contradicted by Karlin [Karlin, L. (1959). Reaction time as a function of foreperiod duration and variability. *Journal of Experimental Psychology*, 58, 185–191] who did not observe the typical sequential effects with short FPs. To investigate temporal preparation for short FPs, three experiments were conducted, examining the sequential FP effect comparably for short and long FP-sets (Experiment 1), assessing the influence of catch trials (Experiment 2) and the case of a very dense FP-range (Experiment 3) on sequential FP effects. The results provide strong evidence for sequential effects within a short FP context and thus support the trace conditioning account of temporal preparation.

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1. Introduction

In reaction time (RT) tasks, a warning signal (WS) typically precedes the imperative response stimulus (IS). Since the pioneering work of Woodrow (1914), it has been repeatedly shown that RT is strongly influenced by the interval between the WS and the IS, that is, by the foreperiod (FP, Niemi & Näätänen, 1981, for a review). This FP effect depends on whether the FP duration varies randomly from trial-to-trial (variable FP condition) or remains constant within a block of trials and only varies across blocks (constant FP condition). In the constant condition, mean RT usually increases progressively as the FP duration is increased. In the variable condition, however, mean RT usually decreases as the FP duration increases. These two FP effects are well-established and they can be observed for both simple and choice RT tasks (Bertelson & Boons, 1960; Mattes & Ulrich, 1997; Sanders, 1998, p. 173). Since the WS conveys no information about the response, these effects reflect a state of non-specific preparation, sometimes referred to as temporal preparation (Müller-Gethmann, Ulrich, & Rinkeauer, 2003; Rolke & Hofmann, 2007).

The traditional view of temporal preparation presupposes that participants intentionally prepare for the moment when the IS is delivered (Los & Van den Heuvel, 2001). Central to this view is the assumption that a high preparatory state can be maintained only for a brief duration, that is, 0.1–0.3 s (Alegria, 1974; Gottsdanker, 1975). Accordingly, the individuals need to synchronize this brief preparation period with the moment of IS presentation, because optimal performance can only be achieved when the IS is occurring during this preparation period. However, the individual's strategy to anticipate the imperative moment, that is, the moment of IS presentation (Los & Van den Heuvel, 2001) greatly differs between the constant FP condition and the variable one. In the constant condition, the individual's ability to predict the imperative moment deteriorates as FP is lengthened, which in turn impairs the synchronization of the preparation period with the imperative moment at longer FPs (Näätänen, Muranen, & Merisalo, 1974). Accordingly, RT typically increases with increasing FP-length in the constant condition.

In the variable condition, however, there is not only one possible moment but several critical moments at which the IS may occur. For example, if the IS occurs with equal probability at each critical moment, the conditional probability of IS presentation during a single trial increases gradually as time goes by, that is, as the

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FP ages (Niemi & Näätänen, 1981, p. 137). It is usually believed that individuals become aware of this probability increase. As a result, their expectancy about IS occurrence grows gradually with the aging of FP. This growth of expectancy is assumed to enlarge the preparatory state, producing short RTs at a long FP_n and thus accounting for the observed FP–RT effect in the variable condition (Niemi & Näätänen, 1981; Sollers & Hackley, 1997). Thus, the classical view can explain the basic FP–RT effects.

Los and coworkers (Los & Heslenfeld, 2005; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001), however, have recently challenged this traditional view of an intentionally driven preparation process. They put forward a completely different theoretical viewpoint, arguing that response-related preparation is driven by a process of trace conditioning. In this form of classical conditioning, the unconditioned stimulus (US) is not simultaneously presented together with the conditioned stimulus (CS) but somewhat after the CS. In this situation, the CS can produce response-related activation at the moment when the US will occur (Gallistel & Gibbon, 2000; Grossberg & Merrill, 1992; Machado, 1997). Pertaining to the case of temporal preparation, Los and Van den Heuvel (2001) pointed on the conceptual similarity between the trace conditioning paradigm and the temporal preparation paradigm. According to the authors, the IS corresponds to the US, whereas the WS acts as the CS that unintentionally initiates response-related activation at critical moments. In particular, their model relies on four assumptions (cf. Los & Van den Heuvel, 2001, p. 372). First, the conditioned response has scalar property, that is, the preparatory peak is sharpened for early critical moments but takes more time to build up and decay when the critical moment is more remote from the WS. Second, the conditioned strength at a critical moment is reinforced when the IS occurs at this moment. Third, the conditioned strength at a critical moment remains unchanged when the IS occurs at an earlier critical moment, and fourth, decreases when the IS occurs at a later critical moment. Los (2004, p. 120) further specified this assumption arguing that when a critical moment is bypassed, it is subject to conditioned inhibition and therefore becomes associated with non-responding. This model refers to RT as a dependent measure, which is inversely related to the strength of the conditioned response at the imperative moment.

In the constant FP condition, activation builds up only at the imperative moment. In the variable FP condition, however, the IS always occurs at random times after the WS; hence reliable response strength cannot develop. In this situation, the individuals have been shown to prepare according to FP-length of the preceding trial (Los & Van den Heuvel, 2001). That is, reinforced response strength from the previous trial carries over to the next trial and elicits response-related activation at the moment which was imperative in the previous trial. Hence, especially short RTs are implied when the FP of the preceding trial is repeated. In fact, this trial-to-trial reinforcement can readily account for the finding that RT decreases with FP in a variable FP condition (see, Los & van den Heuvel, 2001).

As indicated just before, this trial-to-trial reinforcement also implies predictions about intertrial sequential effects that have been repeatedly observed in variable FP experiments. In brief, it has often been reported that, when a particular FP is preceded by a longer one in the preceding trial, RT is longer than when the preceding FP is equally long or shorter (e.g., Baumeister & Joubert, 1969; Karlin, 1959; Schupp & Schlier, 1972; Vallesi, Shallice, & Walsh, 2007; Van der Lubbe, Los, Jaskowski, & Verleger, 2004; Woodrow, 1914; Zahn & Rosenthal, 1966). These asymmetrical sequential FP effects have become the principal argument for demonstrating the superiority of the conditioning view over the classical view. Whereas the classical view cannot suitably account for sequential effects, the conditioning view provides a rather direct and plausible account (Los & Van den Heuvel, 2001, p. 371).

There are three possible FP sequences in the variable FP condition. First, a FP can be repeated in the subsequent trial. As mentioned before, RT is predicted to be short on the subsequent trial, because response strength was reinforced at the imperative moment in the preceding trial. Second, the FP can alter from long to short. In this case, a long RT should result because the imperative moment was not reinforced in the preceding trial. Finally, the FP can alter from short to long. In this case, the conditioning account predicts relatively short RTs, because later imperative moments are less frequently bypassed and thus less frequently associated with non-responding. Accordingly, response strength to an IS should increase with FP-length and should be maximal at the latest imperative moment (see Los, 2004, p. 120, for a detailed explanation). Hence, the conditioning view implies an asymmetric sequential FP effect in that a long FP_{n-1} prolongs RT in a subsequent trial with a short FP_n , whereas a short FP_{n-1} should not produce such a prolongation.

Most studies that have reported this asymmetrical sequential effect employed FPs with a mean FP usually above one second (Appendix 1). The choice of these FP-sets appears somewhat sub-optimal, since substantial empirical evidence has shown that human trace conditioning in conventional settings is usually maximal for CS–US intervals between 0.25 and 0.60 s (see Anderson, 2000, p. 41; Mauk & Buonomano, 2004). This notion also agrees with the predictions of formal conditioning models (e.g., Machado, 1997, p. 242; Moore, Choi, & Brunzell, 1998, pp. 4–8; Sutton & Barto, 1998, chap. 6). Specifically, the core assumption of these models is that a CS initiates a cascade of neural activation and when the US occurs during this process, an associative link is established between the representation of the CS and the one of the US, that is, these two representations become “time-tagged” (Moore et al., 1998; Osman, Albert, Ridderinkhof, Band, & van der Molen, 2006). The neural activation triggered by the CS, however, decays within a few seconds and, consequently, the CS–US linkage is particularly effective at short intervals but less effective at long ones. Hence, according to trace conditioning models, one should also expect an asymmetrical sequential FP effects in a short variable FP-set.

However, unlike conventional settings of trace conditioning (e.g., human eyelid conditioning) this prediction is not confirmed within the context of mental chronometry, in which mean RT typically serves as measure of performance. Karlin (1959) examined sequential FP effects with a very short FP-set. In one condition, FPs were 1.6, 2.0, and 2.4 s and the typical asymmetrical sequential FP effect was observed; in another condition, the FPs were especially short, that is, 0.4, 0.5, and 0.6 s. In this condition, an anomalous sequential FP effect was obtained, which differed entirely from those obtained at longer FPs. Specifically, RT increased with increasing FP_n after the presentation of a short FP_{n-1} , instead of the typical decrease. Furthermore, the mean FP–RT function in this condition actually increased rather than decreased with FP-length. Hence, Karlin’s study provides conflicting data for the conditioning view. If sequential FP effects are the signature of trace conditioning, as proposed by Los and Van den Heuvel (2001), one would expect a clear asymmetrical sequential FP effect within this short variable FP context.

There are several factors that might be responsible for the abnormal RT pattern in Karlin’s (1959) study. First, one may argue that immediate arousal effects elicited by the WS are operating at this short FP-set and thus override the effects of temporal preparation (Bertelson & Tisseyre, 1969). However, this explanation seems unlikely since arousal is largely dependent on WS intensity (Ulrich & Mattes, 1996), and this intensity was low (30 dB) in Karlin’s study. Second, Karlin employed a simple instead of a choice RT task. It is therefore possible that premature responses (no catch trials were used) or occasional responses to the WS (the same tone

functioned as WS and as IS) concealed the sequential FP effect. Third, Karlin used a very dense FP-range (FPs: 0.4, 0.5, 0.6 s) which may not have induced sufficient temporal uncertainty to reveal a sequential FP modulation on RT (see, Klemmer, 1957; Niemi & Näätänen, 1981, p. 137). Instead of adapting temporal preparation from trial-to-trial, the individuals may have always prepared for the shortest imperative moment, resulting in optimal performance in short FP_n trials but suboptimal performance in medium or long FP_n trials.

Unlike Karlin (1959), Alegria (1975b) found a flattened standard FP-RT effect using a very dense FP-range (0.6, 0.7, 0.8 s). Since Alegria (1975b) used a choice RT task and FPs above 0.6 s, it is not clear why his results differed from Karlin's (1959) observation. Hence, the question of how individuals prepare for the IS at very short variable FPs remains unclear. Moreover, the divergence between findings in conventional trace conditioning research (Mauk & Buonomano, 2004; Moore et al., 1998) and in the context of chronometric RT research (Alegria, 1975b; Karlin, 1959) clearly shows that this question is not trivial.

In the present study, three experiments were conducted to study the cognitive processes underlying temporal preparation within a very short temporal context. In order to address our major question, whether there is evidence for an asymmetrical sequential FP effect within a short variable FP context, Experiments 1 and 2 examined temporal preparation with FPs below 0.6 s using an auditory WS and a visual IS. To ensure that temporal uncertainty imposed by the FP variability (Klemmer, 1957, p. 198) is sufficient, the FP-range was larger than in Karlin's (1959) short FP-set. Experiment 1 used stimuli similar to the ones used by Los et al. (2001), a condition with three short FPs (0.2, 0.4, 0.6 s), and a control condition with three longer FPs (1.2, 2.4, 3.6 s). A choice RT task was employed to control for anticipatory responses. Experiment 2 examined sequential effects within a short FP context only (0.2, 0.4, 0.6 s), using a simple RT task. To investigate the role of anticipatory responses for the sequential FP effect, a condition with no catch trials was compared to a condition with 25% catch trials. Finally, a supplementary goal was to clarify the reasons why Karlin did observe an abnormal RT pattern in his study. Experiment 3 therefore more directly replicated Karlin's experiment, using a very dense FP-range (FPs: 0.4, 0.5, 0.6 s). In addition to Karlin's simple RT task, we also employed a choice RT task.

2. Experiment 1

In Experiment 1, we used two FP-sets to assess whether there is evidence for sequential effects within a short temporal context, and whether short FPs reveal a similar asymmetrical pattern of sequential FP effects compared to long FPs. Anticipatory responding was controlled by using a choice RT task. In the short FP condition, we employed three FPs of 0.2, 0.4, and 0.6 s, whereas in the long FP condition, three FPs of 1.2, 2.4, and 3.6 s were used. These FP-durations were selected to keep the proportional relationship, that is, the relative FP-range, between the short and long FP-set constant (Niemi & Näätänen, 1981, p. 137).

2.1. Method

Participants. Twenty-two (5 male, 17 female) volunteers (mean age = 29.5 years, SD = 8.5) took part in two experimental sessions. All participants but one were right-handed and all of them had normal or corrected-to-normal vision.

Stimuli and apparatus. The experiment took place in a dim and noise-shielded room. It was run on a standard IBM computer with color display (19", 150 Hz refresh rate) and was programmed in MATLAB™ using the Psychophysics Toolbox extensions (Brainard,

1997; Pelli, 1997). Participants were seated at a distance of about 60 cm in front of the computer screen. The auditory WS (1000 Hz, 70 dB SPL) was presented binaurally via headphones. The visual stimuli were displayed in blue (7.1 cd/m²) at the center of a grey (38.4 cd/m²) computer screen. A "+" sign (0.5° × 0.5° angle of vision) served as fixation cross and the IS consisted of the letters "L" and "R" (1.14° × 0.86° angle of vision).

Procedure and design. Each trial started with the presentation of the auditory WS for 100 ms and a fixation cross in the center of the screen. After the FP had expired, the IS replaced the fixation cross. Participants performed a two-choice RT task and responded with either the left shift-key (left index finger in case of L) or the right shift-key (right index finger in case of R). The response terminated the IS. If no response occurred, however, 2 s after IS onset, the IS was terminated. A constant intertrial-interval of 1.5 s separated subsequent trials. Feedback was given only in case of an erroneous response or in case of response interval expiration. In case of an erroneous response, the word "falsch" (wrong) was presented for 0.3 s, whereas in case of interval expiration, the words "zu langsam" (too slow) were presented for 0.3 s. A short rest period followed after a block of 150 trials. Participants performed 120 practice trials and 1500 experimental trials in each of the two FP conditions and each condition was run on a separate day. The order of these two conditions was counterbalanced across participants. Participants were instructed to respond quickly and accurately. This experiment contained the three factors FP-set [short (0.2, 0.4, 0.6 s) vs. long (1.2, 2.4, 3.6 s) FP-set], foreperiod duration in the previous trial (FP_{n-1} : short, medium, long) and foreperiod duration in the current trial (FP_n : short, medium, long) in a within-subject design.

2.2. Results and discussion

All trials with responses shorter than 100 ms or longer than 1000 ms were considered outliers and their corresponding trials were discarded (0.37%) from further data analysis. *p*-Values were, whenever appropriate, adjusted for violations of the sphericity assumption using the Greenhouse-Geisser correction. A within-subject ANOVA with factors FP-set, FP_{n-1} , and FP_n was performed on mean RT of correct responses and error percentage. Statistical effect size is reported using partial η^2 ; this measure is equal to the ratio $SS_x/(SS_x + SSE)$, where SS_x represents the sum of squares of source X and SSE is error sum of squares term associated with this source.

Fig. 1 summarizes the results and depicts RT and error percentage as a function of FP-set, FP_{n-1} , and FP_n . Error percentage was generally low with an average of about 3% and did not reveal any significant effects. There was a main effect of the factor FP-set on RT, $F(1,21) = 219.3$, partial $\eta^2 = .91$, $p < .001$, indicating that RT was shorter in the short FP-set (366 ms) than in the long FP-set (437 ms). This RT benefit for the short FP-set might be attributable to a better general ability to process short time intervals than long ones (e.g., Klemmer, 1957; Näätänen et al., 1974). There was also a main effect of FP_n on RT, $F(2,42) = 47.5$, partial $\eta^2 = .69$, $p < .001$, that is, RT decreased as FP_n increased (417, 395, and 392 ms). This main effect replicates the well-established FP-RT effect in variable FP experiments. In addition, the FP in the preceding trial also influenced RT in the current trial as revealed by a main effect of FP_{n-1} on RT, $F(2,42) = 117.2$, partial $\eta^2 = .85$, $p < .001$; that is, RT increased as FP_{n-1} decreased (394, 403, and 409 ms).

There was also a $FP_{n-1} \times FP_n$ interaction effect on RT, $F(4,84) = 36.4$, partial $\eta^2 = .63$, $p < .001$, replicating the typical asymmetrical sequential FP effect, that is, when the preceding FP was long, RT in a current trial decreased with increasing FP and this effect was weaker when a short FP preceded a current trial. There was also a significant FP-set $\times FP_n$ interaction on RT, $F(2,42) = 8.3$,

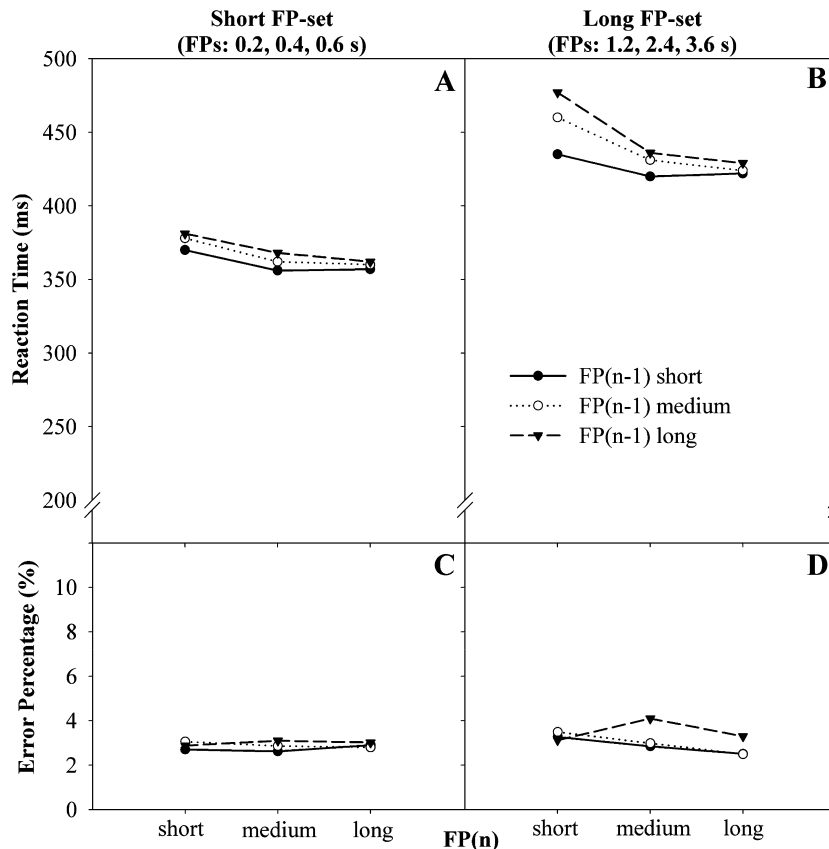


Fig. 1. Reaction time (panel A, B) and error percentage (panel C, D) as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n) in Experiment 1. Data are separately displayed for the short FP-set (left panel, FPs: 0.2, 0.4, 0.6 s) and the long FP-set (right panel, FPs: 1.2, 2.4, 3.6 s).

partial $\eta^2 = .28$, $p < .01$, and also a significant FP-set \times FP_{n-1} interaction on RT, $F(2,42) = 27.2$, partial $\eta^2 = .56$, $p < .001$, indicating that the size of the FP-RT effect was smaller for the short FP-set than for the long FP-set. Finally, there was a FP-set \times FP_{n-1} \times FP_n interaction on RT, $F(4,84) = 17.6$, partial $\eta^2 = .46$, $p < .001$, indicating that the asymmetry of the sequential FP effect was smaller for the short FP-set than for the long FP-set.

In order to assess whether the asymmetrical sequential FP effect for the short FP-set was statistically reliable, additional ANOVAs were performed, separately for the short and for the long FP-set. Most important, there was also a significant FP_{n-1} \times FP_n interaction on RT for the short FP-set, $F(4,84) = 3.6$, partial $\eta^2 = .15$, $p < .05$, indicating that this short FP-set produced a reliable asymmetrical sequential FP effect. An analogous analysis replicated this well-established interaction effect on RT for the long FP-set, $F(4,84) = 41.6$, partial $\eta^2 = .66$, $p < .001$. Thus, Experiment 1 showed clear-cut evidence that the asymmetrical sequential FP effect even occurs at very short (below 0.6 s) FP-sets.

All in all, Experiment 1 replicated the classical FP-RT effect within the variable FP context. In addition, this FP-RT effect was modulated by the preceding FP, showing an asymmetrical sequential FP effect. Most important, however, the sequential FP effect was not restricted to the long FP-set but was also present for the short FP-set of FP-durations below 0.6 s. Although the evidence for a sequential FP effect within the short FP-set is well in line with the conditioning account of temporal preparation (e.g., Los & Van den Heuvel, 2001), this result contrasts with the one observed by Karlin (1959) who did not obtain the typical sequential FP effect within his short FP condition, using a simple RT task. Hence, it remains to be shown whether the asymmetrical sequential FP effect found in Experiment 1 can be reliably replicated in a simple RT

condition. Since response selection is not required in a simple RT task, a large degree of anticipatory responses in the short FP condition of Karlin's study might have masked the sequential FP effect.

3. Experiment 2

In Experiment 2 we assessed sequential FP effects in a simple RT task employing only the short FP-set of Experiment 1 (FPs: 0.2, 0.4, 0.6 s). By means of a simple RT task, we aimed to examine the role of anticipatory responses on the asymmetrical sequential FP effect. In particular, we employed the catch trial technique to control for anticipatory responses; that is, we compared the asymmetrical sequential FP effect in a condition with 0% catch trials (referred to as no-CT condition) to a condition with 25% catch trials (referred to as CT condition).

3.1. Method

Participants. Twenty-two volunteers (8 male, 14 female) took part in the two experimental sessions (mean age = 25.5 years, SD = 7.0). All participants but two were right-handed and all of them had normal or corrected-to-normal vision.

Stimuli and apparatus. All stimuli were identical to Experiment 1.

Procedure and design. The procedure and design was identical to Experiment 1 except for the following modifications. First, we employed only the short FP-set (0.2, 0.4, 0.6 s). Instead of two FP-sets, we employed two CT conditions in which either no (0%) catch trials or 25% catch trials were included. In a typical catch trial, no IS was presented. Second, participants performed a simple instead of a choice response task. That is, irrespective of whether the letter L

or R was presented, participants always responded by pressing the right shift-key with their right index finger. Participants were asked to respond quickly and to avoid premature responses. They performed 48 practice trials in each session, 1578 experimental trials in the no-CT condition and 1920 trials (1578 plus 342 CTs) in the CT condition. The two CT conditions were run on two separate days, and the order of these two experimental sessions was counterbalanced across participants. This experiment contained the three factors CT (no-CT vs. CT), FP_{n-1} (previous foreperiod: short, medium, long), and FP_n (current foreperiod: short, medium, long) in a within-subject design.

3.2. Results and discussion

Premature responses and trials with RTs shorter than 100 ms were defined as anticipatory responses (Kornblum, 1973); participants were not allowed to produce a second response following an anticipatory response prior to the IS. RTs longer than 800 ms were considered outliers and excluded from RT analyses (0.13%). Correct responses within this interval were used to compute mean RT. Few responses occurred during catch trials (1.31%). Trials following a catch trial in which a response was made were discarded from data analysis. Separate ANOVAs were performed on RT and on the percentage of anticipatory responses, with factors CT, FP_{n-1} , and FP_n .

The results are displayed in Fig. 2, which depicts mean RT and percentage of anticipatory responses as a function of CT, FP_{n-1} , and FP_n . The costs to withhold the responses in some trials in the CT condition were mirrored in the main effect of CT on RT, $F(1,21) = 43.2$, partial $\eta^2 = .67$, $p < .001$. That is, RT was prolonged in the CT condition (277 ms) compared to the no-CT condition

(250 ms). As in Experiment 1, the main effect of FP_n on RT, $F(2,42) = 21.8$, partial $\eta^2 = .51$, $p < .001$, indicated a decrease of RT with increasing FP_n (274, 255, and 261 ms). Also consistent with Experiment 1, FP_{n-1} influenced RT, $F(2,42) = 24.5$, partial $\eta^2 = .54$, $p < .001$. Whereas the factor CT slightly yet significantly modulated the variable FP effect, $F(2,42) = 5.8$, partial $\eta^2 = .22$, $p < .05$, the influence of the preceding FP was unaffected by CT, $F < 1$. Importantly, the asymmetrical sequential FP effect again showed up in the $FP_{n-1} \times FP_n$ interaction on RT, $F(4,84) = 16.1$, partial $\eta^2 = .43$, $p < .001$. Most interesting is the absence of any influence of CT on this asymmetrical sequential FP effect as indicated by the non-significant three-way interaction CT \times $FP_{n-1} \times FP_n$ on RT, $F < 1$.

As one might expect, the inclusion of catch trials drastically decreased the percentage of anticipatory responses (0.8% vs. 10.3%), $F(1,21) = 19.2$, partial $\eta^2 = .48$, $p < .001$. This result supports our assumption that catch trials prevent premature responses. Due to the anticipation of the imperative moment, anticipatory responses increased with increasing current FP (1.4%, 5.2%, 10.0%), resulting in a main effect of FP_n on anticipatory responses, $F(2,42) = 26.4$, partial $\eta^2 = .56$, $p < .001$. In addition, as indicated by the main effect of FP_{n-1} , anticipatory responses also increased with decreasing preceding FP (3.9% vs. 5.5% vs. 7.2%), $F(2,42) = 24.8$, partial $\eta^2 = .54$, $p < .001$. The influence of the current FP was more pronounced in the no-CT condition compared to the CT condition, as indicated by a main effect of FP_n on anticipatory responses, $F(2,42) = 27.4$, partial $\eta^2 = .57$, $p < .001$, and the influence of the preceding FP was also stronger in the no-CT condition than in the CT one, as indicated by a main effect of FP_{n-1} on anticipatory responses, $F(2,42) = 21.3$, partial $\eta^2 = .50$, $p < .001$. There was only a slight tendency towards an asymmetrical sequential FP effect

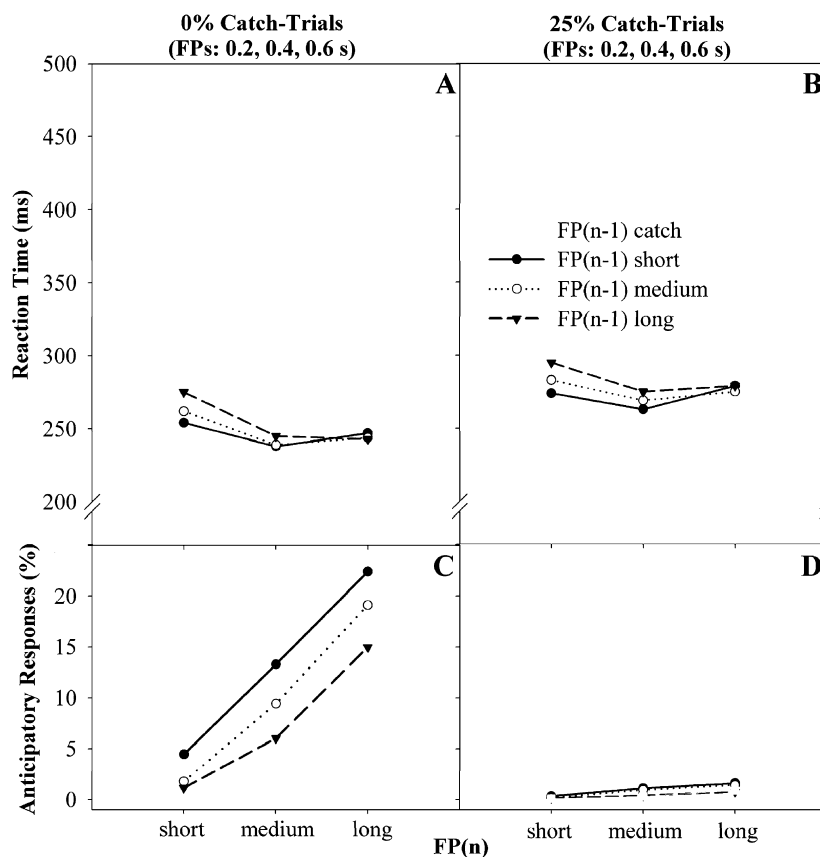


Fig. 2. Reaction time (panel A, B) and percentage of anticipatory responses (panel C, D) as a function of preceding foreperiod (FP_{n-1}) and current foreperiod (FP_n) in Experiment 2. Data are separately displayed for the condition with 0% catch trials (left panel) and the condition with 25% catch trials (right panel), using three FPs of 0.2, 0.4, and 0.6 s.

on anticipatory responses, $F(4,84) = 2.6$, partial $\eta^2 = .11$, $p = .10$, but no modulation of this marginal sequential FP effect by CT, $F(4,84) = 2.1$, partial $\eta^2 = .09$, $p = .15$.

In order to assess whether the asymmetrical sequential FP effect for the CT condition was statistically reliable, separate ANOVAs were performed for the no-CT and the CT condition. There was a significant $FP_{n-1} \times FP_n$ interaction on RT for the no-CT condition, $F(4,84) = 10.2$, partial $\eta^2 = .33$, $p < .001$, replicating the asymmetrical sequential FP effect (Experiment 1, short FP-set) with a simple RT task. The ANOVA for the CT condition revealed also an interaction effect on RT, $F(4,84) = 11.8$, partial $\eta^2 = .36$, $p < .001$. Thus, in contrast to Karlin (1959), Experiment 2 provides clear evidence that the typical asymmetrical sequential FP effect can also occur in a simple RT condition, irrespective of catch trials.

Importantly, the asymmetrical pattern of the sequential FP effect on RT was virtually identical in the two CT conditions. Nevertheless, there was a weak $CT \times FP_n$ interaction effect on RT, which obviously reflects a stronger RT increase at the longest FP_n in the CT condition than in the no-CT condition (Fig. 2). To examine whether this effect originates from a reduction in conditioned strength at the latest critical moment after catch trials, we inspected the sequential effect of catch trials. According to the trace conditioning account, the effect of a preceding catch trial should be particularly strong at the longest FP_n because the latest critical moment is only bypassed in catch trials but not in any other FP_{n-1} trial (Los & Agter, 2005). As can be seen in Fig. 2, preceding catch trials relative to other FP_{n-1} indeed increased RT mainly at the longest FP_n . In order to test this differential sequential effect of catch trials statistically, we performed an additional ANOVA that included a planned contrast of the case when a long FP_n was preceded by either a catch trial or a long FP_{n-1} against the case when a short FP_n was preceded by either a catch trial or a long FP_{n-1} . Indeed, the analysis revealed that the sequential effect of catch trial differed from the sequential effect of long FP_{n-1} . This was indicated by the FP_{n-1} (levels: long vs. catch) $\times FP_n$ (levels: long vs. short) interaction effect, $F(1,21) = 60.6$, partial $\eta^2 = .74$, $p = .001$. Whereas a catch trial compared to a long FP_{n-1} did not increase RT at short FP_n (284 vs. 295 ms) it clearly increased RT at long FP_n (302 vs. 279 ms). Thus, the RT increase at the longest FP_n in the CT condition compared to the no-CT condition can be attributed to a sequential effect of catch trials, which mainly exerts its influence at a long FP_n . This finding is consistent with the trace conditioning account (cf. Los & Agter, 2005).

Taken together, Experiment 2 replicated the typical asymmetrical sequential FP effect for the short FP-set of Experiment 1 within a simple RT condition. Although the participants showed a clear tendency to anticipate the IS in the no-CT condition, this anticipation behavior was reduced in the CT condition (i.e., 25% catch trials). Importantly, there was a similar asymmetrical sequential FP effect on RT in both the no-CT and the CT condition. In conclusion, Experiment 2 provides evidence that the asymmetrical sequential FP effect on simple RT performance can be observed irrespective of whether anticipatory responses are prevented (by means of catch trials) or not. It thus appears unlikely that anticipatory responses have caused the abnormal RT pattern in Karlin's (1959) study.

4. Experiment 3

The results of the Experiments 1 and 2 provide clear-cut evidence for an asymmetrical sequential FP effect within an FP context below 0.6 s, and thus confirmed the predictions derived from the trace conditioning account. However, since Experiment 2 demonstrated that anticipatory responding does not alter the asymmetrical pattern of the sequential FP effect, it still remains unclear why Karlin (1959) did not observe the typical RT pattern in a condition with short FPs. An alternative yet plausible explanation

is that the FP-range employed in Karlin's study was too dense and therefore did not produce sufficient temporal uncertainty. Notably, Klemmer (1957) has clearly shown that the relative FP-range (i.e., the ratio between the longest and the shortest FP in a set of variable FPs) is the most important predictor of FP-RT effects (for a similar view, see Näätänen, 1970; Vallesi & Shallice, 2007, p. 1386). Experiment 3 therefore replicated more directly Karlin's (1959) study, using the same small FP-set (0.4, 0.5, 0.6 s) in a simple RT task. In addition, since Alegria (1975b) found a flattened but typical FP-RT effect with a similar dense FP-range (FPs: 0.6, 0.7, 0.8 s) on choice RT performance, we also included a choice RT condition.

4.1. Method

Participants. Thirty volunteers (15 male, 15 female) took part in the two experimental sessions (mean age = 25.1 years, SD = 6.4). All participants but 4 were right-handed and all of them had normal or corrected-to-normal vision.

Stimuli and apparatus. All stimuli were identical to Experiments 1 and 2.

Procedure and design. The procedure and design was identical to Experiment 2 except for the following modifications. First, we employed the identical short FP-set as was used by Karlin (0.4, 0.5, and 0.6 s). Second, we employed two task conditions, of which one was a simple RT and the other a choice RT task. In the simple RT condition, participants always responded by pressing the right shift-key with their right index finger, irrespective of whether the letter L or R was presented. In the choice RT condition, participants responded by pressing either the left shift-key with their left index finger (in case of "L") or the right shift-key with their right index finger (in case of "R"). No catch trials were included. Participants performed 48 practice trials and 1,830 experimental trials in each of the experimental sessions. The two conditions (i.e., simple RT vs. choice RT) were run on two separate days, and the order of these two experimental sessions was counterbalanced across participants. This experiment contained the three factors task (simple RT vs. choice RT), FP_{n-1} (preceding foreperiod: short, medium, long), and FP_n (current foreperiod: short, medium, long) in a within-subject design.

4.2. Results and discussion

For the simple RT condition, premature responses and RTs shorter than 100 ms were defined anticipatory responses. As in Experiment 2, participants were not allowed to produce another response after an anticipatory response. RTs longer than 800 ms were considered outliers and their corresponding trials were discarded (0.61%). For the choice RT condition, RTs shorter than 100 ms and longer than 800 ms were considered outliers (0.75%); correct responses within this interval were used to compute mean RT; incorrect responses were used to compute error percentage. First, an overall ANOVA was performed including the factors Task (simple vs. choice), FP_{n-1} , and FP_n , and with RT as dependent measure. Second, for a more in-depth analysis, separate ANOVAs were performed for the simple RT task and for the choice RT tasks, with the factors FP_{n-1} , and FP_n , and with RT and percentage of anticipatory responses (simple RT condition), or error percentage (choice RT condition) respectively, as dependent variables.

Fig. 3 depicts mean RT, anticipatory responses and error percentage as a function of Task, FP_{n-1} , and FP_n . As one expects, the overall ANOVA revealed that simple RTs were much faster (220 ms) than choice RTs (351 ms), $F(1,29) = 316.9$, partial $\eta^2 = .92$, $p < .001$. Additionally, the ANOVA indicated that the FP-RT pattern differed between the task conditions, Task \times FP_n inter-

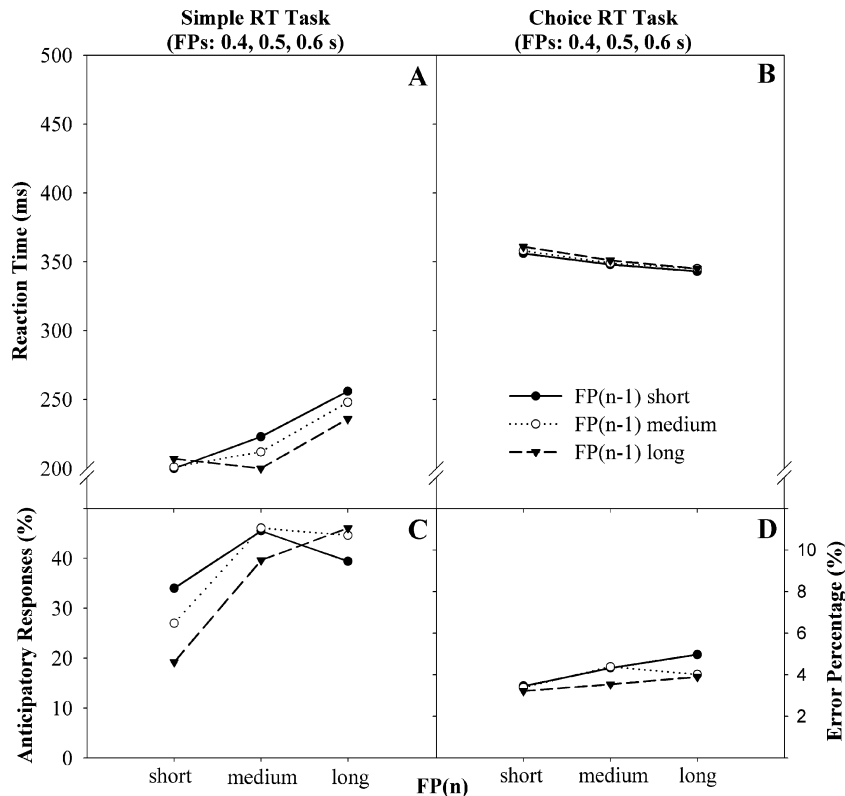


Fig. 3. Reaction time (panel A, B) and percentage of anticipatory responses (panel C) and error percentage (panel D) as a function of the preceding foreperiod (FP_{n-1}) and the current foreperiod (FP_n) in Experiment 3. Data are separately displayed for the simple RT condition (left panel) and the choice RT condition (right panel), using three FPs of 0.4, 0.5, and 0.6 s.

action on RT, $F(2,58) = 31.5$, partial $\eta^2 = .52$, $p < .001$. The $FP_{n-1} \times FP_n$ interaction indicates the asymmetrical sequential FP effect, $F(4,116) = 11.1$, partial $\eta^2 = .28$, $p < .001$; however, the asymmetry of the sequential FP effect differed between the two task conditions, as indicated by the Task $\times FP_{n-1} \times FP_n$ interaction effect, $F(4,116) = 5.9$, partial $\eta^2 = .17$, $p < .01$.

Simple RT condition. In contrast to Experiment 2, an upward-sloping FP-RT effect was observed. RT increased from the shortest towards the longest FP_n (203, 212, 247 ms), $F(2,58) = 19.8$, partial $\eta^2 = .41$, $p < .001$. However, RT decreased with increasing FP_{n-1} (226, 220, 214 ms), $F(2,58) = 9.8$, partial $\eta^2 = .25$, $p < .01$. Importantly, there was also a $FP_{n-1} \times FP_n$ interaction effect on RT, $F(4,116) = 9.2$, partial $\eta^2 = .24$, $p < .001$, indicating a reversed asymmetrical sequential FP effect similar to the one observed by Karlin (1959). In particular, responses in short FP_n trials were always fast irrespective of FP_{n-1} . In contrast, responses in long FP_n trials were on average slower and showed a sequential modulation. Precisely, in long FP_n trials, responses were relatively fast when FP_{n-1} was also long compared to when FP_{n-1} was short.

Anticipatory responses across all FP_n conditions were much more frequent (38.2%) than in the no-CT condition of Experiment 2 (5.5%), and clearly increased with FP_n -length (26.7%, 44.4%, 43.4%), $F(2,58) = 20.5$, partial $\eta^2 = .41$, $p < .001$. Moreover, anticipatory responses were more frequent as FP_{n-1} increased (34.9%, 39.2%, 40.3%), $F(2,58) = 29.0$, partial $\eta^2 = .50$, $p < .001$. There was also a sequential modulation as indicated by the $FP_{n-1} \times FP_n$ interaction effect on anticipatory responses, $F(4,116) = 18.9$, partial $\eta^2 = .40$, $p < .001$. FP_{n-1} influenced anticipatory responding in short FP_n trials but not in long FP_n trials. That is, participants anticipated more in short FP_n trials when FP_{n-1} was short (34.0%) than when FP_{n-1} was medium (27.0%) or long (19.2%). In contrast, they committed always a high level of anticipatory responses in long FP_n trials, irrespective of FP_{n-1} .

In sum, the simple RT condition revealed especially fast responses and an extraordinary high percentage of anticipatory responses in short FP_n trials, even though FP_{n-1} was long. This is consistent with the results of Karlin (1959) and suggests that participants mainly prepared for an early imperative moment without re-preparing in long FP_n trials.

Choice RT condition. In contrast to the simple RT condition, a standard but small downward-sloping FP-RT effect was obtained (358, 349, 344 ms), $F(2,58) = 88.1$, partial $\eta^2 = .75$, $p < .001$. Additionally, there was also a main effect of FP_{n-1} on RT, $F(2,58) = 9.9$, partial $\eta^2 = .26$, $p < .001$. This effect, however, was extremely small. RT increased with increasing FP_{n-1} but only by 3 ms (349, 351, 352 ms). The asymmetrical sequential FP effect in the choice RT condition was far from significant ($F = 0.8$). This is in contrast to Alegria (1975b) who actually observed the asymmetrical sequential FP effect using a very dense FP-range of FPs above 0.6 s (0.6, 0.7, 0.8 s).

In contrast to Experiment 1, FP_n had also an effect on error percentage, showing a 25% increase in error percentage with FP_n -length (3.4%, 4.1%, 4.3%), $F(2,58) = 12.8$, partial $\eta^2 = .31$, $p < .001$. This decrement in participant's performance efficiency towards the longest FP_n is consistent with the interpretation that participants prepared for an early imperative moment but did not re-prepare in long FP_n trials. In addition, FP_{n-1} did also affect error percentage, $F(2,58) = 4.1$, partial $\eta^2 = .12$, $p < .05$. More errors occurred when FP_{n-1} was short than when FP_{n-1} was long (4.3%, 3.9%, 3.6%). This shows that although participants probably attained peak preparation at an early moment, it was nevertheless adjusted according to FP_{n-1} . No significant $FP_{n-1} \times FP_n$ interaction effect on error percentage was observed but only a slight tendency towards a sequential FP effect on error percentage ($p = .07$).

In sum, the choice RT condition of Experiment 3 showed a clearly diminished FP-RT effect, compared to Experiment 1 (short

FP-set), due to the dense FP-range. The increase of error rate with longer FP_n showed that participant's performance efficiency decreased and therefore supports the view that peak preparation was attained at an early imperative moment, as was already suggested for the simple RT pattern of Experiment 3.

Conclusion. Taken together, Experiment 3 revealed a reversed sequential FP effect in the simple RT condition and a typical but very small FP-RT effect in the choice RT condition. Importantly, the RT pattern in the simple RT condition clearly indicates that Karlin's (1959) finding was not an anomalous result but a reliable empirical phenomenon that occurs when average FPs are small and the FP-range is very dense. The overall pattern of results (simple and choice RT condition) is consistent with the view that participants already attained maximal preparation at the short FP_n and were not able to re-prepare when the IS did not occur at the short FP_n . Instead, they may have relied on residual preparatory activity from the early imperative moment (Alegria, 1974; Alegria, 1975b). Since there was nevertheless some sequential modulation on RT as well as on anticipatory responses in the simple RT condition, participants may have adjusted the moment of attaining peak preparation from trial-to-trial, but probably not between distinct critical moments (as is usually the case in situations that enable re-preparation, i.e., when a broad FP-range is used). For instance, they may have shifted a single moment of peak preparation in a rather analog way, that is, after a short FP_{n-1} they expected the IS somewhat earlier, after a long FP_{n-1} trial somewhat later (cf. Grosjean, Rosenbaum, & Elsinger, 2001)¹.

5. General discussion

In the present study, we examined sequential effects in variable FP experiments, which have recently been proposed to originate from a trace conditioning process (Los & Van den Heuvel, 2001). Since trace conditioning in conventional settings is most effective when the FP interval is especially short (i.e., between 0.25 and 0.60 s), a clear-cut asymmetrical sequential FP effect should be observed within a short FP context. In contrast to this prediction, Karlin (1959) did not find the typical pattern of sequential FP effects with FPs below 0.60 s but a reversed sequential FP effect. The aim of the present study was to examine whether the sequential FP modulation can also be observed within a short temporal context. A supplementary goal was to clarify the reason why Karlin did observe an abnormal RT pattern in his study.

Accordingly, three experiments were conducted, examining the sequential FP effect for a short (FPs: 0.2, 0.4, 0.6 s) and a long (FPs: 1.2, 2.4, 3.6 s) FP-set (Experiment 1; choice RT), estimating the influence of catch trials (Experiment 2, simple RT; no-CTs vs. 25% CTs), and more directly replicating Karlin's study (Experiment 3; simple vs. choice RT; FPs: 0.4, 0.5, 0.6 s). The results of Experiments 1 and 2 clearly demonstrated the typical asymmetrical sequential FP effect for short FPs on choice (Experiment 1) and simple RT performance (Experiment 2). In addition, Experiment 3 replicated Karlin's (1959) finding of a reversed sequential FP effect on simple RT performance and thus shows that his observation was not an anomalous result, but was the result of the very dense FP-range used by Karlin. This suggests that the reduced time uncertainty prevented the typical sequential FP effects from occurring. In sum, the present study confirmed the predictions derived from

trace conditioning accounts, showing clear trial-to-trial adaptation of temporal preparation in a short FP context. In addition, Experiment 3 shows that when the FP-range is too dense, the typical asymmetrical sequential FP effect does not occur.

5.1. Influence of temporal context on sequential FP effects

Consistent with our hypothesis, Experiment 1 yielded a sequential FP effect not only for the long FP-set but also for the short FP-set. The sequential modulation in the short FP condition was clear-cut, demonstrating that the moment of attaining peak preparation is adapted in a trial-by-trial manner. This finding is consistent with the trace conditioning model (Los & Van den Heuvel, 2001; Los et al., 2001) which assumes that conditioned response activation in a current trial reaches maximum at the moment that was imperative in the previous trial and thus enhances RT performance. It should be noted that the data of Experiment 1 revealed a smaller asymmetrical sequential FP effect for the short FP-set than for the long FP-set, both in terms of RT differences (see Fig. 1) and statistical effect size (partial $\eta^2 = .15$ vs. $.66$). This finding suggests that conditioned activation influences RT differently than other measures of conditioning (e.g., leg flexions response, eyeblink reflex). There are several reasons for this difference.

First, unlike conventional settings of trace conditioning (e.g., human eyelid conditioning) in which the CS produces an autonomous, reflex-like response to the US, the individual's responses to an IS in variable FP experiments are much more under the intentional control of the individuals. From this point of view, conditioned activation elicited at critical moments may represent only mediating effects on RT performance in that it enhances cognitive processing at critical moments but does not take control over behavior (Los & Van den Heuvel, 2001, p. 373). Second, conditioned autonomous responses may be much more fine-grained in time than that of large effector systems, and therefore are more likely subject to temporal adaptation when the CS-US interval varies within a small range. Third, whereas conventional indices of trace conditioning (i.e., mean timing accuracy; mean scalar variance) mostly show conformity with the scalar properties of timing behavior (see, Lejeune & Wearden, 2006), speed-based measures obviously do not. For example, at millisecond FPs, responses are on average especially fast (e.g., due to higher level of arousal at short FPs), and therefore, sequential FP variations can only induce small RT differences among the FP conditions. Hence, this property of RT measures raises a problem for the direct comparison of sequential FP effects across different average time intervals that probably cannot be resolved by using similar relative FP-ranges (Niemi & Näätänen, 1981, p. 137).

5.2. Influence of catch trials on sequential FP effects

In Experiment 2, we replicated the finding of Experiment 1, using a short FP-set (0.2, 0.4, 0.6 s) and controlling for anticipatory responses using the catch trial technique (no-CT vs. CT condition). Catch trials prevented participants from executing anticipatory reactions, showing an additive upward-shift of the whole RT pattern in the CT condition compared to the no-CT condition (277 vs. 250 ms). However, the asymmetrical sequential FP effect occurred in both, the no-CT and the CT condition. This suggests that catch trials affect a rather different processing stage than temporal preparation. Whereas temporal preparation may affect predominantly pre-motor stages, as has recently been suggested (e.g., Bau-senhart, Rolke, Hackley, & Ulrich, 2006; Los & Schut, 2008; Müller-Gethmann et al., 2003), catch trials may exert their effect at a later stage, for instance at the motor stage (e.g., Alegria, 1978; Correa, Lupiáñez, Milliken, & Tudela, 2004; Los & Agter, 2005). More specifically, the inclusion of catch trials could have simply raised the

¹ To check that the observed reversed sequential FP effect is a robust phenomenon and not an artificial result due to the criterion used to define AR, we performed an additional ANOVA (factors: FP_{n-1} , FP_n , dependent variable: RT) in which mean RT was computed by including all response times after the IS. The obtained RT pattern was similar to that reported in Experiment 3, showing that the reversed sequential FP effect is a robust phenomenon and not dependent on whether anticipatory responses are included in the computation of mean RT, or not.

threshold for motor execution and thus prevent anticipatory responding (i.e., motor readiness model, Brunia, 1993; Mattes, Ulrich, & Miller, 1997; Näätänen, 1972; Näätänen and Merisalo, 1977, p. 135).

Although the catch trial effect was mainly additive, it nevertheless affected temporal preparation at late imperative moments. More precisely, the inclusion of catch trials changed the FP-RT function especially at the longest FP_n , showing an increase in RT in the CT condition, compared to the no-CT condition. This finding is consistent with other studies (Buckolz & Rodgers, 1980; Correa et al., 2004; Drazin, 1961; Los & Agter, 2005) that revealed a similar late upward-sloping of the FP-RT function in a condition with catch trials. The literature provides two possible explanations of this effect, one in terms of statistical expectancy (Buckolz & Rodgers, 1980) and one in terms of trace conditioning (Los & Agter, 2005). According to the expectancy account, the conditional probability that the IS will *not* occur after the WS (i.e., that the current trial is a catch trial) increases as the FP ages. As a result, the individual's expectancy that the IS will occur decreases with the length of FP, thus prolonging RTs especially at late imperative moments. According to the trace conditioning account, the increase of RT in long FP_n trials should be particularly strong after catch trials, since in catch trials the imperative moments are bypassed and therefore become associated with non-responding (Los & Agter, 2005). Indeed, the analysis of the catch trial sequential effect in the CT condition revealed that RT in long FP_n trials was increased when the preceding trial was a catch trial compared to when it was a non-catch trial. Therefore, the catch trial effects found in the present study are clearly consistent with the trace conditioning account (Los & Agter, 2005).

5.3. Influence of the FP-range

Experiment 3 used an FP-set with a very small FP-range, both in a simple and a choice RT condition. This change in the FP-range from Experiments 1 and 2 to Experiment 3 resulted in a reversal of the typical FP-RT effect in the simple RT condition, and in a strong flattening of the typical FP-RT effect in the choice RT condition. Whereas the typical asymmetrical sequential FP effect was also reversed in the simple RT condition, it was virtually absent in the choice RT condition. Hence, the RT pattern observed in the simple RT condition demonstrates that Karlin's (1959) finding of a reversed sequential FP effect is a robust phenomenon that occurs in simple RT tasks when the FP-range is very dense. We suggest that when the FP-range is very dense, the individuals may not represent three distinct imperative moments but a single relatively noisy one to which they attain preparation. The result pattern of the simple RT condition indicates that participants attained preparation at an early imperative moment because responses were especially fast and a high amount of anticipatory responses were observed in short FP_n trials. The observation of a reversed sequential effect, however, shows that the moment of peak preparation was still influenced by the preceding trial. We suggest that, although participants adjusted their moment of peak preparation in a trial-by-trial manner, they did not adjust between three distinct critical moments (as they would in situations with a broader FP-range) but in a rather analog fashion, by rescheduling a single moment of peak expectation. In particular, participants may have expected the IS after a short FP_{n-1} somewhat earlier, but after a long FP_{n-1} somewhat later in time.

Critically, when the small FP-range does not enable a sharp-edged representation of three distinct critical moments but only a noisy representation of a single critical moment, then the process that produces the asymmetrical sequential FP effects at short FP_n (namely conditioned inhibition of previously bypassed distinct imperative moments (Los & Van den Heuvel, 2001; p.

372; Los & Agter, 2005), is not expected to occur. As a consequence, no sequential FP effect in short FP_n trials should be expected in this situation. Importantly, a rather analog sequential adjustment of a single but early preparatory peak should result in a sequential modulation at later imperative moments, as is exactly observed in the simple RT condition of Experiment 3. We suggest that the reversed sequential FP effect resulted because the attained state of "early peak readiness" could be maintained for only a short time (i.e., about 0.3 s, Alegria, 1974; Alegria, 1975a; Gottsdanker, 1975), and thus participants had to rely on residual preparatory activity in long FP_n trials. Consequently, responses were optimally fast in short FP_n but varied in long FP_n trials according to FP_{n-1} .

Moreover, the flattened FP-RT function in the choice-condition, combined with the increased error rate at longer FP_n , is consistent with our interpretation that participants primarily prepared for a single early imperative moment. If temporal preparation had increased with FP_n -length, this should have resulted in more efficient performance. Note that this was exactly the case in the short FP condition of Experiment 2, in which RT decreased but error percentage remained constant (2%) with increasing FP_n .

The observed differences between simple and choice RT in Experiment 3 may be the result of processing differences involved in simple and choice RT performance. Whereas in the simple RT task, a state of motor readiness can be attained by solely elevating motor activation near the response threshold (i.e., temporal anticipation, Brunia, 1993; Mattes et al., 1997; Näätänen & Merisalo, 1977), a state of cognitive peak readiness, as is required in the choice RT task, involves less motor activation but is established by optimizing the allocation of attentional capacity at an expected moment of IS expectation (Los & Schut, 2008, pp. 41–42). Naturally, since cognitive processing (i.e., stimulus categorization, response selection) cannot start before IS presentation, a pure temporal anticipation strategy would produce a large error rate, thus preventing participants from temporally anticipating the IS. All in all, although simple and choice RT performance in Experiment 3 revealed clear differences, the results clearly show that when the FP-range is very dense and does not allow re-preparation, the asymmetrical sequential FP effect will not occur or will be even reversed.

6. Conclusion

In line with the predictions derived from conventional trace conditioning research, the present study demonstrates evidence that temporal trial-to-trial adaptation occurs within a very short variable FP context. This was independent of whether a choice RT or a simple RT task was used, and independent of whether anticipatory responses were prevented by employing the catch trial technique (Experiments 1 and 2). However, if the FP-range is dense and does not provide sufficient temporal uncertainty, the asymmetrical sequential FP effect does not occur in a typical fashion. This was examined in Experiment 3 in which we replicated the case of a reversed sequential FP effect with a simple RT task and with a very dense FP-range, as originally observed by Karlin (1959). In sum, the present findings are in line with the trace conditioning account of temporal preparation that considers trial-to-trial learning as a major factor that contributes to the ubiquitous FP-RT function in variable FP experiments (Los & Agter, 2005; Los & Van den Heuvel, 2001; Los et al., 2001).

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Appendix 1

FP-sets employed in several previous studies for assessing sequential FP effects

Study	FPs	Mean FP	RT task
Woodrow (1914)	4, 8, 12, 16, 20	12	Simple RT
Klemmer (1956)	0.2–2.2 3.2–5.2 6.2–8.2	1.25 4.25 7.25	Simple RT
Karlin (1959)	0.2–8.2	4.25	Simple RT
Drazin (1961)	0.4, 0.5, 0.6 0.8, 1.0, 1.2 1.6, 2.0, 2.4 2.8, 3.5, 4.2	0.5 1.0 2.0 3.5	Simple RT
	<i>Experiment 1</i>		
	0.5–2.5 1.0–2.0 1.25–1.75	1.5 1.5 1.5	
	<i>Experiment 2</i>		
Zahn and Rosenthal (1966)	0.125–1.125 0.25–1.25 0.5–1.5 1.0–2.0 2.0–3.0	0.625 0.75 1.0 1.5 2.5	Simple RT
	1, 3 3, 10	2.0 8.0	Simple RT
	2, 4, 8, 16	7.5	Simple RT
	2.5, 3.0, 3.5 2, 3, 4 1, 3, 5	3 3 3	Simple RT
	0.8–5.8 0.8–7.4 0.8–12.4	2.5 3.3 5.8	Simple RT
	1, 3, 5 1, 2, 3, 4, 5, 6 2, 4, 6, 8, 10, 12 4, 8, 12, 16, 20, 24	3.0 Simple RT Simple RT	Simple RT
Possamai, Granjon, Reynard, and Requin (1975)	1.5, 3.0	2.25	Simple RT
Alegria (1975a)	0.6, 0.7, 0.8	0.7	Simple RT
Alegria (1975b)	0.6, 0.7, 0.8	0.7	Choice RT
Alegria and Delhaye-Rembaux (1975)	1.5, 3.0, 4.5	3.0	Simple RT
Granjon and Reynard (1977)	1.5, 3.0	2.25	Simple RT
Granjon, Possamai, Reynard, and Oberti (1979)	1.5, 3.0	2.25	Simple RT
Los et al. (2001)	0.5, 1.0, 1.5	1.0	Choice RT
Los and Van den Heuvel (2001)	0.5, 1.0, 1.5	1.0	Choice RT

Study	FPs	Mean FP	RT task
Van der Lubbe et al. (2004)	0.5, 1.5, 2.5	1.5	Choice RT
Los and Agter (2005)	0.3, 0.6, 1.2	0.7	Choice RT
Los and Heslenfeld (2005)	0.4, 1.4	0.9	Choice RT
Vallesi, Shallice, and Walsh (2007)	0.5, 1.0, 1.5	1.0	Simple RT; choice RT

Note. FP-length is displayed in seconds (s); the table contains only studies with normal participants; clinical and developmental studies are not included.

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